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Review

Review of Key Technologies for Offshore Floating Wind Power Generation

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Abstract: In recent years, due to the global energy crisis, increasingly more countries have recognized the importance of developing clean energy. Offshore wind energy, as a basic form of clean energy, has become one of the current research priorities. In the future, offshore wind farms will be developed in deep and distant sea areas. In these areas, there is a new trend of floating offshore wind platforms replacing fixed wind power platforms, due to their low cost, ease of installation, and independence from the water depth. However, the stability of offshore floating platforms is poor and their power fluctuations are significant; furthermore, they are more prone to failure because of sea wind, waves, and currents. This paper summarizes and analyzes the current research progress and critical technical issues of offshore floating wind power generation, such as stability control technology, integrated wind storage technology, wind power energy management, and long-distance transmission of electricity for floating wind power generation at sea. Finally, future research directions for key offshore wind power technologies are presented.

Keywords: offshore wind energy; energy storage technology; energy management

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1. Introduction

With increasingly severe environmental and energy problems, people have realized the importance of developing clean energy. European countries, the United States, Japan, and other developed countries have invested in searching for new energy sources. There is a consensus to accelerate research into developing and utilizing nuclear, wind, solar, and other clean energy sources. More researchers are devoting themselves to the study of clean energy. Of clean energy sources, wind energy has been developed for the longest and is the most mature technology [1]. Thus, it is important to vigorously undertake the collection and utilization of wind energy.

There are many advantages to developing offshore wind resources compared to onshore wind resources. Firstly, the quality of wind energy at sea is good. Because the sea is smoother than land and has fewer obstacles, wind speed at sea is more stable, slightly fluctuating and infrequently changing, so the probability of turbine failure is lower. Furthermore, wind speed in the vertical direction does not significantly change, so wind energy is also higher at lower heights. Secondly, offshore wind farms can collect more wind energy. According to the statistics, the effective wind energy density in the coastal areas of southeast China is above 200–300 W/m^2. The number of hours of wind speed greater than or equal to 6 m/s is about 4000 h per year [2]. Thus, offshore wind farms can generate more electricity than onshore wind farms. Thirdly, offshore wind farms do not take up land resources. Offshore wind farms are built far from land. With today's increasing shortage of urban land resources, establishing offshore wind farms offers a new solution to the energy problems of coastal cities. With the development of wind power technology, the global offshore wind industry is increasing. According to the 2021 Global Wind Energy Council (GWEC) report [3], the cumulative global installed capacity of offshore wind power in 2020 was 35.2 GW, an increase of 21.4% year-on-year compared to 2019, as Figure 1 shows.

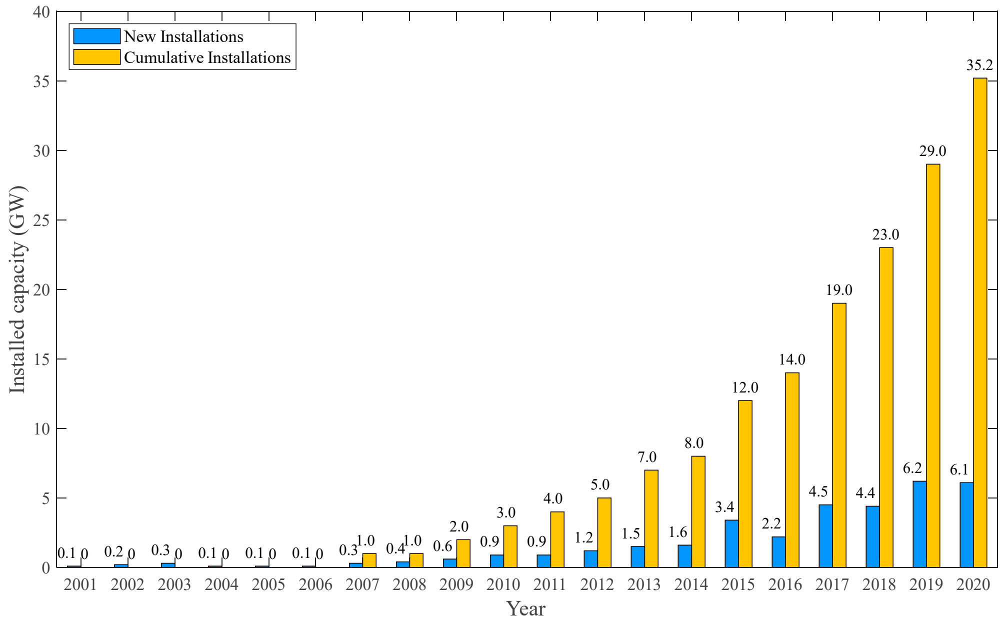

Figure 1. New and cumulative installed capacity of global offshore wind power from 2001 to 2020 [3].

Compared with coastal offshore wind power, far offshore wind power resources are more abundant, the available waters are more extensive, and the impact on the production and life of coastal residents and fishermen and the marine ecological environment is negligible. Therefore, offshore wind power is gradually developing toward the far offshore deep-sea zone. However, as the water depth increases, traditional fixed offshore wind turbines are costlier to install and more difficult to construct in deep waters [4,5]. Floating offshore wind turbines are not limited by water depth and can simplify unit lifting. Their installation costs are low, making the development of wind energy in the deep sea possible. Therefore, floating wind turbine technology has attracted increasing attention.

Although floating turbines have broader development and application prospects than fixed turbines, there are also more difficulties and challenges in developing and designing such turbines. Because floating wind turbines float on the sea surface and in both water and air, they are subjected to aerodynamic loads acting on the turbine blades like a fixed wind turbine, and also to hydrodynamic loads from currents and waves, as well as mooring loads from the mooring system acting on the supportive platform [6]. Especially in extreme conditions, the significant coupling of various loads causes floating wind turbines to have a considerable movement response, which may cause structural damage and even lead to the capsizing of the offshore wind platform. In addition, because the floating wind turbine will fluctuate up and down with the sea surface, its height position and tilt angle may change significantly in a short time, so its output power will change more obviously [7]. Therefore, the risk of wind turbine operation is increased. For floating offshore wind farms, each turbine's height and tilt angle may simultaneously differ [8]. Hence, the output power of each turbine greatly varies, which puts greater requirements on the energy management of floating offshore wind farms. In addition, achieving high efficiency and low loss of long-distance power transmission for offshore floating wind farms is also a pressing problem.

A study by [9] reviewed numerical methods for analyzing the aerodynamics of floating offshore wind turbines and the hydrodynamics of floating platforms, providing a reference for future aerodynamic and hydrodynamic analyses of offshore floating wind turbine platforms. It also provided suggestions for future work studying the dynamics of offshore floating wind turbine platforms. However, it did not consider the dynamic response characteristics of wind power platforms under the action of wind and wave coupling loads. Other studies [10,11] reviewed control techniques for floating offshore wind turbines. They classified the control methods of offshore floating wind turbines according to different control objectives and analyzed the advantages and disadvantages of each control method in detail, giving researchers a clearer perception of the various techniques in this field. However, they did not take into account the impact of the interaction of the wind turbines in the offshore wind farm on the control of the wind turbines. A study by [12] reviewed the existing methods for analyzing the combined environmental loads on the motion characteristics and structural response of floating offshore wind platforms. It provided a theoretical basis for subsequent research on improving the attitude stability of offshore floating wind turbines. However, it does not consider specific solutions for improving the stability of floating offshore wind turbines. A study by [13] reviewed the challenges and opportunities in the installation, operation, maintenance, and decommissioning of floating offshore wind turbines. It provided some new research directions for researchers in offshore floating wind power generation. However, it did not consider the key technologies and future research directions for integrated wind-storage offshore wind platforms. A study by [14] reviewed the research progress of integrated DC transmission systems for large offshore wind farms, and [15] reviewed critical technologies in multi-terminal DC transmission systems for offshore wind power based on modular multilevel converters. These studies summarized some new ideas, methods, and research directions for scholars studying the problems of offshore wind power grid connection. However, for floating offshore wind farms, power fluctuations are much more significant, putting higher requirements on the regular operation of DC transmission systems.

Today, many countries are increasing their efforts to develop offshore wind energy resources. However, many developers are discouraged by the high costs of manufacturing and installing fixed offshore wind turbines. The low cost of manufacturing and installing floating offshore wind turbines has made them a new option for offshore wind resource development. However, there are often greater technical challenges when using floating offshore wind turbines for offshore wind energy development. Therefore, in this paper, we provide an overview of these problems and their solutions. We hope this paper will serve as a reference for developers of offshore wind resources to generate ideas and to solve the problems that have been encountered during the construction of existing offshore floating wind power plants.

We designed this paper according to the actual construction process of an offshore wind farm, i.e., designing the structure of the offshore wind turbine, equipping the offshore wind power with energy storage, managing the energy between multiple offshore wind turbines, and sending the offshore wind power to the shore for grid connection. Through this paper, we hope to provide offshore wind resource developers with a comprehensive understanding of the key technical issues faced when constructing a floating offshore wind farm. Therefore, this paper is organized as follows. The structure and stability control of offshore floating wind turbines are given in Section 2. Section 3 presents offshore energy storage integrated with wind power generation technology. Section 4 illustrates energy management technology for offshore wind power generation. Section 5 presents long-distance DC transmission technology for offshore wind power. Section 6 provides an outlook on future research directions in floating offshore wind power. Section 7 concludes this paper.

2. Floating Offshore Wind Power Generation Technology

2.1. *Types of Floating Wind Turbines*

Currently, the dominant offshore floating wind power platforms are spar-buoy platforms (spar), semi-submersible platforms (semi), tension leg platforms (TLP), and barge platforms (barge) [16]. The four structural forms are shown in Figure 2. The design center of gravity of the Spar is much lower than its floating center, and the interaction of gravity and buoyancy is used to make the platform stable. This kind of platform is less affected by the action of currents and has better overall stability. However, because of its larger draft volume and its single submerged column usually being longer, this kind of platform often has specific water depth requirements, generally greater than 100 m [17].

A semi is designed with distributed semi-submersible floats around the turbine. When the platform is subjected to the action of sea wind and currents, a controller can control the gravity and buoyancy of the distributed floats to adjust the attitude of the offshore platform to resist the action of external forces [18]. However, the control method of this platform is more complicated, especially in the harsh marine environment, and the controller's requirements are more demanding.

The buoyancy of the TLP is much greater than its gravity, and the bottom of the platform is connected to a fixed pile on the seabed through a tension tendon. The platform is stabilized by the interaction of the excess buoyancy generated by the platform in the water and the tension of the tendon, which tightens the whole system vertically. The longitudinal oscillation of this platform is small and its stability is good. However, the tension tendon is subject to significant tension, which can cause damage and lead to severe accidents on the platform [19].

Barge-type platforms (Barge) draw on the buoyancy principle of barges and use the buoyancy of the platform to counteract gravity. This kind of platform is easy to install and is less costly. However, it is more sensitive to the fluctuation of seawater and is less stable [20]. It is generally only applicable to areas where the seawater fluctuation is not considerable.

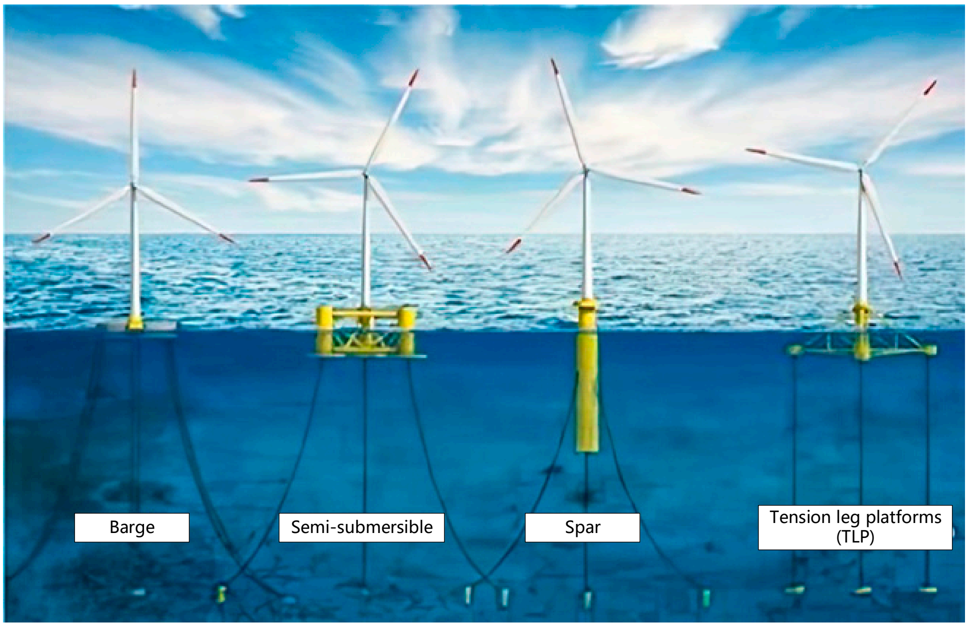

Figure 2. Four types of offshore floating wind power platform structures [21].

2.2. *Attitude Stability Control Technology for Floating Offshore Wind Turbines*

Attitude stability control of offshore floating wind turbines is usually achieved by means of structural control. Depending on the method used, structural control schemes can be broadly categorized into three main groups: passive, active, and semi-active control. In passive control, the parameters are constant, and no external forces are required; therefore, there is no need to provide energy [22]. In semi-active control, the coefficients of the damping devices (usually springs and dampers) are tuned by closed-loop control algorithms in response to the dynamics of the structure. Finally, active methods are more complex and require an actuating force. One actuator that can be used to reduce the vibration is a pitch actuator, which is used to control the angle of the blades and can reduce tower acceleration [23]. One approach using this active control strategy to reduce the vibration of the tower of a wind turbine using pitch angle control is called active tower damping (ATD), where the parameters are optimized to dampen the vibrations [24].

A floating offshore wind turbine will fluctuate up and down and oscillate back and forth with the change of waves, making it prone to capsizing and collapsing in the harsh offshore environment, so it is crucial to maintain the stability of the floating offshore wind turbine attitude. Currently, tuned liquid dampers (TLDs) and tuned mass dampers (TMDs) are widely used to stabilize offshore floating wind turbines. TLDs are usually installed on the bottom of offshore wind platforms. They use the wave forces generated by the swaying of the water in the TLDs to dissipate energy and, thus, counteract the effects of unbalanced forces on the wind turbine. A tuned liquid column damper (TLCD) is a variation of a TLD that dissipates energy through water flow between two water columns [25]. When the platform tilts, the damper can change the position of the center of gravity of the damper by adjusting the weight of the two ends of the U-tube through the action of a valve, thus resisting the unbalanced external forces to restore the attitude of the offshore platform. Multiple TLCDs are connected to form a multi-tuned liquid column damper (MTLCD) [26]. This structure is more robust to oscillations and can effectively reduce the parasitic oscillations generated by the system. Jaksic et al. [27] analyzed the effect of an MTLCD on the dynamic performance of a tension-leg wind power platform; the analysis showed that the MTLCD could significantly reduce the dynamic response of a tension-leg wind power platform. A tuned liquid column-gas damper (TLCGD) uses a gas spring effect in the sealed column of the TLCD. This structure controls the vibration frequency of the liquid, thus providing an additional option for tuning the frequency of the TLCD [28]. In addition, Hokmabady et al. [29] combined a tuned liquid column ball gas damper (TLCBD) and a TLCGD to form a tuned liquid column ball gas damper (TLCBGD). Compared with the TLCGD system, the TLCBGD system has a better vibration suppression effect. However, the manufacturing cost of TLCBGD is greater and the control process is more complex. The basic structures of several tuned liquid dampers are shown in Figure 3.

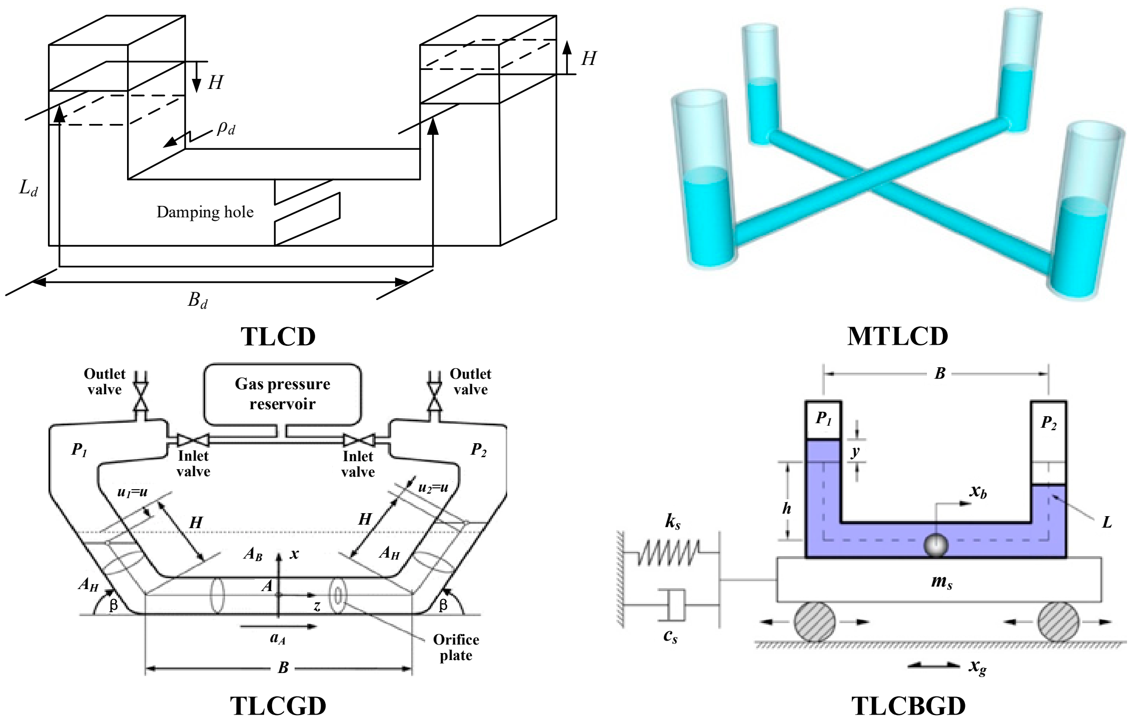

Figure 3. Schematic diagrams of the structures of several types of tuned liquid dampers [26,29–31].

A TMD is usually installed in the nacelle of a wind turbine and consists of a mass block, a damping element, and a controller. When the system is unbalanced, the position of the mass obstruction in the damper can be controlled by the controller to change the system's center of gravity, thus restoring the system to equilibrium. Yang et al. [32] designed tuned mass dampers for barge-type offshore wind turbine platforms and analyzed the TMD mass ratio and TMD gravity moment effects on the vibration suppression effect. Some of the main parameters of the designed TMD are shown in Table 1. In addition, Yang et al. used the GA algorithm to optimize the parameters of the TMD and found the optimal mass ratio of a barge-type TMD to be around 19%. However, whether this mass ratio is also optimal for other forms of floating wind platforms has yet to be verified. Dinh et al. [33] considered the aerodynamic characteristics of the blade, variable mass and stiffness per unit length, gravity, and the interaction between the blade, nacelle, mast, mooring system, and TMD, and compared and analyzed single-column offshore wind platform lateral vibration passively controlled by a single-tuned mass damper and a multi-tuned mass damper. A single TMD could reduce up to 40% of the nacelle sway displacement and the spar roll, and the reduction observed with multiple TMDs was 50%. The influence of the spar TMD is more significant than that of the nacelle TMD. Spar TMDs are less effective when their positions are lower. An eddy current tuned mass damper (EC-TMD) utilizes the principle of eddy current damping, which is friction-independent, does not produce fluid leakage, does not require sealing to be considered, and has promising applications [34,35]. Two types of EC-TMDs that have received attention from scholars are horizontal eddy current-tuned mass dampers (HEC-TMDs) and pendulum eddy current-tuned mass dampers (PEC-TMDs), the structures of which are shown in Figure 4. The dampers have been analyzed and verified to reduce the vibration displacement at the top of offshore wind turbine towers under extreme wind loads [36]. Yang et al. [37] proposed magnetic rheological elastomer (MRE)-based tuned mass dampers for offshore wind turbines. Their magnetorheological elastomer can rapidly change its elastic modulus through magnetic field changes to achieve a fast response of the damper to unbalanced forces. Jahangiri et al. [38] proposed a three-dimensional control method for multiple-tuned mass dampers for single-column offshore wind turbine platforms. They showed that the control method could effectively reduce the three-dimensional vibration of the tower and platform under extreme conditions.

Table 1. Primary parameters of a barge-type wind turbine [32].

Primary Parameters	Values
Rotor, hub diameter	126 m, 3 m
Hub height	90 m
Rotor mass	110,000 kg
Nacelle mass	240,000 kg
Tower mass	347,460 kg
Platform mass (including ballast)	5,452,000 kg
Platform dimensions	$40 \times 40 \times 10$ m^3
Length from the reference point to the platform mass center and the portion above the mean sea level	0.28 m, 63.90 m

2.3. Response Characteristics Analysis of Floating Wind Turbine under Wind and Wave Loads

The main cause of instability of offshore floating wind platforms is the effect of wind and wave loads at sea, and research has shown that wind and wave loads have different effects on the floating body system [39]. The wind load is the main cause of the longitudinal deflection of the system and must be overcome by the anchor chain connected to the seafloor, while the wave load mainly causes the periodic longitudinal sway of the system. The effects of wind and wave loads on stiffness must be considered when designing anchor chains, support plates, and other rigid structures. Therefore, correct analysis of the effects of wind and wave loads on the aerodynamic and hydrodynamic performance of offshore floating wind turbines is of great importance for the design of stable structures, control methods, and related parameters for offshore wind platforms. Li et al. [40] studied the effects of a uniform wind field, steady wind field with wind shear, and turbulent wind field on the power generation and aerodynamic performance of offshore floating wind turbines. The results reveal that wind shear and incoming turbulence have a significant effect on the stability of floating wind turbines. For a six-degree-of-freedom offshore floating wind turbine, the wheezing and pitching motions impact the wind turbine's power output. Jang et al. [41] discussed the non-constant aerodynamic performance and instability of floating wind turbines using a non-constant lifting surface approach based on a free wake model. The results show that a floating turbine may have greater aerodynamic power output under the certain longitudinal motion of the platform. Chen et al. [42] investigated the aerodynamic characteristics of floating offshore wind turbines under the simple harmonic motion of the platform with different periods and amplitudes using computational fluid dynamics simulations with coupled dynamic and sliding mesh techniques and the non-constant Reynolds-averaged Navier–Stokes method. The results show that combined longitudinal rocking motion reduces a floating wind turbine's average power generation, indicating that the complex platform motion can adversely affect the power generation of floating offshore wind turbines. Wen et al. [43] investigated the effect of surge motion on floating offshore wind turbine power and thrust characteristics using a free-vortex approach.

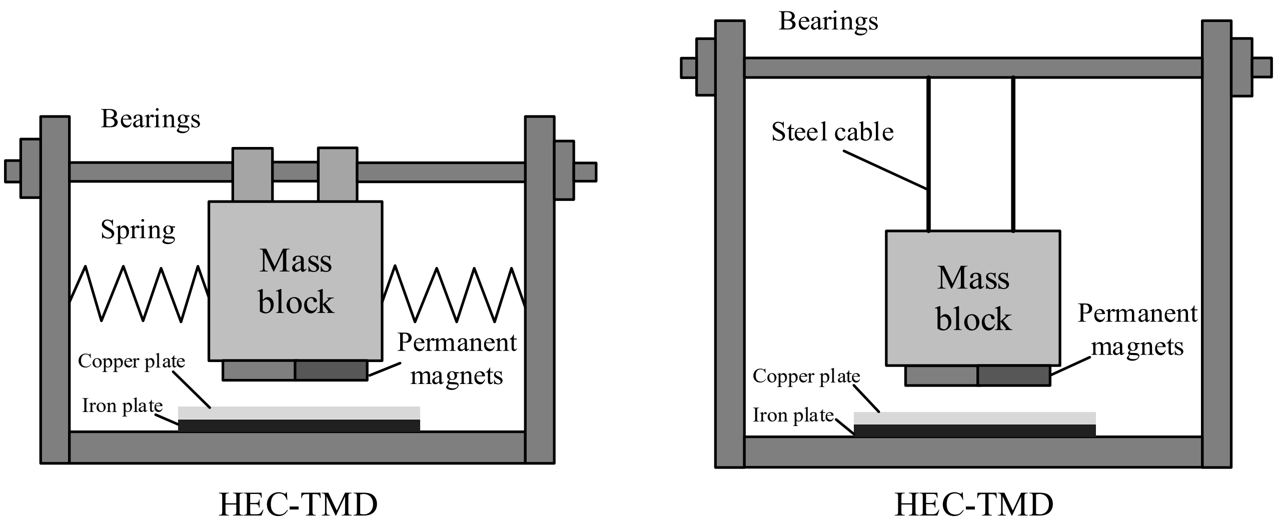

Figure 4. Schematic diagram of two types of EC-TMD structures [36].

3. Floating Offshore Wind Storage Integration Technology

Compared to fixed offshore wind turbines, the output power of floating offshore wind turbines is more volatile, intermittent, and irregular, which can cause shocks and hazards to the grid if directly connected. Equipping floating offshore wind turbines with a suitable energy storage system is the primary way to improve their power stability. At the same time, the energy storage system can also alleviate offshore wind power's "wind abandonment" problem. The basic architecture of an offshore floating wind farm with energy storage is shown in Figure 5. Each offshore floating wind turbine transmits the collected power through a transformer to an offshore distributed energy storage plant, which selects charging or discharging according to power fluctuations to ensure stable power output, and finally transmits it to the shore for grid connection through high-voltage DC transmission.

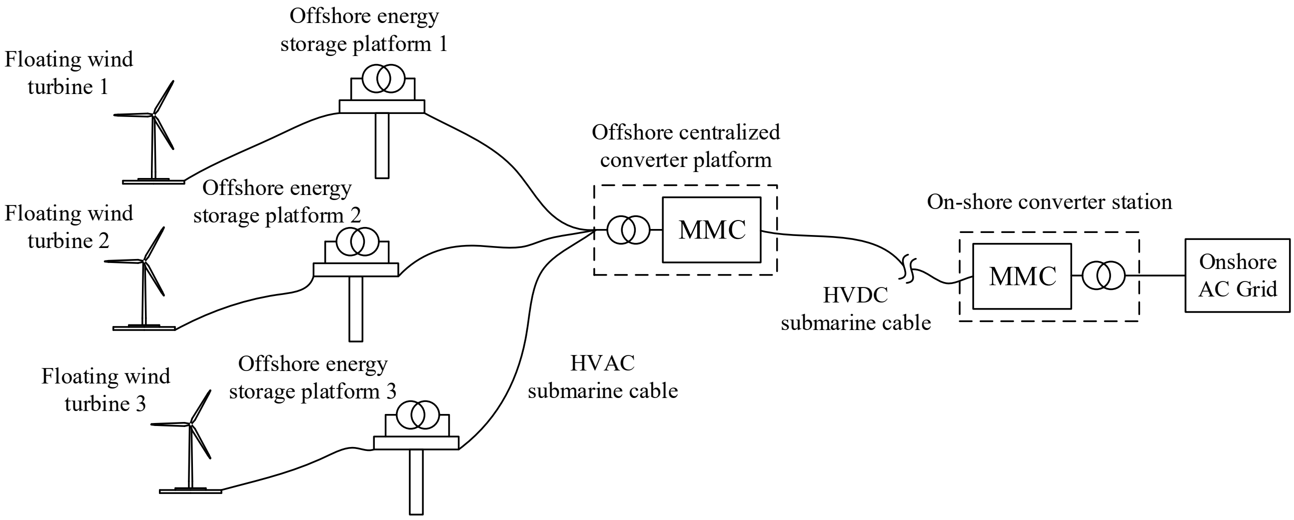

Figure 5. The basic architecture of an offshore floating storage-integrated wind farm.

3.1. Offshore Energy Storage Technology

3.1.1. Pumped Storage

Offshore pumped storage is the most extensive and technically mature offshore energy storage system available [44]. It can also provide higher power ratings (>100 MW) than any other storage technology, except compressed air energy storage [45]. Traditional forms of pumped storage use the interconversion of electrical energy from water and gravitational potential energy, which requires two reservoirs of different heights. When the system needs energy storage, electrical power drives the pumping motor to pump water from the lower reservoir to the higher reservoir, thus converting electrical energy into gravitational potential energy storage. When electrical power is needed, the controller opens the water valve connecting the two reservoirs and water from the higher reservoir flows into the lower reservoir to drive a turbine, generating electricity for the system. This method requires the construction of a sizeable, pumped hydropower plant, which is costly. Offshore pumped storage has the natural advantage of abundant seawater resources. Ioakimidis et al. [46] analyzed the economics and feasibility of integrating seawater-pumped storage into the energy system of San Miguel Island (Azores). The results showed that implementing the storage system would allow for more reliable use of intermittent energy on the island and increase renewable energy sources, thus reducing fuel imports and generating significant economic benefits. In 2016, in the German StEnSea project, M. Puchta et al. [47] proposed a novel form of offshore pumped storage. As shown in Figure 6, this form takes advantage of the hydrostatic effect of water in the deep sea. A hollow concrete sphere is installed in deep water for energy storage. When the system needs to store energy, electrical energy drives the pumping motor to pump the water out of the concrete sphere. When energy needs to be released, seawater flows into the concrete ball under the action of deep-sea hydrostatic pressure and drives the turbine to generate electricity. In 2017, this form of pumped storage was successfully tested in a pilot experiment at Lake Constance, as shown in Figure 7. Hahn et al. [48] conducted a preliminary techno-economic assessment of the StEnSea concept for power balancing services. The results showed that the StEnSea storage could be cost-competitive compared with commercialized pumped storage technologies.

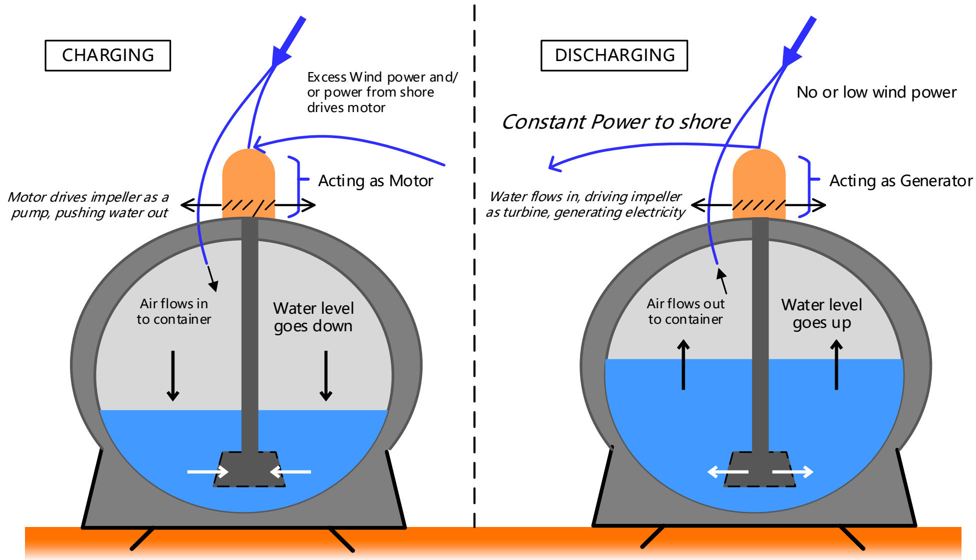

Figure 6. The new form of underwater pumped storage in the StEnSea project in Germany [47].

3.1.2. Compressed Air Energy Storage

Underwater compressed air storage is another offshore energy storage technology with great potential for development. Compared with onshore compressed air storage, its technical characteristics lie in its process of compressing air and releasing it, often with the help of underwater pressure, which makes it work at a much lower cost. Underwater compressed air energy storage can be divided into rigid and flexible container storage forms. A rigid storage container has a fixed shape and volume, and its storage chamber and the outside world are connected. Therefore, the entry and exit of air can be controlled by the inflow and outflow of seawater into and out of the storage chamber. A flexible gas storage container does not have a fixed shape and volume, and seawater cannot enter the storage chamber. It works by using underwater pressure to control the volume of the flexible gas storage container, thereby controlling the flow of air in and out of the storage container [49]. Underwater compressed air storage often consists of a compressor, expander, and heat storage system [50]. As Figure 8 shows, when the system stores energy, the motor drives the compressor, which compresses the air and generates heat. The heat storage system stores this heat and the cooled air is stored in the storage container. When the system needs to release electricity, the air in the storage vessel is pumped into the expander under the action of seawater, and the heat storage system in the expander exothermally expands the air, driving the power generation device to generate electricity.

The grid-connected architecture of an offshore wind farm with offshore compressed air energy storage is shown in Figure 9. Its gas storage unit is installed on the seafloor, and an energy conversion unit is built on the surface and connected to the onshore grid through a subsea cable. To improve the efficiency of underwater compressed air storage, offshore energy storage power plants often design multi-stage underwater compressed air storage structures. Wang et al. [51] proposed a new multi-stage underwater compressed air structure. Each stage is located at a different depth so that the air can be compressed step by step, thus greatly improving the offshore compressed air storage's energy consumption and efficiency. Guo, Xu et al. [52] analyzed the underwater compressed air energy storage system's thermodynamic and economic depth coupling characteristics based on the flexible heat exchanger model. They obtained the coupling relationship and optimal design range between the key parameters of the underwater compressed air energy storage system.

Figure 7. Lake Constance offshore pumped storage experiment in 2017 [53].

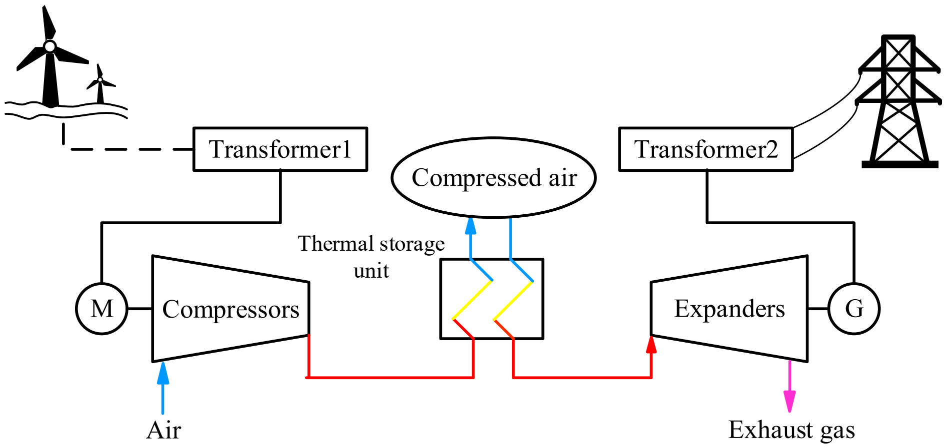

Figure 8. The basic workflow of offshore compressed air energy storage [49].

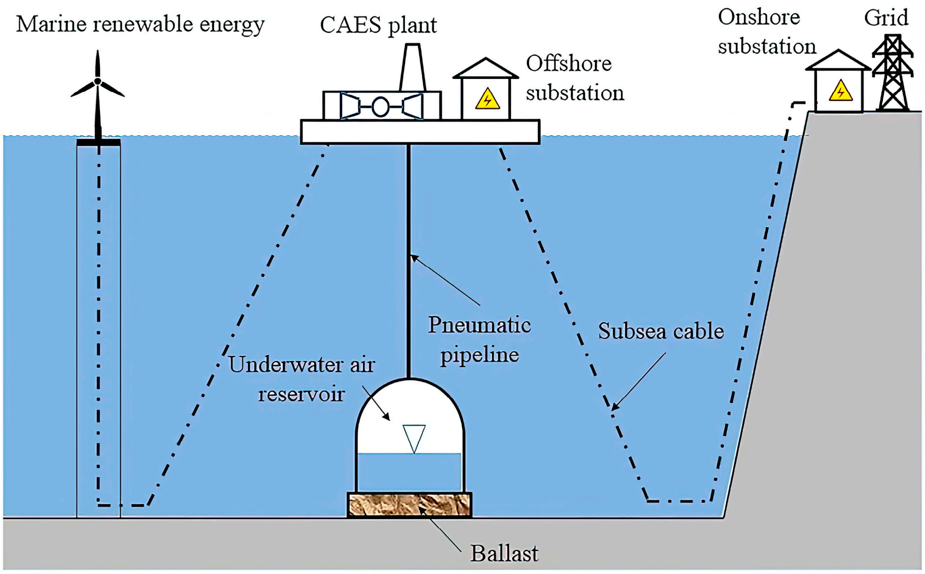

Figure 9. Schematic diagram of an offshore wind farm with offshore compressed air energy storage connected to the grid. CAES stands for compressed air energy storage [53].

3.1.3. Electrochemical Energy Storage

Offshore electrochemical energy storage is offshore battery energy storage. Due to the particular characteristics of the offshore environment, to be suitable for floating offshore wind platforms, electrochemical energy storage batteries generally require:

(1) Adaptation to the ambient temperature at sea;
(2) Adaptation to vibration and shock;
(3) Adaptation to humidity, salt spray, and moldy working environments;
(4) No environmental hazards from battery leaks.

For a long time, the above requirements have limited offshore applications of electrochemical energy storage. Moreover, a larger power input–output of the energy storage system is required for large offshore wind farms, which puts higher demands on offshore electrochemical energy storage. The most widely used and extensive battery energy storage materials are lead–acid batteries, Li-ion batteries, and sodium–sulfur batteries [53]. Lead–acid batteries are the oldest and most widely used secondary batteries. However, they still present many challenges: toxicity, environmental pollution, short life cycle, poor deep discharge and low-temperature performance, low energy density, hydrogen precipitation, etc. However, lead–acid batteries accounted for the largest share of utility-scale BES systems until 2013 due to their mature and relatively inexpensive technology [54,55].

Compared to lead–acid batteries, Li-ion batteries offer significantly better overall performance: higher round-trip energy efficiency, a longer life cycle, higher energy density, and less environmental pollution. However, Li-ion batteries are more expensive because each cell requires overcharge protection circuitry, and conventional electrode materials are expensive. In addition, overheating is a common problem with Li-ion batteries, which can degrade the performance of batteries and increase the risk of fire and explosion [56].

Currently, NaS (sodium–sulfur) batteries are the most mature high-temperature batteries. A thermal management system is required to maintain a temperature of approximately 300 °C to 350 °C, thus ensuring that the electrodes (molten sodium and molten sulfur) remain in a liquid state. NaS batteries have many advantages over lithium-ion batteries. First, they have excellent fast response performance, allowing full power discharge and charging within 2 ms. Secondly, they are more economically competitive than Li-ion batteries due to cheaper materials, and their economic viability increases with scale-up. Third, self-discharge is almost negligible. Fourth, NaS batteries are easier to maintain [54]. In addition to the above forms of battery energy storage, Simpson et al. proposed using liquid metal batteries for energy storage in offshore wind power generation. Compared with Li-ion batteries, liquid metal batteries have a lower cost and longer life, and their chemical composition is neither volatile nor flammable, making them safer [57].

3.2. Control and Optimal Scheduling of Integrated Offshore Wind Storage System

After determining the form of energy storage equipped for offshore wind power, another important topic is how to improve the output power quality of offshore wind farms through the control method of the energy storage system. There are two critical aspects to improving power quality: one is to reduce the fluctuation of the wind farm output power to reduce the impact of the wind power plant on the grid, and the other is to improve the frequency stability to ensure the safe operation of the wind farm.

The main methods of suppressing the power output fluctuations of wind farms are the sliding average filtering method and the wavelet packet decomposition method. The principle of the sliding average filtering method is to sum the latest obtained wind output power value with the n most recent historical wind output powers and take the average value. This average value is used as the target output power of the wind turbine. Finally, the target power of the wind turbine and the actual output power are used to calculate the compensation power of the energy storage. This method is simple and easy to implement, and has a significant suppression effect on periodic power fluctuations. However, it often poorly suppresses the occasional impulse-type disturbances in the wind power generation process, and may even produce severe oscillations. The wavelet decomposition method can decompose the fluctuating wind power into different frequencies. The low-frequency power that meets the requirements of wind power fluctuation is used as the target output power of wind power. In contrast, the power of other frequencies is used as the compensation power of the energy storage. The wavelet decomposition method has obvious advantages in applying hybrid energy storage for wind power leveling, which can allocate wind power of different frequencies to different forms of energy storage to compensate according to the different response speeds of different forms of energy storage. The disadvantage of wavelet decomposition filtering is the difficulty of calculation and slow calculation speed. In addition, the choice of wavelet scale for wavelet decomposition is difficult. Power noise influences the filtering effect on a small scale. At large scales, it causes the filtered power to lose some important local singularities. Zhang et al. [58] proposed a control strategy consisting of a sliding average filtering method and a model predictive control method for coordinated operation. The strategy integrates the BESS output, the SOC of BESS, and the joint wind-storage output power smoothing effect to achieve optimal control of BESS. Simulations show that this strategy has a better power smoothing effect than conventional low-pass filtering and limits the SOC of the BESS to a specific interval, thus reducing the BESS's maximum charge/discharge depth and saving the investment cost of energy storage. Liu et al. [59] applied the wavelet packet decomposition algorithm to smooth wind power fluctuation. By comparing the empirical modal decomposition algorithm, the results show that the wavelet packet decomposition algorithm can save the maximum charging and discharging power of energy storage and use capacity under the same wind power fluctuation limit.

The principle of energy storage participation in wind farm frequency regulation and improving the frequency stability of wind farm power systems is to take advantage of the correlation between power system frequency and active power. There are huge advantages of energy storage systems in the frequency regulation of wind farm power systems. The frequency regulation capacity of the energy storage system is 3.3 times higher than the frequency regulation capacity of traditional units. The response of energy storage systems is fast, their power can be bi-directional, and their ability to track minor disturbances is vital. Zhang et al. [60] proposed a coordinated frequency regulation control strategy for wind storage systems based on synchronous virtual machine (VSG) technology, which can significantly reduce the capacity configuration of the energy storage system and improve the frequency regulation of wind farms by stabilizing the system frequency. Li et al. [61] proposed a fuzzy control strategy to coordinate the dynamic frequency response of wind storage systems that fully uses the active reserve margin of wind turbines and the limited capacity of energy storage devices to realize the dynamic cooperative operation of wind power and energy storage.

Although the above control methods can reduce fluctuations in wind farm output power and frequency, the weather significantly impacts offshore wind farms. Control methods for onshore wind farms often cannot meet the grid requirements for power and frequency fluctuations when applied to offshore wind farms, especially when extreme weather such as hurricanes and typhoons occur at sea. In this regard, Su et al. [62] used a fast unfolding cluster algorithm to partition the offshore wind power cluster by optimizing the modular function; then, using the cluster as a unit, the offshore wind power output is optimized by energy storage to reduce the fluctuation of the offshore wind power output. Ji et al. [63] proposed a synergistic control scheme for an integrated wind energy conversion system based on offshore semi-direct drive wind turbines with battery energy storage. The energy storage system is used to maximize the utilization of offshore wind power and as a backup power source for the wind turbine auxiliary system during typhoon periods. The scheme involves two main modes of operation: grid-connected mode and off-grid mode. Typically, an offshore wind storage system works in grid-connected mode, capturing wind energy, generating electricity, and supplying it to the load through the transmission system. When a typhoon hits, it switches to grid-disconnected mode to protect the variable speed wind energy conversion system (WECS) of the semi-direct drive wind turbines and the grid from safety incidents. Falcão et al. [64] used energy storage systems to improve the transient response of offshore wind farms when there is a failure in the offshore wind farm by adjusting the input and output of the battery storage system to control frequency shifts. Liu et al. [65] investigated the configuration principle of energy storage participation in frequency regulation, enabling electrochemical energy storage to participate in frequency stabilization under droop control and virtual inertia control. The control methods of the above offshore wind storage integration systems are summarized in Table 2.

Table 2. Offshore wind storage integrated system control methods.

Ref. No.	Method	Characteristics
[61]	Fast unfolding clustering algorithm.	Reduces fluctuations in offshore wind power output.
[63]	Offshore wind storage cooperative power control.	Maximizes offshore wind utilization and protects the grid and wind farms during typhoon periods.
[64]	Offshore wind storage cooperative frequency control.	Mitigates frequency shifts in case of faults in offshore wind farms or onshore grids.
[65]	Offshore wind storage cooperative frequency control.	Enables electrochemical energy storage to participate in frequency stabilization with droop control and virtual inertia control.

Equipping offshore wind farms with energy storage systems is one of the more popular ways to mitigate fluctuations in wind farm output power and imbalances in power generation and demand. However, energy storage systems are expensive to install, have a limited operational life, and often have different storage operating costs for charge and discharge depth conditions. In addition, the factors that affect the operating cost of the integrated offshore wind storage system are the operation and maintenance costs of the offshore wind turbine, the maximum and minimum wind speed limits, and the fatigue load power loss. Therefore, how to adjust the charging and discharge control strategy of energy storage to reduce the operating costs of the integrated wind storage system while ensuring the output power quality of offshore wind farms is also an important issue.

Wind storage-integrated system scheduling methods are mainly classical mathematical, planning-based, and heuristic algorithms. The advantages of classical mathematical methods are tight mathematical reasoning and the ability to achieve real-time processing. However, such methods rely on explicit expressions of objective functions. The processing results may be poor for scenarios that are difficult to abstract into explicit mathematical expressions or where the expressions change over time. Planning-based methods are suitable for handling time-series-related decision problems, but they are computationally expensive and do not enable real-time decision-making. Heuristic algorithms can solve problems with larger data sizes and more complex scenarios. However, these methods are less robust and cannot be rigorously mathematically proven. Paul et al. [66] proposed a multi-objective optimization framework for optimal battery storage system capacity for the coordinated operation of large offshore wind farms and battery storage systems. The framework integrates battery cost and lifetime, wind turbine availability, unprovided expected energy, load hour losses, and wind energy constraints. It minimizes the mismatch between the predicted generation schedule and the actual generation. However, this method requires a large amount of environmental data and is computationally complex. Tian et al. [67] considered a voltage source converter's capacity limitation and the coordination role of offshore wind farms and battery storage systems. They proposed a multi-period optimal scheduling model based on a voltage source converter for multi-terminal DC (VSC-MTDC) systems and AC grids. The scheduling method can obtain the offshore energy storage system's optimal charging and discharging power. The coordination with the generation of the offshore wind farm can adjust the wind energy injected into the AC grid to meet the load demand

and minimize the total operating cost. Wang et al. [68] proposed an optimization and control method for offshore wind power systems with energy storage based on economic model predictive control (EMPC). This method can improve wind farms' efficiency and economic performance through overall system optimization while explicitly operating each wind turbine using a formally designed control framework, thereby extending its lifetime. However, this control method requires strict accuracy of the environmental model. If the environmental model of the offshore wind farm is not accurate enough, it will not be easy to obtain practical scheduling results. Liu et al. [69] used the improved non-dominated sorting genetic algorithm-II (NSGA-II) to solve the multi-objective scheduling problem to minimize the total operating cost and power loss. Simulation results show that the proposed method effectively improves the operational performance of the offshore wind farm and achieves the optimal operating cost and minimum power loss. However, this method may fall into the local optimum and not find the global optimum scheduling solution during calculations. The optimal scheduling methods for the offshore wind storage integrated systems above are summarized in Table 3.

Table 3. Offshore wind storage integrated system scheduling method.

Ref. No	Method	Advantages	Disadvantages
[66]	Multi-objective optimization framework.	Integrates battery cost and lifetime, wind turbine availability, unsupplied expected energy, load hour losses, and wind energy limitations.	Requires large amounts of environmental data and complex calculations.
[67]	Multi-cycle optimal scheduling model.	Allows optimal charging and discharging power for offshore energy storage systems and minimizes total operating costs.	Long calculation time.
[68]	Economic model predictive control.	Improves the efficiency and economic performance of wind farms while extending the lifetime of energy storage systems.	The accuracy of the environmental model has a large impact on the control effect.
[69]	Improved NSGA-II.	Effective improvements in operating costs and power loss minimization.	Easy to fall into local optimum.

4. Energy Management Technologies for Offshore Wind Power

4.1. Offshore Wind Power Prediction Techniques

Wind power prediction technology is an essential means to achieve energy management and optimal scheduling of offshore wind power. The most commonly used wind power prediction methods can be divided into physical and artificial neural network methods [70]. The physical method refers to taking the local meteorological and surface information as the initial conditions, using a computer to solve the mathematical relationship between the wind turbine speed and the local meteorological and surface information satisfied, and then obtaining the output power from the output power curve of the wind turbine. Since this method essentially solves a system of differential equations to obtain the output power, it does not require historical data but only current data information. However, the physical modeling process of this method is very complex and computationally intensive [71]. The output power obtained by this method is often in error with the actual output power due to the variability of various environmental conditions. Therefore, the physical method is often used for medium-term or long-term wind power predictions, especially in the siting of wind farms [72].

The artificial neural network approach aims to develop a nonlinear and linear relationship between wind speed, wind direction, temperature data, and power generation. Previous historical data is used as training data to define this statistical relationship. An artificial neural network model typically consists of an input layer, one or more hidden layers, and an output layer [73,74]. Each layer consists of processing units called neurons, connected by certain weight relationships. The artificial neural network gradually corrects these weight relations by comparing the errors in model predictions and online power measurements through a training process and compensates for the errors in the system. Afterward, the neural network will predict the wind power output from the data obtained from past and current measurements. Artificial neural network-based wind power prediction methods are easy and inexpensive to model and robust [75,76]. However, neural networks usually require a certain learning time to achieve the required prediction accuracy of the system. Moreover, prediction is generally short-term and prediction accuracy decreases as the prediction time increases [77,78].

Compared with onshore wind farms, offshore wind farms are more influenced by weather factors, and there is usually a problem of the wake effect affecting the prediction of offshore wind power, so appropriate improvements are often needed when using the above prediction methods for power prediction of offshore wind farms. Su et al. [79] proposed an ultra-short-term offshore wind power prediction model based on a dual-attention long short-term memory (LSTM) network. The method introduces a feature and temporal dual-attention mechanism based on the LSTM neural network, which improves the accuracy and interpretability of ultra-short-term offshore wind power predictions. However, the computation time of LSTM neural networks is much longer than that of traditional neural networks. Fu et al. [80] proposed an improved long short-term memory-temporal convolutional network (LSTM-TCN) model for ultra-short-term offshore wind power prediction. The model considers the state of offshore wind turbines, turbine wake, and spatial distribution characteristics of the field cluster, making it highly adaptable to abrupt changes in offshore wind speed and other operating conditions. Qi et al. [81] considered the atmospheric stability inside an offshore wind farm. They used the encoding–decoding framework of the power wind model for power prediction of an offshore wind farm, which corrected the power loss due to the poor atmospheric stability and thus reduced the power prediction error. However, using convolutional neural networks to optimize LSTMs may cause overfitting problems in LSTMs. Lu et al. [82] proposed a new two-stage hybrid model to predict short-term wind power. The first stage uses a complete integrated empirical mode decomposition with adaptive noise to preprocess the raw data to make it smoother. The second stage uses a multi-objective gray wolf optimizer to optimize the prediction model to ensure the stability and accuracy of the prediction. However, this method demands a large amount of computer memory in the calculation process, which requires high computer performance. Lin et al. [83] proposed a new method for power prediction based on isolated forests and deep learning neural networks to mitigate the impact of data outliers on prediction in an offshore monitoring and data acquisition system. The method has better prediction characteristics with sensors generating uncalibrated data due to performance degradation. However, this method often does not work well when dealing with environmental data with noise. Zheng et al. [84] designed a deep neural network for offshore wind power prediction. They compared the deep neural network prediction results with BP neural and wavelet neural networks. The comparison results show that the proposed method can better cope with the uncertainty of data. However, again, this method often only works well when dealing with environmental data without noise. Dokur et al. [85] proposed a hybrid offshore wind power prediction model based on swarm decomposition (SWD) and a meta-extreme learning machine (Meta-ELM). The signal is decomposed by implementing a population prey algorithm in SWD to determine the redundant information in the wind speed dataset. At the same time, the Meta-ELM provides faster computational speed and a lower computational burden. Several of the above methods for offshore wind power prediction are summarized in Table 4.

Table 4. Offshore wind power output prediction methods.

Ref. No.	Method	Advantages	Disadvantages
[79]	Double attention LSTM.	Improves the accuracy and interpretability of ultra-short-term offshore wind power output prediction.	Long calculation time.
[80]	Improved LSTM-TCN model.	Strong adaptability to common offshore conditions, such as sudden changes in wind speed.	Overfitting problems may occur.
[81]	Encoding–decoding framework for wind power model.	The atmospheric stability inside the offshore wind farm is considered to correct for the loss of the wake effect due to poor atmospheric stability.	The calculation process requires a large amount of computer memory.
[82]	Multi-objective gray wolf optimizer.	Effective improvements in operating costs and power loss minimization.	Easy to fall into local optimum.
[83]	Isolated forests and deep learning neural networks.	Improved stability and accuracy of predictions.	Does not work well with noisy data.
[84]	Deep neural networks.	Better copes with data uncertainty.	Network parameters are more difficult to adjust.
[85]	Swarm decomposition (SWD) and meta-extreme learning machine (Meta-ELM).	Faster and lower computational burden.	The computational accuracy of meta-limit learning machines is not as high as that of traditional neural networks.

4.2. Offshore Wind Farm Power Allocation

An important aspect of achieving maximum output and safe and reliable operation of offshore wind farms is the optimal allocation of active power to each unit in the wind farm. Compared to onshore wind farms, offshore wind farms are characterized by "high density and high concentration," so there is poor atmospheric stability inside the wind farm. When the sea wind blows through an offshore wind farm, the wind speed and direction received by the wind turbines in the back row are affected by the wind turbines in the front row. When the sea wind passes through multiple offshore turbines, the wind speed and direction vary even more, and turbulence can even form inside the wind farm [86]. Therefore, offshore wind farms usually have the problem of the wake effect, which affects the power distribution of offshore wind farms. For example, the wake effect at the Horns Rev offshore wind farm in Denmark is shown in Figure 10.

Currently, we can suppress wake effects on the power of offshore floating wind farms in three main ways. One is to optimize the layout of each wind turbine in an offshore wind farm. This approach requires an accurate grasp of the environmental conditions at sea and a clear understanding of each environmental condition's impact on the wind turbines' output power. Yang et al. [87] used a simulated annealing algorithm to optimize a wind farm's layout to ensure the wind farm's energy output while making the wake loss uniform for each wind turbine. The second option is to optimize the power output of each wind turbine to reduce the impact of the front wind turbine on the wind energy received by the rear wind turbine. Wang et al. [88] proposed an active output method that considers the wake effect of wind farms, allowing wind farms to have a larger active output when the wake effect is more pronounced inside the wind farm. The method first establishes a simplified model of wake flow, groups wind turbines according to the model and optimizes the active power output, and finally uses the data fitting and extreme value principles to obtain control information for critical parameters of each unit. Third, the yaw angle of each wind turbine can be planned so that the front and rear wind turbines are not facing in a straight line, thus weakening the influence of wake and stabilizing the airflow inside the wind farm. Wu et al. [89] combined online simulation and machine learning technology to optimize the control of the reference active power and reference yaw angle of the turbine, overcoming the difficulties in wind farm power optimization caused by the wake effect.

Figure 10. Picture of the wake effect at the Horns Rev offshore wind farm in Denmark [90].

The uneven fatigue distribution of each unit in an offshore wind farm is another important factor that leads to the mismatch of wind farm output. The fatigue of the units will accumulate, meaning that they will fail in the long run and affect the regular operation of the wind farm [91]. A reasonable power allocation according to the distribution of fatigue load in the wind farm can avoid excessive accumulation of fatigue load, reduce the occurrence of failure, and extend units' life. Among them, Su et al. [92] proposed a unified control method for fatigue distribution and active power in offshore wind farms based on optimal control theory combined with a multi-intelligent distributed control method, achieving fatigue uniformity and ensuring the synchronization of maintenance of each unit without reducing the total power generated. Liao et al. [93] used fatigue coefficients to evaluate the fatigue load on the wind turbine. They used particle swarm algorithms to optimize the offshore wind farm's fatigue distribution and achieve a reasonable power distribution.

For floating offshore wind farms, the working environment is more complex and the possibility of damage to the controller is much higher than in onshore wind farms. In the case of traditional centralized control, damage to the controller or communication lines can lead to the breakdown of the entire offshore wind farm. With the rapid development of multi-agent technology and theory, distributed control methods based on multi-agent power coordination distribution have been widely studied and applied. Each wind turbine can be considered an agent for offshore wind farms. However, compared with distributed control on land, the impact of each environmental parameter of the offshore wind turbine on the wind turbine output is more complex, and more factors need to be considered. Su et al. [92] designed a hierarchical state machine and intelligent body for offshore wind farms, which included a top-level state machine and a limit power generation state sub-state machine. The top-level state machine can change the wind farm between three top-level states to limit power generation, respond to grid disturbances, and free power generation. The limit power generation state sub-state machine considers the effect of the wake effect on the fatigue coefficient of the generator set for reasonable power allocation. Through the interaction of the agent, the coordinated operation of each generating unit of the whole wind power plant is realized. Wang et al. [94] proposed a distributed master–slave control strategy for offshore wind farms under fault conditions, which first establishes a model of offshore wind turbine cluster systems based on Hamiltonian energy theory, and then designs a master–slave control strategy in a weakly connected topology to ensure the stable operation of wind turbines in the case of single-unit failure and communication failure of master–slave units. Nguyen et al. [95] proposed a distributed reactive power coordination and voltage control method for offshore wind farms based on a pilot-following diffusion algorithm. Compared with the traditional consistency method, this method has faster convergence of reactive power, which improves the dynamic response of PCC voltage and the accuracy of reactive power distribution among offshore wind turbines.

5. Long-Distance Transmission Technology for Floating Offshore Wind Farms

5.1. Offshore Wind Power Prediction Techniques

In recent years, with the continuous progress of wind power technology, offshore wind power has gradually developed in deep-sea and far-sea areas. Additionally, transmission lines for offshore wind power have been growing. The problems brought on by long-distance AC transmission lines, such as significant losses, noticeable capacitive effects, high line costs, and susceptibility to AC faults, have gradually come to the fore [96]. The flexible DC transmission technology has become another research hotspot for offshore wind power technology because it can effectively solve the problems mentioned above brought by long-distance AC transmission and has received wide attention.

Modular multilevel converters (MMC) are widely used in flexible DC transmission due to their superior maneuverability, low harmonics, and low loss characteristics. Taking the topology of a half-bridge MMC is shown in Figure 11 as an example. However, as the scale of offshore wind power continues to expand and the capacity of offshore wind power continues to grow, the MMC circuit becomes prone to large power and voltage fluctuations, and larger sub-module capacitors are needed to suppress such fluctuations [97]. Optimizing the structure and control method of the MMC circuit to reduce the power and voltage fluctuations under high power conditions and reduce the size of its sub-module capacitance has become an essential issue in research on flexible DC power transmission.

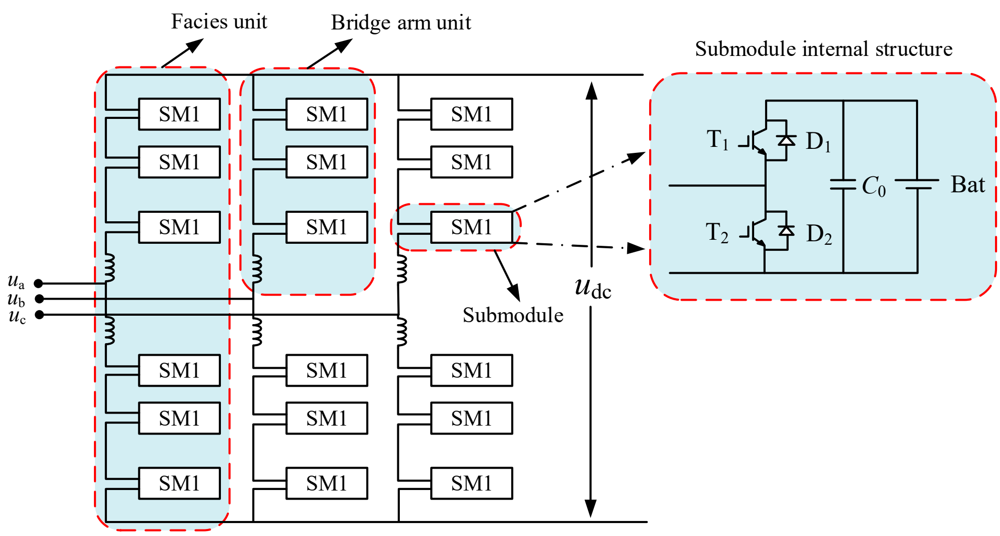

Figure 11. Half-bridge MMC topology [98].

One way to solve the problem of the large size of MMC converters, which are prone to power voltage fluctuations, is to increase the operating frequency of offshore wind farms to the power frequency range 100–400 Hz [99]. Compared with the original method, a smaller capacitor can meet the requirements because of the high frequency and lower energy stored and released by the MMC submodule capacitor in each cycle. In addition, the appropriate selection of the working frequency for offshore wind farms can also reduce the investment cost of the whole project and the operating losses of the system [100]. Zhang et al. [99] proposed an MMC-based grid-following medium-frequency offshore wind grid DC delivery scheme. The wind turbine adopts the grid-following control method with high technical maturity, and the frequency of the wind turbine is increased to medium frequency. Li et al. [101] replaced the centralized MMC converter with multiple distributed small MMC converters in the medium-frequency offshore wind grid. This method can effectively reduce the length of the necessary AC lines, and the capacity and size of the offshore converter can be further reduced.

Existing flexible DC transmission for offshore wind farms often uses a centralized commutation method, with the structure shown in Figure 12. Currently, centralized MMC converters are usually optimized using additional auxiliary converters and DC energy dissipation devices. Fang et al. [102] proposed a new auxiliary converter topology for offshore wind DC MMC converters that consists of three parts: a low-voltage AC output unit, a high-voltage sub-module string, and a resonant branch. The resonant frequency of the resonant branch is designed to be at the circulating frequency of the circuit, which significantly reduces the internal circulating current and the DC bias of the AC output voltage. Yao et al. [103] proposed a centralized DC power dissipation device based on a sub-module controllable discharge topology, in which a controllable discharge circuit consisting of diodes, thyristors, and power dissipation resistors is connected in parallel at both ends of the MMC sub-module IGBT. By controlling the conductivity of the thyristor, the controller can realize electrically precise discharge control of the submodule. Wu et al. [104] reduced the voltage fluctuation range and, at the same time, reduced the cost and footprint of the MMC system by connecting thyristors in parallel with energy dissipation resistors in series at both ends of the submodule capacitor.

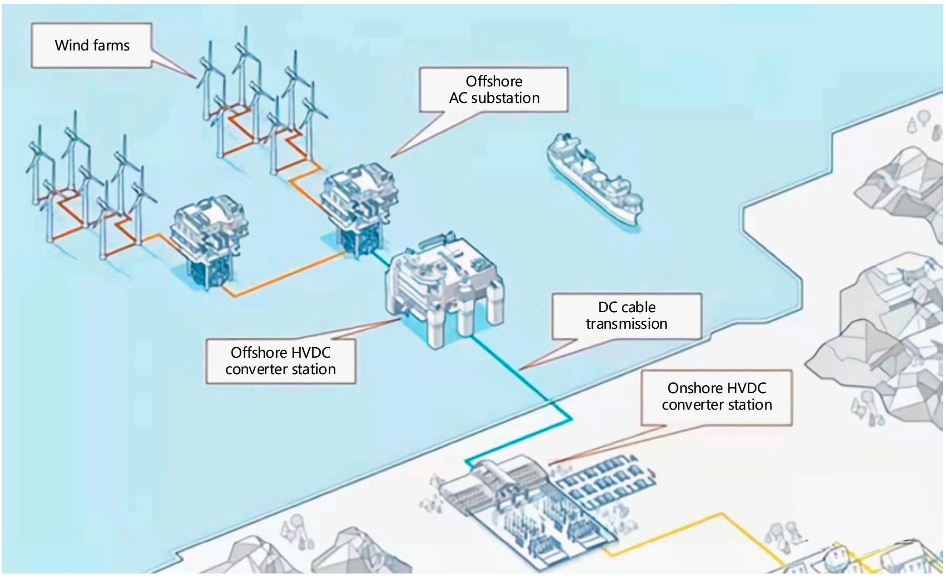

Figure 12. Centralized converter method for offshore wind power DC transmission [105].

5.2. Control of Offshore Wind Power Long-Range Transmission Converter

The ability of an MMC to achieve flexible conversion between AC and DC lies in the charging and discharging characteristics of the capacitors in its sub-modules. A large number of capacitors often exist in an MMC converter. Sudden changes in voltage during converter start-up may cause damage to the capacitors inside the converter and thus cause converter failure. Therefore, ensuring that the MMC can be smoothly and safely started, i.e., through the start-up control of the MMC system, is crucial. Cai et al. [106] proposed a start-up sequence connecting an offshore wind farm to an MMC-HVDC system and pre-charging the offshore MMC converter using an auxiliary generator so that the inrush current at start-up is within acceptable limits. However, pre-charging consumes more energy and can increase the start-up cost of the MMC. Wang et al. [107] proposed a hierarchical start-up control scheme for MMC systems in a multi-terminal HVDC transmission system for offshore wind farms. This method enables the MMC capacitor voltage to gradually reach its nominal state with minimum start-up power loss through effective sequential start-up control. Yan et al. [108] proposed a start-up control scheme based on an improved nearest-level modulation method to mitigate the passive-side converter's inrush current after pre-charging and effectively reduce the oscillation phenomenon during MMC start-up. This start-up control scheme is simple and easy to implement. However, this method has a long start-up time and cannot achieve fast start-up of the MMC.

Since offshore wind farms work in a harsh environment and are threatened by fishing vessels and fish, their possibility of failure is much greater than that of onshore wind farms. Therefore, improving the fault ride-through capability of MMC through control methods is also the focus of current research. Ye et al. [109] analyzed the effect of a current-limiting inductor on AC faults. They proposed a fault ride-through method for MMC-HVDC systems with a current-limiting inductor, which improves the fault ride-through capability of MMC by adjusting the zero-sequence modulation of circulating current suppression to desaturate the AC module and decouple the fault characteristics. However, this method requires accurate parameters for the capacitors and inductors in the circuit. When the capacitor and inductor parameters are not precise, the suppression of the loop current will not be achieved. Freytes et al. [110] replaced the original AC-side capacitor with a voltage controller at the MMC-HVDC AC-side connection. When the current is below its limit, the voltage control device behaves as a conventional PI controller. When the voltage is above the limit, the voltage control device combines a feedforward current term and elliptical limits in a dual synchronous rotating coordinate system to achieve current limitation. This control method can switch between control modes without control logic, and is also effective for AC faults, which can effectively limit the current. To mitigate the DC overvoltage problem during offshore MMC-HVDC faults and improve DC voltage recovery performance after faults, Li, Zhu et al. [111] proposed a two-stage voltage drop control scheme and an adaptive voltage rise control scheme. The two-stage voltage control is a voltage steep drop control stage and voltage-dependent active current control (VDACC). This method can quickly and accurately balance the MMC voltage constraint to the rated voltage. The adaptive voltage control scheme can significantly improve the post-fault recovery dynamics of the DC voltage when a fault is removed. A summary of the above MMC converter control methods for offshore wind farms is shown in Table 5.

Table 5. MMC converter control methods for offshore wind farms.

Ref. No	Method	Advantages	Disadvantages
[106]	Pre-charging of the offshore MMC converter by an auxiliary generator.	Keeps inrush current at start-up within acceptable limits.	Requires additional power consumption.
[107]	Layered start-up control scheme.	Achieves minimal start-up power loss.	Start-up time will increase.
[108]	Improved recent level modulation method.	Reduces inrush current in passive side converters after pre-charging and effectively mitigates oscillations during MMC start-up.	Complex control process.
[109]	Zero-sequence modulation for adjusting circulating current rejection.	Improves the fault ride-through capability of MMC.	Stringent requirements for capacitive and inductive parameters in the circuit.
[110]	The voltage controller replaces the original AC side capacitor.	Switching between control modes with-out control logic allows for effective current limiting.	Greater controller cost.
[111]	Two-stage voltage drop control scheme and adaptive voltage rise control scheme.	Significantly improves post-fault recovery dynamics of DC voltages.	Slower fault recovery.

6. Future Research Outlook

Offshore wind energy development has entered a new stage, the main signs of which include: (1) wind energy resources can be developed to provide important support for meeting energy demand; and (2) wind energy feed-in tariffs can compete with conventional energy [112]. Therefore, it is of great significance to vigorously develop offshore wind power resources. However, as the scale of offshore wind power continues to expand and new technologies and methods are introduced, offshore wind power development is also facing more problems and challenges that need to be studied and explored by scholars. Future offshore wind power technology research directions are as follows:

(1) Methods to improve the stability of floating offshore wind power platforms. Current offshore floating electric platforms still have poor stability. Under extreme environmental conditions, the platform can easily vibrate, tilt, and overturn. Improving the mechanical structure of offshore wind power platforms and control methods to protect platforms in extreme conditions while still meeting the stability requirements of wind power equipment is an important issue at present.

(2) Multi-energy complementary offshore wind power technology. Offshore clean energy is abundant. In addition to wind energy, there is also solar energy, wave energy, tidal energy, hydrogen energy, etc. Installing a variety of other energy generation devices on offshore wind power platforms can improve the overall power generation capacity of the wind power platform and improve the efficiency of power generation. In addition, it can alleviate the impact on the grid due to the instability of offshore wind energy and improve the stability and safety of offshore wind power.

(3) Energy management and optimal scheduling schemes for offshore wind power. Due to the harsh environmental conditions at sea, wind speed and direction are variable. The distribution of power generation and fatigue inside the offshore wind farm is often uneven. Accurately predicting the offshore wind power output and carrying out scientific energy management and optimal scheduling of offshore wind power according to wind power output and fatigue distribution of wind farms is also a topic worth studying.

(4) Offshore wind power long-distance transmission technology. MMC-HVDCs are the main method for offshore wind power transmission. However, they are also prone to power and voltage fluctuations. The MMC converter capacitor volume is too large. Appropriate improvements and optimization of MMC converter topology and control methods can reduce the volume and cost of MMC converters and improve the power quality of HVDCs.

7. Conclusions

Ensuring the safe and stable operation of offshore wind farms, reducing the negative impact of offshore wind power on the grid, and reducing the cost of offshore wind farm operation are the primary goals of offshore wind power research. In this regard, this paper reviewed critical technologies for offshore floating wind power generation. The research status and questions of floating offshore wind power generation technology, offshore wind storage integration technology, energy management strategies for offshore wind power generation, and long-distance transmission technology were comprehensively discussed, and the future research directions were summarized and prospected. This paper provides a reference for future research on critical offshore wind power technologies.

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