Wind-Solar Co-generation System Based on Spar-type Floating Foundation

Pengyu Cao*

Mining Technology Institute, Taiyuan University of Technology, Taiyuan, China

*Corresponding author: caopengyu0737@link.tyut.edu.cn

Abstract. With China's "double carbon" goal, the development of renewable energy must be accelerated, wind and solar energy is considered the best alternative to fossil energy, the vast area of the ocean, wind resources are more abundant and stable. In this paper, based on the sea condition of maximum water depth of 200 m, maximum wave height of 8m and period of 10 s, an ocean floating platform with Spar type floating foundation is designed to realize the joint development of wind and solar energy. Among them, the wind power generation power is 15 MW and the solar power generation power is 2.44 MW, the total power generation power is 17.44 MW. The initial stability test results of the floating platform show that the center of gravity is lower than the floating center, the initial stability height is 61.87 m, and the initial stability is stable; the load on the whole floating platform is 2297169 N when the wind speed is 10 m/s; the maximum positive wave force on the whole floating platform is 187235339 N and the maximum negative wave force is 187228513 N under the set sea condition; the cost of the floating platform the total cost of the floating platform was estimated to be 200 million RMB, and the cost was 11.5 million RMB/kW. In this paper, only one working condition is considered when calculating the wind load, and many assumptions are taken when calculating the wave load, and the calculation results are somewhat different compared with the actual results. In the future, the dynamic response of the floating platform under different operating conditions can be calculated with the help of numerical calculation software.

Keywords: spar, floating offshore wind turbine, combined solar–wind system, wind load, cost.

1. Introduction

With the continuous development of social economy, the country's demand for energy is increasing year by year. Traditional fossil energy is not renewable and emits more pollutants in the process of use, which is more damaging to the environment. The development of green energy is conducive to solving problems such as energy shortage and environmental pollution [1]. China has a huge area of marine land, and the problem of power shortage in the islands is serious. Compared with land, the ocean has great potential for green energy development. Currently, ocean green energy includes tidal, tidal, wave and salt differential energy from seawater, as well as wind and solar energy from the sea. Of all the current renewable energy sources, wind and solar are considered the best alternatives to fossil energy. Due to the impact of the ship channel occupation and environmental protection factors, offshore wind power offshore distance increased year by year, in Beijing Wind Energy International Conference, the National Energy Board said it will increase efforts to promote the scale of wind power development, the future of wind farms will move to deep sea [2].

Offshore wind turbines are divided into fixed and floating types. As offshore wind turbines continue to move into the deep sea, floating wind turbines are developing rapidly. According to publicly available data, Europe has installed more than 83% of the world's floating wind turbines [3]. The Hywind Tampen (88 MW installed capacity) in the UK is undergoing pre-construction preparations with the ultimate goal of reducing the cost of the Hywind wind farm by 40% compared to Phase 1. According to the plan, in the next 10 years of time, Europe to build an installed capacity of about 7 GW of offshore floating wind farms, floating wind turbines will be commercialized by 2030 [4].

For floating wind turbines, the platform foundation is an important component. In 2006, the wind-sea concept foundation structure emerged, in which three wind turbines are installed on the same triangular floating foundation, which is restrained on the seabed by a mooring system. The three

Norwegian companies considered this structure to have good prospects for commercialization, and conducted scaled-down model tests after 2010 under the combined action of water tanks, wind tunnels and wind waves, respectively, and the test results were in good agreement with the numerical analysis, which verified the excellent performance of this structure [5].

In this paper, we designed the Spar type floating platform based on the 5 MW horizontal axis wind turbine announced by NREL and referring to the published information of wind-sea wind turbine. The platform combines horizontal axis wind turbines with solar cells. Three horizontal axis wind turbines are installed at the three corner points of the floating platform. The solar cells, with a total area of about 12 221 m^2, are installed on the deck of the floating platform to form a complementary power generation system with the wind turbine. The whole system meets the unconditional stability, and the height of its center of gravity is lower than the height of the floating center; the wind and wave loads on the whole floating platform are calculated under the maximum wave height of 8 m and the period of 10 s; and the approximate cost of the whole floating platform is estimated.

2. Method

2.1. Floating platform structure design

Floating structures can be used in deeper waters (water depths greater than 50 m), and currently there are several types of marine floating structures: semi-submersible, TLP, and Spar. Spar type foundation has a larger draft and is suitable for water depths greater than 100 m. The lower part of the foundation is a ballast tank and the upper part is a floating tank. The semi-submersible type has a shallow draft, low maintenance cost in case of failure, its assembly and installation can be done in shallow water, suitable for shallow water environment, and it is vulnerable to ice load and extreme wave conditions due to its more structures at the surface line. The TLP-type platform has high soil requirements and many installation steps, and is not suitable for the current wind power development environment. Based on the sea condition of maximum water depth 200 m, maximum wave height 8 m and period 10 s, Spar type foundation is selected for the floating platform.

2.2. Calcuation of initial stability

Since the floating foundation designed in this paper is Spar type, as long as the Spar type foundation satisfies the condition that the center of gravity is lower than the floating center, it can satisfy the unconditional stability. Equation (1) is the formula for the center of gravity:

$$Gx=\sum G_i x_i \tag{1}$$

where, G is the gravity, x is the center of gravity coordinates, G_i is the gravity of each member of the floating foundation, and x_i is the center of gravity coordinates of each member of the floating foundation.

2.3. Load calculation

2.3.1 Theory of wind load

Floating platforms are in the marine environment and are subject to rapidly changing wind and wave sizes and directions. The ability to accurately describe environmental parameters and calculate environmental loads is critical for floating platforms. The wind load is related to the height, shape and windward area of the object, which can be decomposed into horizontal force and lift force [6]. In this paper, only horizontal forces are considered, and equation (2) is the formula for calculating horizontal forces.

$$F_i^w=C_i^w(\alpha)v^2 \tag{2}$$

where, i denotes degrees of freedom, usually taken as 1, 2, 6, indicating longitudinal swing, transverse swing and first swing； F_i^w denotes the wind load corresponding to each degree of freedom；

α indicates the wind angle; C_i^w indicates the wind coefficient, which is generally derived from model experiments; and v indicates the speed of the wind relative to the object, usually taking 10m wind speed at sea level.

Equation (3) is the expression of wind coefficient C_i^w in the specification of China Classification Society [7].

$$C_i^w(\alpha)=0.613\sum_{j=1}^{n}(C_s C_h A_j(\alpha)) \tag{3}$$

Where, C_s represents the shape coefficient of the wind-receiving member, which can be determined by wind tunnel experiments or selected according to Table 1; C_h indicates the height coefficient of the wind member, and the value is taken according to the Table 2; $A_j(\alpha)$ denotes the projected area of wind angle α on the jth windward member in the wind direction.

Table 1. Shape factor C_s

Component shapes	Shape factor C_s
Spherical	0.4
Cylindrical	0.5
Large flat surfaces (hull, deckhouse, smooth lower deck surface)	1
Deck room clusters or similar structures	1.1
Derricks	1.25
Exposed beams and trusses under the deck	1.3
Stand-alone structures (cranes, beams, etc.)	1.5

Table 2. Height factor C_h

Height above sea level (m)	Height factor
0~15.3	1.00
15.3~30.5	1.10
30.5~46.0	1.20
46.0~61.0	1.30

2.3.2 Wave load theory

Wave loads are the most important environmental loads to which multi-column Spar floating foundations are subjected. Due to the water depth of 200 m, it is a deepwater environment. According to the dispersion equation, the wave wavelength is 156 m, and the diameter of each column of the hard cabin is much smaller than the wavelength, so the wave load can be calculated by Airy wave theory and Morrison equation. Airy wave theory that the fluid is uniform, non-viscous, non-spin potential incompressible fluid, the wave height is much smaller than the wavelength and water depth, the waveform can be reduced to a sine curve [7, 8]. Equation (4) is the wave front equation:

$$\eta=\frac{H}{2}\cos(kx-\omega t) \tag{4}$$

where, H is the wave height, t is the time, k is the number of waves, and ω is the wave frequency.

The origin of the wave surface equation coordinate system is in the horizontal plane, the vertical direction is the z-axis, and the wave propagates forward along the positive direction of the x-axis. Equation (5) is the velocity potential equation. The velocity and acceleration of the water quality point in the wave are obtained from the derivation of Equation (5).

$$\phi=\frac{Hg}{2\omega}\frac{\mathrm{ch}[\mathrm{k}(\mathrm{y}+\mathrm{d})]}{ch(kd)}\sin(kx-\omega t) \tag{5}$$

It is assumed in the calculation that the platform will not undergo relative motion under the wave load. According to the Morrison equation. Equation (6) is the formula for calculating the wave load acting on top of a cylindrical structure with a vertical length of dz. Equation (7) is the formula for calculating the wave force acting on a cylindrical member of length z.

$$dF=\frac{\pi D^2}{4}\rho C_M a_1 dz+\frac{\rho}{2}C_D D u^2 dz \tag{6}$$

$$F=\int(\frac{\pi D^2}{4}\rho C_M a_1+\frac{\rho}{2}C_D D u^2)dz \tag{7}$$

where, ρ is the density of seawater, D is the diameter of the member, C_M and C_D are the mass force coefficient and drag coefficient, and u and a_1 are the velocity and acceleration of the fluid at the projection center of the member.

2.4. Calculation of Construction Cost

The whole construction project mainly includes installation works, construction works, equipment and others, so the project construction cost mainly contains installation works cost, construction works cost, equipment purchase cost and other costs [9]. In this paper, due to the author's lack of relevant knowledge reserve and the shortage of time, only the raw materials involved in the floating platform as well as the price of the generator set and related supporting facilities are considered, and the estimation results are for reference only.

3. Floating Platform Design and Initial Stability Test

3.1. Floating Platform Designs

3.1.1 Introduction of Wind Turbine Model

The design of the floating platform is based on the 5 MW turbine designed by the Renewable Energy Research Institute (NREL), and the turbine model diagram is shown in Fig. 1, the main parameters are shown in Table 3.

Table 3. Basic parameters of wind turbine [10]

Wind turbine parameters	Value
Power Rating	5 MW
Blade diameter	126 m
Wheel diameter	3 m
Tower height	90 m
Cut-in, rated, cut-out wind speed	3 m/s, 11.4 m/s, 25 m/s
Cut out, rated wind turbine speed	6.9 rpm, 12.1 rpm
Rated leaf tip speed	80 m/s
Axis inclination, yaw angle	5°, 2.5°
Impeller weight	110 t
Cabin weight	240 t
Tower weight	347.46 t
Total weight of wind turbine	697.46 t
Wind turbine center of gravity position	-0.2 m, 0.0 m, 64 m
Top Diameter	3.9 m
Bottom Diameter	6 m

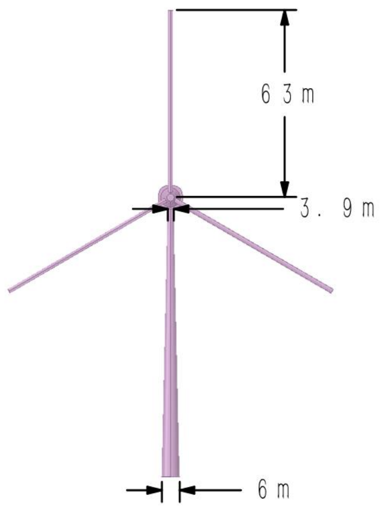

Fig. 1 5 MW wind turbine model

3.1.2 Introduction of Multi-column Spar Type Floating Foundation

The multi-column Spar floating foundation designed in this paper mainly consists of rigid cabins, soft cabins, columns and pendulous swing plates [11]. The detailed parameters of the floating foundation are shown in Table 4; the model diagram is shown in Fig. 2, the main body division is shown in Fig. 3.

Table 4. Details of floating base structure

Parameters	Value
Total height of foundation	165 m
Rigid cabin quality	3 988 817 kg
Length of rigid cabin	90 m
Diameter of the central column of the rigid cabin	Φ16.5 m
Rigid cabin shell and divider thickness	18 mm
Rigid cabin side column	4×Φ13 m
Soft cabin wall thickness	27 mm
Soft cabin quality	79 098 801 kg
Density of soft cabin ballast filling	2 800 kg/m^3
Soft cabin ballast filler mass	77 658 000 kg
Soft cabin length	15 m
Column thickness	10 mm
Column dimensions	60 m×Φ2 m
Column weight	18 426 kg
Pendulum quality	387 250 kg
Pendulum spacing	20 m
Number of pendants	2
Pendulum thickness	25 mm
Pendulum size	30 m×30 m

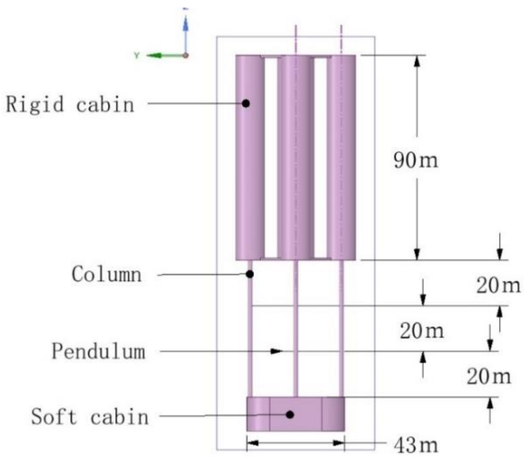

Fig. 2 Multi-column Spar type floating foundation conc

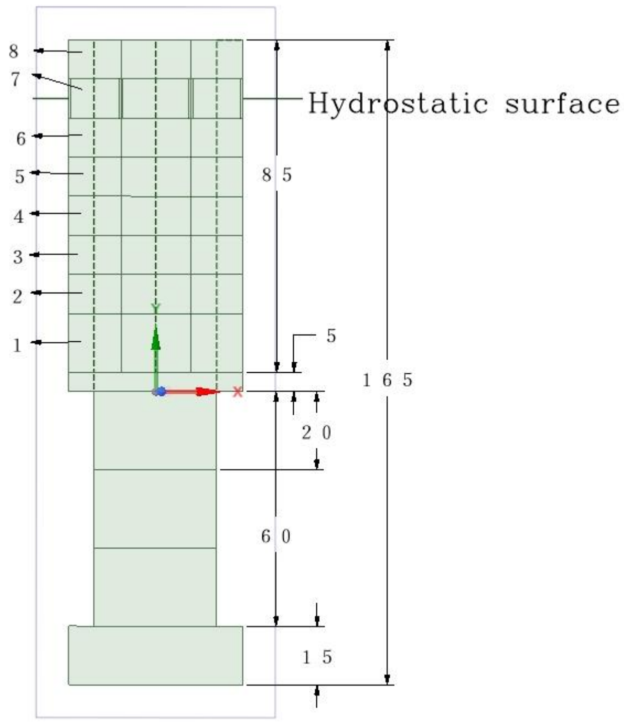

Fig. 3 Spar floating foundation body division diagram

Among them, the rigid cabin is divided into 8 compartments, 90 m long, and the thickness of the shell and divider of each compartment is 18 mm. Compartment 1 is a variable floating compartment with a height of 20 m, and the floating compartments 2-8 are fixed floating compartments with a height of 10 m in each compartment. As compartment No. 7 is near the surface line, the force here is larger, and the compartment adopts a double-shell structure, while the rest of the compartments are single-shell structures with a double-shell spacing of 0.5 m.

3.1.3 Introduction to wind-solar power generation systems

Since wind and solar energy are subject to large fluctuations due to weather, combining wind turbines and solar panels to form a wind-solar power generation system can improve the smoothness of the power output of the power generation system, while also effectively using solar energy. The solar arrays are fixed to a truss structure to capture solar energy, and the solar array are designed in the shape of truncated pyramids to reduce the wind load on the solar arrays. Assuming that the rated power of 1 m^2 solar panel is 200 W, the power generation of the solar array is about 2.44 MW. The masses of the solar panels and support trusses are shown in Table 5.

Table 5. Solar array related parameters [12]

parameters	Value
Weight of support truss(kg/m^2)	0.023
Weight of solar panels(kg/m^2)	0.033
Total area(m^2)	12221
Total rated power(MW)	2.44

3.1.4 Floating Platform Structure

The overhead projection of the floating platform is a square triangle, and the three columns of the wind turbine are located on the three vertices of the equilateral triangle, and the distance between the centers of the columns is 168 m. The columns are connected by cross braces, and the cross section size of the cross braces is 4.5 m×3 m, and the right angles are transitioned by rounding. The floating foundation structure is shown in Fig. 4.

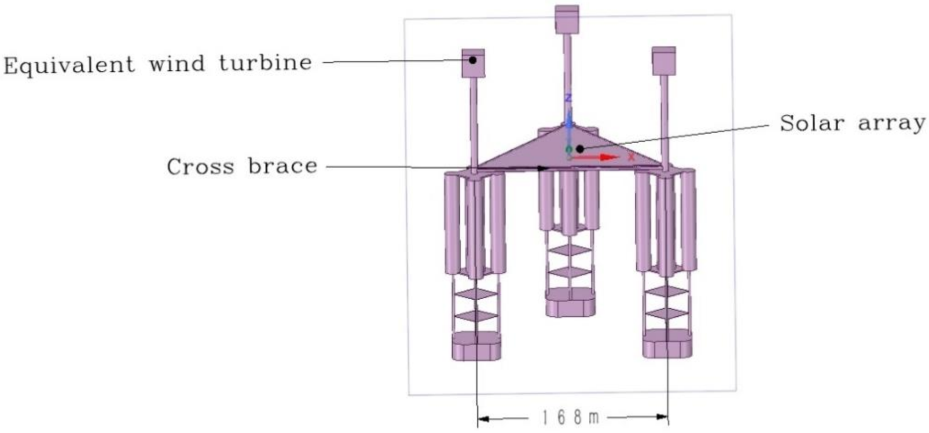

Fig. 4 Floating platform structure

3.2. Initial Stability Test

Total mass of floating platform is 252 845 326 kg, required buoyancy according to equation (8). According to equation (8), the height of the hard cabin exposed to the water is 18m .The origin of the selected coordinate system is located on the water surface line. The distribution table of the center of gravity is shown in Table 6, and the distribution table of the center of buoyancy is shown in Table 7. According to equation (1), the height of the center of gravity is calculated to be -131.87m and the height of the floating center is -70m. The center of gravity is located below the floating center, the initial stability height is 61.87m, and the initial stability is stable.

$$\rho g v = \rho g[\pi(R_1^2 + 4R_2^2)h + V_{\text{soft cabin}} + V_{\text{column}}] \times 3 = M_{\text{total}} g \tag{8}$$

Table 6. Distribution of center of gravity

Components	Weights (kg)	Center of gravity height (m)
5MW Wind turbine	2 092 380	82
Rigid cabins	11 966 451	-27
Pendulums	1 161 750	-102
Soft cabins	237 296 403	-139.5
Column	55 278	-102
Cross brace	1 167 300	21
Solar array	684	21.5

Table 7. Floating center distribution

Components	Center of center height (m)
Rigid cabins	-36
Pendulums	-102
Soft cabins	-139.5
Column	-102

4. Load Calculations

4.1. Wind load

Assuming a wind speed of 10 m/s and normal power generation, equation (9) is the formula for calculating the pressure over the swept area of a single wind wheel [11]. p_H was caculated as 59 Pa According to equation (9). The horizontal wind force acting on the top of the tower (at the hub) during normal power generation is 7.1×10^5 N.

$$p_H=\frac{\rho}{2}C_{FB}u^2 \tag{9}$$

where, ρ is the density of air, taken as 1.29 kg/m^3; C_{FB} is the coefficient, which is taken as $\frac{8}{9}$ according to the Bates formula; u is the wind speed.

Equation (10) is the wind load calculation formula provided in the API code. For a single tower, the wind load calculated from equation (10) is 14367 N. For the part of the hard tank above the water surface the wind load on a single central column is calculated as 9578.25 N.Similarly, for a single rigid tank side column, the wind load received is7 546.5 N. For the solar panel on the floating platform, its windward side is trapezoidal, the upper bottom is 180 m long, the lower bottom is 184 m long, and the height is 2 m, so the wind load calculated according to equation (10) is 11739 N. The whole floating platform has 3 wind turbines, 3 towers, 3 rigid cabin center columns, 12 rigid cabin side columns and a set of solar array; the wind load on the whole platform is 2297169 N.

$$F=\frac{\rho}{2}u^2C_SA \tag{10}$$

4.2. Wave loads

The material used for floating foundation is steel, according to the specification k is 5×10^{-6}, water depth (d) is 200 m, time (T) is 10 s, H is 8 m, draught depth is 147 m. For a single hard cabin central column, according to equation (5) can be found out the velocity of the water quality point is $0.0017\cosh(ks\frac{d}{d+\eta})\cos\alpha$, and the acceleration is $0.0011\cosh(ks\frac{d}{d+\eta})\sin\alpha$. According to equation (7), when $\alpha\in\left[0,\frac{\pi}{2}\right]\cup\left[\frac{3}{2}\pi,2\pi\right]$, the wave load can be calculated as equation (11). When $\alpha\in\left[\frac{\pi}{2},\frac{3}{2}\pi\right]$, the wave load is shown in equation (12).

$$F_1=-241.2(50+\cos\alpha)[\sinh\frac{106}{50+\cos\alpha}-\sinh 8]\sin\alpha+0.0031(200+4\cos\alpha)(\cos\alpha)^2\left[4-\frac{212}{200+4\cos\alpha}+\frac{1}{4}\left(\sinh 1\,6-\sinh\frac{848}{200+4\cos\alpha}\right)\right] \tag{11}$$

$$F_1=-241.2(50+\cos\alpha)[\sinh\frac{106}{50+\cos\alpha}-\sinh 8]\sin\alpha-0.0031(200+4\cos\alpha)(\cos\alpha)^2[4-\frac{212}{200+4\cos\alpha}+\frac{1}{4}(\sinh 1\,6-\sinh\frac{848}{200+4\cos\alpha})] \tag{12}$$

Similarly, for a single rigid cabin side column, when $\alpha\in\left[0,\frac{\pi}{2}\right]\cup\left[\frac{3}{2}\pi,2\pi\right]$, the wave load is shown in equation (13). When $\alpha\in[\pi/2,3/2\,\pi]$, the wave load is is shown in equation (14).

$$F_2 = -149.6(50 + \cos\alpha)[\sinh\frac{106}{50+\cos\alpha} - \sinh 8]\sin\alpha + 0.0024(200 + 4\cos\alpha)(\cos\alpha)^2[4 - \frac{212}{200+4\cos\alpha} + \frac{1}{4}(\sinh 1\,6 - \sinh\frac{848}{200+4\cos\alpha})] \quad (13)$$

$$F_2 = -149.6(50 + \cos\alpha)[\sinh\frac{106}{50+\cos\alpha} - \sinh 8]\sin\alpha - 0.0024(200 + 4\cos\alpha)(\cos\alpha)^2[4 - \frac{212}{200+4\cos\alpha} + \frac{1}{4}(\sinh 1\,6 - \sinh\frac{848}{200+4\cos\alpha})] \quad (14)$$

The whole platform has 3 rigid cabin central columns and 12 rigid cabin side columns. When $\alpha \in \left[0, \frac{\pi}{2}\right] \cup \left[\frac{3}{2}\pi, 2\pi\right]$, the wave load on the whole platform is is shown in Equation (15). When $\alpha \in \left[\frac{\pi}{2}, \frac{3}{2}\pi\right]$, the wave load on the whole platform is is shown in Equation (16).

$$F = -2518.8(50 + \cos\alpha)[\sinh\frac{106}{50 + \cos\alpha} - \sinh 8]\sin\alpha + 0.0381(200 + 4\cos\alpha)(\cos\alpha)^2[4 - \frac{212}{200+4\cos\alpha} + \frac{1}{4}(\sinh 1\,6 - \sinh\frac{848}{200+4\cos\alpha})] \quad (15)$$

$$F = -2518.8(50 + \cos\alpha)[\sinh\frac{106}{50 + \cos\alpha} - \sinh 8]\sin\alpha - 0.0381(200 + 4\cos\alpha)(\cos\alpha)^2[4 - \frac{212}{200+4\cos\alpha} + \frac{1}{4}(\sinh 1\,6 - \sinh\frac{848}{200+4\cos\alpha})] \quad (16)$$

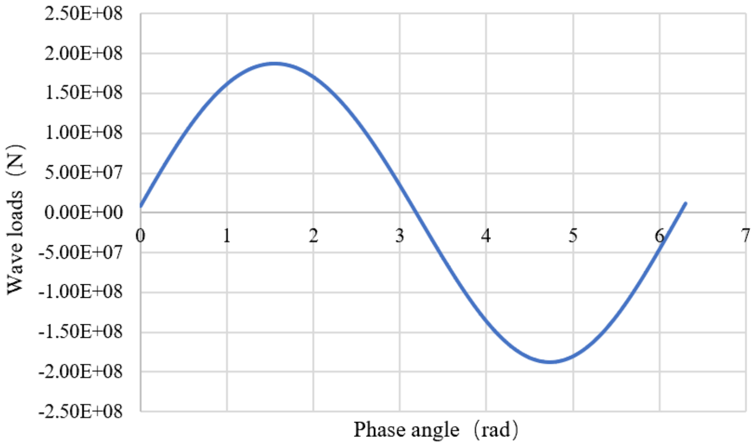

Fig. 5 Morrison force on floating platform

The Morrison force on the floating platform is shown in Fig. 5, and the final calculation yields a maximum positive wave force of 187235339 N and a maximum negative wave force of 187228513 N.

5. Construction budget

The whole floating platform consists of hard cabin, cross brace, column, pendulum and soft cabin. The component prices and material prices involved in the floating platform are shown in Table 8 and Table 9. The soft cabin is a concrete ballast, and the ballast price is calculated to be 38.14 million RMB; the rigid cabin, cross braces, columns and pendants are steel structures, and the price of these components is calculated to be 83.2 million RMB if only material prices are considered. For the 5 MW wind turbine, in addition to the generator, blade, tower, but also to install transformers, power distribution equipment, etc., this part of the total cost of about 4 million. For wind turbines, the price of a complete wind turbine set is 20 million RMB. The whole floating platform needs 3 sets of wind turbines with a total price of 60 million RMB. The total cost of solar cells and trusses is 12.22 million

RMB. The cost of the entire structure is about 200 million RMB. The total power generation is 17.44 MW, and the cost per kW is 11.5 thousand RMB.

Table 8. Component prices

Components	Single price(RMB)	Number
Blade	1.5 million	9
Tower	3 million	3
Auxiliary equipment	4 million	3
Generators	8.5 million	3
Solar array	600	12 221 m^2
truss	400	12 221 m^2

Table 9. Material prices

Material	weight(t)	Single price(RMB)
Steel	14 350	5 800/t
Concrete	237 296.4	161/t

6. Conclusion

In this paper, a floating offshore structure is designed, which integrates wind turbine and solar panel to maximize the use of offshore green energy, and Spar type foundation structure is chosen for the foundation of the structure. The Spar type has a large base draft and is suitable for working in deep water environments, meeting unconditional stability due to the presence of ballast tanks. The initial stability of the platform was calculated, and the calculated initial stability height was 61.87 m, and the initial stability was stable. The wind load on the platform at a constant wind speed of 10 m/s is 2297169 N. Under the sea condition of water depth 200 m, wave height 8m and period 10 s, the maximum positive wave force on the platform is 187 235339 N and the maximum negative wave force is 187 228513 N calculated by Airy wave theory and Morrison equation. A rough estimate of the power generation capacity and cost of the floating platform was made, and the total cost was calculated to be 200 million RMB, with a total power generation capacity of 17.44 MW and a cost of 11.5 thousand per kW of power generation. In this paper, only one working condition is considered when calculating the wind load, and the dynamic response of the wind turbine under severe working conditions is not considered; many assumptions are used when calculating the wave load, resulting in some discrepancies between the calculation results and the actual situation, and the dynamic response of the floating platform under different working conditions can be calculated with the help of numerical calculation software in the future.

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