Simulation study on pitch system of floating wind turbine

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Abstract. Due to the complex sea conditions, floating wind turbines produce unbalanced loads. Firstly, this paper will take NERL-5MW floating wind turbine as the model, and apply brainstorming algorithm (BSO) to the independent pitch system based on PID azimuth weight coefficient. Then, a joint simulation will be carried out in OpenFAST-Matlab/ Simulink to study its impact on the load of floating wind turbine. Finally, the simulation results reveal that compared with the independent pitch system based on PID azimuth weight coefficient, the proposed method can reduce the load of the floating platform to a certain extent.

1. Introduction

Vigorously developing new energy power generation is a key move to achieve the "double carbon" goal [1]. Solar power generation, wind power generation and hydropower generation are the backbone of new energy power generation to jointly help the power sector achieve low carbon emissions [2]. Wind power plays an important role in new energy power generation. Offshore wind power generation is the development focus of wind power generation, and the expansion of offshore wind power generation to deep sea is the inevitable trend of the new era of socialism with Chinese characteristics.

Offshore floating wind turbine platform is mainly composed of wind turbine, tower, floating platform and mooring system [3], and is used in deeper sea areas, which means that floating wind turbine faces more complex load environment than offshore wind turbine. Domestic and foreign scholars have gradually carried out relevant research on how to reduce the load of floating wind turbine. A control strategy based on state feedback is proposed in reference [4], and an independent blade pitch controller is designed; A linear quadratic regulator control method based on multi-objective optimization is proposed in reference [5]; In reference [6], a new pitch control strategy is proposed by combining multivariable control and feedforward control; Reference [7] designed an expert PID controller to control the change angle of each blade.

After studying the OpenFAST software developed by the National New Energy Laboratory (NREL), based on the nrel-5mw floating wind turbine model, the author proposes a PID azimuth weight coefficient independent pitch control strategy based on brainstorming algorithm (BSO). On the basis of establishing the coupling model of air water mooring system, the azimuth weight coefficient strategy is applied to the PID controller, and the PID azimuth weight coefficient independent pitch controller (K-PID) is built. BSO is used to optimize PID azimuth weight coefficient independent pitch controller (BSO-K-PID). The simulation results show that compared with the PID azimuth weight coefficient independent pitch control strategy, BSO-K-PID independent pitch control strategy can better reduce the load and oscillation of the floating wind turbine platform.
2. Modeling of floating wind turbine

In view of the high installation complexity of floating wind turbine, semi-submersible floating wind turbine is used as the research object in this paper. The platform of this model is composed of one central cylinder connected with the wind turbine tower and three outer cylinders providing buoyancy. The self weight of the outer cylinder and internal bin pressing are used to ensure the relative stability of the platform. The cylinder can be installed on site after being transported to the offshore wind farm.

2.1. Aerodynamic Mode

Under the action of sea wind and wave current, the motion of floating wind turbine platform includes 6 degrees of freedom: roll, pitch, yaw, sway, surge and heave. The aerodynamic load of floating wind turbine mainly comes from wind wheel and tower.

2.1.1. Oedynamic Load of Wind Turbine. Based on the blade element theory, when the air flow acts on the blade element, the blade element surface will produce resistance \( dF \) and lift \( dD \):

\[
dZ = \frac{1}{2} \rho w^2 s C_Z dr \\
dS = \frac{1}{2} \rho w^2 s C_s dr
\]

Where: \( \rho \) is the air density; \( w \) is the relative wind speed; \( s \) is the chord length of leaf element; \( C_Z \) and \( C_s \) characteristic coefficients of drag and lift; \( dr \) is the leaf element length.

According to formulas (1), (2), the normal force \( F \) of the blade is finally obtained and tangential force \( F_t \) generated swing torque \( T_h \) and shimmy torque \( T_b \):

\[
T_h = \frac{1}{2} \rho V^2 s (C_s \sin \varphi - C_z \cos \varphi) dr \\
T_b = \frac{1}{2} \rho V^2 s (C_s \cos \varphi + C_d \sin \varphi) dr
\]

2.1.2. Aerodynamic load of tower. The aerodynamic load \( F_t \) of the tower is calculated according to the rules of China Classification Society:

\[
F_t = 0.613 \sum_{i=1}^{n} A H D_i
\]

Where: \( A \) is the force coefficient of platform member shape; \( H \) is the height coefficient of wind turbine; \( D_i \) is the projected area of the platform member in the wind direction.

2.2. Platform hydrodynamic model

Under complex sea conditions, the hydrodynamic load of the platform mainly includes wave load and current load.

2.2.1. Wave model. The floating wind turbine platform contains members. According to the general calculation method of engineering, Morison equation is used to calculate the wave force on the members of the platform. Any height \( h \) when the platform member is partially upright is subjected to wave force \( F_h \), wave force \( F_h \) is the sum of the inertial force of the acceleration of the water point and the drag force of the velocity of the water point, versus the wave force \( F_h \) wave load \( L \) obtained after integration:

Wave load after integration:

\[
L = \int_0^h \left( 0.5 C_t \rho D V |V| + C_h \rho S \frac{dV}{dt} \right) dt
\]

Where: \( S \) is the area of platform members; \( C_t \) is the drag force coefficient of the platform member; \( C_h \) is the inertia force coefficient of the platform member; \( \rho \) is the density of seawater; \( D \) is the
section diameter of platform member; \( V \) and \( \dot{V} \) are the horizontal instantaneous velocity and acceleration of seawater.

2.2.2. Ocean current model. Because the ocean current will not cause acceleration of water quality points, the ocean current load \( F \) of floating wind turbine \( F_{ht} \):

\[
F_{ht} = 0.5 A_b C_b \rho_h V_h |V_h|
\]

(7)

Where: \( A_b \) is the section diameter of platform member; \( C_b \) is the drag force coefficient of platform members; \( \rho_h \) is the density of seawater; \( V_h \) is the horizontal instantaneous flow velocity of seawater.

2.3. Mooring system model.
The semi-submersible floating wind turbine adopts catenary mooring, with a total of 3 mooring lines. Jonkman J. M. verified through experiments that ignoring the deformation of mooring line and platform inertia of mooring system does not affect the calculation results of catenary static model.

Tension \( L \) borne by the top of three mooring lines:

\[
L = 3 \frac{T_s}{w} (c_h \frac{s w}{T_s} - 1)
\]

(8)

Where: \( T_s \) is the horizontal grasping force of the anchor; \( s \) is the horizontal projection length of the mooring line; \( w \) weight per unit length of mooring line in water.

2.4. Coupling model
Taking the platform, tower and blade as a coupling system and considering the aerodynamic load and hydrodynamic load, the dynamic balance equation is established:

\[
M_t \Delta \ddot{d}_t + C_t \Delta \dot{d}_t + K_t \Delta d_t = \Delta R_t^E
\]

(9)

Where: \( M_t \) is the additional mass matrix of platform, tower and blade at time \( t \); \( C_t \) is the damping matrix of platform, tower and blade at time \( t \); \( \Delta \ddot{d}_t, \Delta \dot{d}_t \) and \( \Delta d_t \) is acceleration increment, velocity increment and displacement increment respectively; \( \Delta R_t^E \) is the external force on the whole floating wind turbine platform.

3. Design of independent pitch controller for floating wind turbine
When the wind speed is greater than the rated wind speed set by the floating wind turbine, the wind turbine will start the independent pitch controller and perform the pitch operation through the actuator. Combined with the realistic background that the floating wind turbine is applied in deeper sea areas, the wind resources are better, but the unbalanced load is more serious. From the point of view of reducing the load of floating wind turbine, this paper designs two independent pitch control strategies, which are independent pitch control strategy based on PID azimuth weight coefficient (K-PID) and independent pitch control strategy based on brainstorming algorithm to optimize PID azimuth weight coefficient (BSO-K-PID).

![Figure 1. Flow chart of independent pitch control](image-url)
3.1. Independent pitch control strategy based on PID azimuth weight coefficient

This paper adopts NREL-5MW floating wind turbine. The difference between the three blades in space is 120°, the height difference between the hub and the sea surface is 90m, and the diameter of the wind turbine is 126m. Because the floating wind turbine adopts a high-power model and the sea condition is more complex, which is easy to lead to a large wind speed difference at the position of the three blades during the operation of the floating wind turbine. Therefore, an independent pitch control strategy for calculating the wind speed at the position of each blade according to the blade azimuth is proposed. Ignore the structural differences between the blades and define the blade azimuth θ, The wind speed at the center of each blade is equivalent to the average wind speed $V_i$:

$$V_i = \left[1 + \frac{R_{fl}}{2H} \sin(\theta + (i-1)120^\circ)\right]^n \times V_{fl}$$  \hspace{1cm} (10)

Where: $H$ is the height from the hub center to the ground (90m); $R_{fl}$ wind turbine radius(63m); $\theta$ is the blade azimuth; $i=1,2,3$ represent blade 1, blade 2 and blade 3 respectively; $V_{fl}$ is the wind speed at the center of the hub; $n$ is the wind shear index.

Weight coefficient $K_i$:

$$K_i = \frac{3 \times \left[1 + \frac{R_{fl}}{2H} \sin(\theta + (i-1)120^\circ)\right]^2}{\sum_{i=1}^{3} \left[1 + \frac{R_{fl}}{2H} \sin(\theta + (i-1)120^\circ)\right]^2}$$  \hspace{1cm} (11)

Where: $K_i$ is the azimuth weight coefficients of the pitch angles of the three blades ($i=1, 2, 3$).

Change value of unified pitch angle output $\Delta \beta_t$ and azimuth weight coefficient output $\Delta \beta_i$ ($i = 1, 2, 3$), the change value of pitch angle of blades 1, 2 and 3 is obtained in combination with equation (13):

$$\Delta \beta_i = K_i \times \Delta \beta_t$$  \hspace{1cm} (12)

3.2. PID azimuth weight coefficient independent pitch strategy based on brainstorming algorithm (BSO)

In 2011, based on the brainstorming method of human creative problem solving, Professor Shi Yuhui proposed a human simulated intelligent optimization algorithm - brainstorming algorithm (BSO). The algorithm mainly includes six processes: initialization, clustering, mutation, generating new individuals, updating and selection. The algorithm is simple, less variables and easy to implement. After generating several individuals and calculating their fitness, the individuals are divided into several categories based on K-means clustering method, and the individuals with the optimal fitness value are updated as the center of the category. Finally, the new individual is compared with the original individual, the optimal individual is selected from the two, and then whether to continue is judged according to the iterative conditions.

Random disturbance represents:

$$x_n^a = x_o^a + H N(\mu, \sigma)$$  \hspace{1cm} (13)

$$H = \log\sigma g \left[\frac{1}{2} N_{max} - N_{now} \right] \cdot 0.44$$  \hspace{1cm} (14)

Where: $x_n^a$ is the A-dimensional component of generating a new individual; $x_o^a$ is the A-dimensional component of the selected individual; $H$ is the adjusted random disturbance parameter; $N(\mu, \sigma)$ m can be value $\mu$, variance $\sigma$ Gaussian function; $\log\sigma g$ is a logarithmic transformation function($\log\sigma g(a) = \frac{1}{1+e^{-a}}$); $N_{max}$ is the maximum number of iterations; $N_{now}$ is the number of iterations being executed; $k$ is the slope parameter (0.44 in this paper).
4. Simulation analysis

Based on OpenFAST-Matlab / Simulink, this paper simulates and analyzes the OC4-Hywind floating platform of NREL-5MW wind turbine. The two independent pitch control strategies proposed in this paper are compared, and the simulation time is 400s.

| Table 1. Main parameters of NREL-5MW wind turbine |
|---------------------------------------------------|
| **Rated power** | 5MW |
| **Hub height** | 90m |
| **Rated generator speed** | 1173.7rpm |
| **Generator efficiency** | 94.4% |

| Table 2. Main parameters of OC4-Hywind floating wind turbine platform |
|---------------------------------------------------------------------|
| **Platform form** | Three pontoon semi-submersible |
| **Anchor chain form** | catenary |
| **Number of mooring lines** | 3 |
| **Unstressed cable length** | 902.2m |
| **Total platform mass** | $1.3547 \times 10^7$kg |

The three-dimensional turbulent wind with an average wind speed of 17m /s is generated by the preprocessing software turbosim. The two-dimensional wind speed map in X direction is shown in Figure 2.

**Figure 2.** Wind speed diagram in X direction

The two independent pitch control strategies proposed in this paper are jointly simulated and compared in OpenFAST- Matlab / Simulink, and the simulation waveform is as follows:

**Figure 3.** Comparison diagram of platform surge displacement
During the simulation, the average wind speed cut into the turbulent wind is 17m / s. even if the parameters of the rotor speed have been configured with the rated speed before the simulation, the large oscillation amplitude will still be caused by other factors in the initial stage of the simulation, which is not in line with the actual situation. After comprehensive consideration, the standard deviation of 100s ~ 400s is listed in the table below.

### Table 3. Numerical comparison of two independent pitch control strategies

| Parameter               | Value             | K-PID | BSO-K-PID |
|-------------------------|-------------------|-------|-----------|
| Platform Heave displacement (m) |                   |       |           |
| Maximum                 | 1.28              | 1.23  |           |
| Minimum                 | -1.10             | -1.17 |           |
| Standard deviation (0~400s) | 0.430             | 0.429 |           |
| Standard deviation (100~400s) | 0.429             | 0.423 |           |
| Platform surge displacement (m) |                   |       |           |
| Maximum                 | 12.5              | 11.7  |           |
| Minimum                 | 4.30              | 4.91  |           |
| Standard deviation (0~400s) | 1.70              | 1.43  |           |
| Standard deviation (100~400s) | 1.24              | 1.16  |           |
| Tower base yaw moment (KN·m) |                   |       |           |
| Maximum                 | 4630              | 5210  |           |
| Minimum                 | -5680             | -5710 |           |
| Standard deviation (0~400s) | 1610              | 1560  |           |
| Standard deviation (100~400s) | 1610              | 1520  |           |

### 5. Conclusion
According to the calculation results of the standard deviation of the simulation waveform and simulation data, after comparison and verification, it can be concluded that under the BSO-K-PID independent pitch control strategy, the shaking of the floating wind turbine platform is reduced and the stability is
better, which can effectively reduce the load of the floating wind turbine platform and alleviate mechanical fatigue to a certain extent.

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