Research on the Influence of Yaw Control on Wind Turbine Performance under Wake Effect

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Abstract. The wake effect causes power loss and severely reduces the power generation capacity of the wind farm. In order to reduce the impact of wakes, the current main method is to optimize the layout of wind farms, which is unrealistic for the completed wind farms. In contrast, yaw control is used to offset the wake, which minimizes the impact of wakes between WTs (Wind Turbines), thereby increasing the generating capacity of the WTs. In this paper, fluent software is used to simulate the effect of wake on the output power of the downwind WT in two tandem WTs, when the upstream WT yaws at different angles. By analyzing the change of the total output power after yaw, it is concluded that the total output power reaches the maximum when the upstream WT yaws 25°.

1. Introduction

In today's society, the demand for renewable energy is growing rapidly, and the scale of wind farms is constantly expanding, and many problems have also followed. The impact of wake between WTs severely limits the increase in generating capacity of the WTs. The wake effect reduces the output power of the downstream WTs and increases the intensity of air turbulence, resulting in a reduction in the WTs’ life. According to statistics, the loss caused by the wake of a large wind farm is about 10% to 20% of the total output [1]. In order to reduce the impact of the wake and increase the output power of the wind farm, the most traditional method is to plan the overall layout of the wind farm [2], and try to avoid the direction of the incoming wind in the same straight line with the WTs [3]. However, this method has drawbacks. First, the wake has a wider distribution range. This solution reduces the density of WTs, reducing the power generation of the wind farm; second, when the direction of the incoming wind changes, the WTs with a yaw system will automatically align with the wind, which may cause wake effects between new WTs [4]. A recent study is to actively control the yaw angle of the upstream WT to make the wake deviate from the downstream WT. The power increase of the downstream WT compensates for the power loss of the upstream WT, thereby increasing the output power of the entire wind farm. Through large eddy simulation, Churchfield M et al. [5] found that when the upstream WT performs yaw operation, the power extraction of an array of WTs increases by 10%. The drift of the wake was first proposed by Jiménez A et al. [6]. In [7], the drift of the WT wake under different yaw angles was calculated. Gebraad PM [8] built a parametric yawed wake model and constructed an optimal function for the wind farm power production using the game theory [9]. Based on a wake interaction model, Jinkyoo Park [10] related the yaw offset angles and the induction factors of WTs to the wind...
speeds experienced by the WTs, an optimization problem is formulated with the objective of maximizing the total power production of a wind farm.

The above studies all use parameter models to optimize the yaw angle or axial induction factor of WTs to maximize power generation. However, this requires a lot of data, and the calculation results cannot be effectively verified. Firstly, this paper uses fluent software to simulate the output power of a single WT under rated operating conditions (wind speed, rotation speed), and the calculated output power is very close to the design value, which proves the feasibility of this method; then, fluent software is utilized to simulate the relationship between the output power of the downstream WT and total power and the yaw angle of the upstream WT. Until the total output power is maximum, the yaw angle at the moment is the best value. It has practical engineering significance.

2. CFD numerical simulation of wake characteristics of single WT

2.1. Governing equation
The CFD method follows three conservation laws: mass conservation, momentum conservation and energy conservation. In general, the CFD method is not suitable for solving problems involving energy conversion, so only the two conservation laws of mass conservation and momentum conservation are considered as the governing equations of CFD numerical simulation.

2.1.1. Mass conservation equation. The variation in the mass of a target fluid in the flow field per unit time is equal to the net flux of the mass of the target fluid (hence the continuity equation). When the fluid is transient and compressible, the mass conservation equation is as follows [11]:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} + \frac{\partial \rho w}{\partial z} = 0 \tag{1}$$

Where $\rho$ is the density of fluid, $t$ is the time, $u, v, w$ are the components of the velocity vector $\vec{u}$ in $x, y, z$ directions, respectively.

Considering that the fluid is in a steady state and incompressible, the density is a constant and does not change with time. At this time, formula (1) can be rewritten as:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{2}$$

2.1.2. Momentum conservation equation. The change rate of the momentum of the target fluid cell with respect to time is equal to the sum of the external forces acting on the fluid cell. Its essence is Newton’s second law, therefore, its momentum conservation equation has the following form [12]:

$$\begin{align*}
\frac{\partial(\rho u)}{\partial t} + \text{div}(\rho \vec{u} \vec{u}) &= \text{div}(\mu \text{grad} \vec{u}) - \frac{\partial P}{\partial x} + S_u \\
\frac{\partial(\rho v)}{\partial t} + \text{div}(\rho \vec{v} \vec{u}) &= \text{div}(\mu \text{grad} \vec{v}) - \frac{\partial P}{\partial y} + S_v \\
\frac{\partial(\rho w)}{\partial t} + \text{div}(\rho \vec{w} \vec{u}) &= \text{div}(\mu \text{grad} \vec{w}) - \frac{\partial P}{\partial z} + S_w \tag{3}
\end{align*}$$

Where $P$ is the pressure on the fluid differential unit, $\mu$ is dynamic viscosity, $S_u, S_v, S_w$ are the generalized source terms acting in the $x, y, z$ directions of the fluid differential unit.
2.2. Geometry modeling and computational domain meshing of single WT

In this paper, a three-dimensional numerical calculation model is built based on the parameters of the UP77 WT with 1.5MW. The WT type and its parameters are shown in Table 1.

| WT type                  | UP77       |
|--------------------------|------------|
| Rated power              | 1500 kW    |
| Rotor diameter           | 77 m       |
| Tower height             | 65 m       |
| Cut-in wind speed        | 3 m/s      |
| Rated wind speed         | 11 m/s     |
| Cut-out wind speed       | 25 m/s     |
| Rated rotating speed of rotor | 17.4 rpm |
| Rotation direction (viewed from upwind) | clockwise |

NACA4412 airfoil was used for blade modeling. The simplified model of hub adopts a cylinder with diameter of 4.5 m and height of 2.6 m. The nacelle is composed of a cuboid with a length of 9 m, a width of 5 m and a height of 5 m, and a quarter of a cylinder with a radius of 5 m. The top diameter of the tower is 3 m, the bottom diameter is 6 m, and the height is 65 m. The blade rotating fluid is an oblate disk that includes the impeller, and the wind turbine fluid is the flow field that encompasses the entire wind turbine. The wind farm is composed of a cuboid, whose length, width, and height are 1440 m, 560 m, and 320 m, respectively. The wind farm mesh model is shown in Fig. 1. Due to the complex geometric shape of the impeller, an unstructured triangular mesh is used to locally increase mesh density of the blade and hub, as shown in Fig. 2.
2.3. Setting of boundary conditions
In this research, the steady incompressible Reynolds-averaged Navier-Stokes (RANS) equations with the shear stress transport (SST) turbulence model are adopted. This three-dimensional numerical simulation calculation used the semi-implicit method of pressure-coupled equations (SIMLEPC algorithm), most wide method for flow field calculation.

The fluid material is set to air. The INLET adopts velocity-inlet, assuming that the INLET is a uniform incoming flow of 11 m/s; the OUTLET adopts free flow (outflow); the BLADES and HUB are set as moving walls, the rotation speed is zero relative to nearby flow field area, and the outer computing domain, nacelle and tower adopt non-slip fixed walls; each surface of the inner rotation domain is the interface between the inner and outer domains, and the interface is set; the impeller rotation domain is the MRF multiple reference coordinate model, which is obtained by the right-hand screw rule, with a rotation speed of 17.4 rpm (revolutions per minute).

2.4. Output power calculation
Import the mesh into the fluent software and set various parameters, set the rpm in the “units”; set the rotation axis and speed of the internal rotation domain in the “Cell Zone Conditions”; set the interface in the “Mesh Interfaces”; and use the “Hybrid Initialization” to initialize until the iteration steps of calculation can satisfy the convergence of each curve.

After the calculation converges, the required performance parameters are derived. The torque of the blade to the rotating axis can be obtained, and use the formula (4) to calculate the output power of the wind turbine:

\[ P = \frac{2\pi n}{60} M \]

Where \( P \) is the output power (W) of the WT, \( M \) is the torque (N \( \cdot \) m) of the blade to the rotating shaft, and is the rotation speed.

After many debugging and settings, under rated working conditions, the wind turbine has a stable output power of 1.4110MW, which is very close to the design value of 1.5MW, with a relative error of 5.93%, indicating the feasibility and effectiveness of this calculation model and method.

3. The influence on the downstream WT due to yaw of the upstream WT in the double WTs

3.1. Numerical calculation model

3.1.1. Wind farm modeling with two WTs. The wind farm is modeled for two 1.5MW wind turbines. The left is the wind speed inlet (INLET), the right is the outlet (OUTLET), and the arrow represents the incoming wind direction. Figure 3 shows the schematic diagram of the wind farm modeling for two tandem WTs. According to the different yaw angles of the upstream WT, it is divided into 6 working conditions, as shown in Table 2.

![Figure 3. Schematic diagram of wind farm modeling for two tandem WTs.](image-url)
Table 2. 6 working conditions divided according to the yaw angle of the upstream WT

| Types of working conditions | one | two | three | four | five | six | seven |
|-----------------------------|-----|-----|-------|------|------|-----|-------|
| Yaw angle of upstream WT ($\theta$) | 0   | 5   | 10    | 15   | 20   | 25  | 30    |

3.1.2. Meshing. Since the upstream WT is required to actively yaw, when dividing the mesh in ICEM CFD software, the upstream WT is rotated clockwise $5^\circ, 10^\circ, ..., 30^\circ$ to obtain the mesh model of the wind farm with two WTs under different working conditions.

Considering that the blades in the rotating domain are surrounded by multiple cross-sectional curves, a local densification method is used when dividing the mesh, that is, the meshes in the inner are denser than those in the outer. The computational domain mesh of the entire flow field of the two WTs model is shown in Figure 4. The minimum value of the overall quality of the mesh under different working conditions is greater than 0.3 (the mesh quality is better within 0.3~1), and the mesh quality meets the requirements, which can better meet the calculation requirements in Fluent software.

![Overall mesh model of wind farm](image)

3.1.3. Boundary conditions. The fluid material is set to air. The INLET adopts velocity-inlet, assuming that the INLET is a uniform incoming flow of 11m/s; the OUTLET adopts free flow (outflow); the BLADES and HUB are set as moving walls, the rotation speed is zero relative to nearby flow field area, and the outer computing domain, nacelle and tower adopt non-slip fixed walls; each surface of the inner rotation domain is the interface between the inner and outer domains, and the interface is set; the impeller rotation domain is the MRF multiple reference coordinate model, which is obtained by the right-hand screw rule, with a rotation speed of 17.4 rpm (revolutions per minute).

3.2. Analysis of wake calculation results

3.2.1. Numerical solution method. This paper studies the low-speed flow field, which is solved by an implicit three-dimensional solver based on pressure separation. The SST $k-\omega$ turbulence model based on the RANS method is adopted. The pressure-velocity coupling algorithm uses the SIMPLEC algorithm, and the spatial discrete format uses PRESTO, pressure interpolation format. Under rated conditions, the steady-state analysis of the entire flow field of two-WTs model is carried out, that is, the incoming wind speed is a uniform inlet wind speed of 11m/s, and the rotating speed is set to 17.4rpm and remains unchanged.

After the calculation is completed in Fluent, the required performance parameters of the WT, namely the torque of the blade to the shaft, are derived, and the output power of the two WTs are calculated according to formula (4).

3.2.2. Analysis of the influence on performance of downstream WT due to yaw of upstream WT. Under different working conditions, the respective output power of the upstream and downstream WTs and
their total power are shown in Figure 5. The upstream WT is represented by WT1, and the downstream WT is represented by WT2.

![Figure 5](image)

**Figure 5.** The relationship between total power of two WTs and yaw angle of upstream WT

Figure 5 shows the relationship between the total power of the two WTs and the yaw angle of the upstream WT. It can be seen that as the yaw angle of the WT1 gradually increases, although the output power of WT1 decreases, the output power of WT2 increases, which is greater than the reduced power of WT1, so the total output power increases. When the yaw angle of WT1 is 25°, the total output power of two WTs is 2.43MW, reaching the maximum, which Increased by 4.7% compared to yaw free.

4. Conclusion

In order to better understand the influence on downstream WT due to yaw of upstream WT in wind farm, a steady-state CFD study was carried out on two 1.5MW tandem WT using a full rotor model. Firstly, after simulating a single wind turbine under rated wind conditions, the output power is calculated to be 1.41099MW, which is very close to the design value of 1.5MW, which proves the feasibility of this model and method; secondly, the steady-state research for two 1.5MW tandem WTs has been carried out. When WT1 yaws at different angles, WT1, WT2 and their total power will change. As the yaw angle of WT1 gradually increases, the output power of WT1 decreases, but the increased output power of WT2 is greater than the reduced power of WT1, so the total output power increases. When the yaw angle of WT1 is 25°, the total output power of the two WTs reaches the maximum, which is a 4.7% increase in total output power compared with no yaw.

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