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Comparison of the effectiveness of analytical wake models for wind farm with constant and variable hub heights

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A B S T R A C T

Extensive power losses of wind farm have been witnessed due to the wake interactions between wind turbines. By applying analytical wake models which describe the wind speed deficits in the wake quantitatively, the power losses can be regained to a large extent through wind farm layout optimization, and this has been extensively reported in literature. Nevertheless, the effectiveness of the analytical wake models in predicting the wind farm power production have rarely been studied and compared for wind farm with both constant and variable wind turbine hub heights. In this study, the effectiveness of three different analytical wake models (PARK model, Larsen model and B-P model) is thoroughly compared over a wide range of wake properties. After the validation with the observation data from offshore wind farm, CFD simulations are used to verify the effectiveness of the analytical wake models for an onshore wind farm. The results show that when using the PARK model the surface roughness value (z_0) must be carefully tuned to achieve good performance in predicting the wind farm power production. For the other two analytical wake models, their effectiveness varies depending on the situation of wind farm (offshore or onshore) and the wind turbine hub heights (constant or variable). It was found that the results of B-P model agree well with the CFD simulations for offshore wind farm, but not for the onshore wind farm. The Larsen model is more accurate for the wind farm with variable wind turbine hub heights than those with constant wind turbine hub height.

1. Introduction

The study of renewable energy has attracted extensive attention in recent years, due to the depletion of traditional fossil fuels and their pollutions on the environments after consumption. Among all the different types of renewable energy sources, currently the wind energy has been the fastest-growing energy source. Most of developed countries as well as some developing countries (e.g., China) have set their goals of 20% of the total electric power consumption to be produced from wind power [1]. In China, driven by the policy from government to increase the wind power installed capacity, more and more large-scale wind farms have been installed in places with abundant wind resources to take full advantage of local wind power [2]. However, for those wind farms with large number of wind turbines, the wake effect has been an unavoidable problem which may reduce the total wind farm power production to a large extent if it is not designed carefully [3]. Researchers have shown that wind farm design can be carried out through the optimization of wind farm layout and control strategy, so as to minimize power losses caused by the wake interactions and maximize the wind farm power [4,5].

The optimization of wind farm is accomplished by applying the wake models to account for the wake interactions between wind turbines, quantitatively. There have been various types of wake models developed to simulate the wind turbine wake [6,7]. It covers the range from the most straightforward model based on similar velocity deficit profiles (also known as analytical wake models), through the moderately complex Ainslie-based models, to the more complex models based on the parabolized Navier-Stokes (N-S) equations, and finally to the complete 3D N-S models [8]. With the order of complexity from the simplest to the most complex, the computational costs of the wake models also increase exponentially. As reported in [9], the wind turbine wake is divided into the rotor region, the near-wake region and the far-wake region. By comparison to the measurements obtained from wind farm experiments [10], it is demonstrated that the complex wake models are more able to capture the flow details of wake including the rotor region and the near-wake region, while the simplified wake models can predict only the averaged wind speed in the

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far-wake region well [8]. When conducting the wind farm layout optimization study with numerous potential combinations of wind turbine positions to evaluate, only the simplified wake models are available while the complex wake models are impractical due to their large computational costs.

Different analytical wake models have been employed for wind farm layout optimization studies in literature [11,12]. Kusiak and Song applied the most popular PARK model to optimize the wind turbine positions on a circular shape wind farm, for the purpose of maximizing the total power production [11]. In [12], the authors employed a new virtual particle wake model to optimized the wind farm layout with complex non-flat terrains. However, their accuracy for predicting the wind farm power output has not been validated systematically, especially for the situation with variable wind turbine hub heights. Since there have been numerous studies on the wind farm layout optimization by considering the use of different wind turbine hub heights [13,14], it is necessary to assess the accuracy of the wake models to understand the validity of the optimization results for the wind farm with different wind turbine hub heights [15,16]. Therefore, the main focus of this work is to study the effectiveness of the analytical wake models by comparison with either from observation data (if available) or from the more detailed models. Due to the fact that most of the current work only considers the power production capability when conducting wind farm optimization [17,18], in this paper only the prediction of wind farm power production is carried out by comparing different kinds of wake models. Other factors like fatigue loads of wind turbine structures and stress distribution of wind turbine components are beyond the scope of this paper.

The effectiveness of the Computational Fluid Dynamics (CFD) models on wind farm study has been verified by researchers in literature [19,20]. Even so, in order to present the current work in more detailed and systematical manner, the validation of CFD simulations is carried out first on a commercial offshore wind farm by comparing with the observation data. After validation, the effectiveness of analytical wake models is studied by comparing the simulations for both constant and variable wind turbine hub heights, since the actual test data of the wind farm are not readily available. The remainder of the paper is organized and explained as follows. In Section 2, a study on different models is introduced which includes three different kinds of models, namely, two wind turbine models (offshore wind turbine and onshore wind turbine), two wind farm models (offshore wind farm and onshore wind farm), and three analytical wake models (PARK model, Larsen model and B-P model). In Section 3, the way in which wind farm power production is predicted through CFD simulations and analytical wake models is presented. For calculation using CFD simulations, the actuator disk theory based on which the wind turbine rotor is simplified in the simulations of wind farm, is given, and the CFD simulation setup is shown. For the calculation of wind farm power production using the analytical wake models, the whole process from determining the wake interaction patterns to the final calculation method is introduced. The results and discussion are presented in Section 4. First is the study on offshore wind farm with observation data to be compared with, then the wind farm with constant wind turbine hub height is studied and finally that with variable wind turbine hub heights is discussed. Section 5 draws the conclusion of the work.

2. Modeling

2.1. Wind turbine models

There are two different wind turbine models applied in this paper. One is an offshore wind turbine model, for which the observation data of wind farm wake are available in literature. The other is an onshore wind turbine model, and the model is widely employed for the wind farm layout optimization study while the test data is unavailable.

2.1.1. Offshore wind turbine

Before studying the effectiveness of the analytical wake models for wind turbines with constant or variable hub heights, the effectiveness of CFD simulations are validated by comparing the results with offshore wind farm data. Therefore, an offshore wind turbine is introduced which is a variable speed pitch-control turbine. The details of the turbine are listed in Table 1 [21].

Apart from the basic information on the wind turbine [22], other important parameters are introduced as well which include the wind turbine power curve and the thrust coefficient. These are shown in Fig. 1(a) and (b), respectively.

2.1.2. Onshore wind turbine

When studying the effectiveness of the analytical wake models for wind turbines with constant or variable hub heights, an onshore wind turbine is employed to compare the results with CFD simulations.

The details of the onshore wind turbine parameters are shown in Table 2. For the study of constant wind turbine hub height, the same value as that in the literature is used which is 60 m. For the study of variable wind turbine hub heights, three different options from 40 m to 80 m are considered.

The wind turbine power curve can be found in [23] which is shown in Fig. 2. The wind turbine thrust coefficient is the constant value of 0.88 when the wind speed is among cut-in and rated speed according to the data from literature.

2.2. Wind farm models

2.2.1. Horns Rev offshore wind farm

Due to the availability of observation data, the Horns Rev offshore wind farm is selected for study and the power production data of which can be obtained from Refs. [24,25].

Fig. 3 indicates the outline of the offshore wind farm with three characteristic wind directions, which are aligned with the wind turbine rows and diagonals resulting in the full wake interaction of the wind turbines. The wind farm is located in the eastern North Sea, 15 km off the westernmost point of Denmark, and it is comprised of 80 identical wind turbines within an area of about 20 km^2 [26]. As can be seen, the wind farm layout has a rhomboid shape. One side of the shape is in the west-east direction, and it is approximately 7° between the north-south direction and the other side. The minimum distance between the adjacent wind turbines is 7d (d is wind turbine diameter) which is exactly the case when the wind direction is 270°. For the other two wind directions, i.e., 222° and 312°, the distance between the adjacent wind turbines are 9.3d and 10.4d, respectively.

2.2.2. Onshore wind farm

After the verification of CFD simulations using the offshore wind farm observation data, the onshore wind farm is applied as the target wind farm to compare the CFD simulation results with

Table 1
Basic information of the offshore wind turbine parameters.

Name	Nameplate power	Rotor diameter	Hub height	Cut-in speed	Rated speed	Cut-out speed
V80-2.0	2 MW	80 m	70 m	4 m/s	16 m/s	25 m/s