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Modeling of horizontal axis wind turbine wakes in Horns Rev offshore wind farm using an improved actuator disc model coupled with computational fluid dynamic

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ABSTRACT

In order to increase the accuracy and ability to predict the total energy gained in wind farms, it is necessary to use accurate wake models. In the present study, an improved methodology is applied on actuator disc in order to take all the operational and geometrical characteristics into account such as airfoil type, angular velocity, twist, and chord distribution. In wind farms, turbines are affected by upstream ones resulting in a non-uniform upstream velocity for each turbine. However, in literature, for all the wind turbines in a wind farm, thrust coefficient curve at undisturbed wind speed is used in order to estimate the upstream speed resulting in some errors. This weakness of actuator disc is resolved by a hybrid methodology based on blade element momentum theory and mass conservation coupled with computational fluid dynamics to be independent of thrust coefficient curve and calculate more accurate incoming velocity according to operational condition. It has been observed that by using the developed model and considering the details of wind turbines and more accurate incoming wind speed, in spite of steady state simulation and low computational cost, the interaction between different turbines is well-described. For turbulence modeling, standard $k-\epsilon$ turbulence model is used and it is shown that the error of power estimation in second row of turbines especially in 270° wind angle is decreased significantly. In large wind sectors, such as 270 ± 10°, ± 15°, 222 ± 10°, ± 15° and 312 ± 5°, ± 10° the proposed model performs as well as LES simulation. The developed methodology is practical for designing and optimization of new wind farms even if the technical specifications such as thrust curve would not be available from manufacturer.

1. Introduction

Considering population increase and reduction of available fossil fuel resources, man has tried to discover alternative sources of energy. Amongst the variety of renewable energy sources, wind energy has attracted much attention for a long time. As a result, many efforts have been made to design and build wind turbines in various types. Each of these types of turbines can be used individually or as a series of turbines called wind farm. At the end of 2016, global renewable generation capacity amounted to 2006 GW in which the share of wind industry was 467 GW [1].

In wind farms, studying the interaction between downstream turbines and wake of upstream turbines plays a significant role in order for predicting output power and fatigue loads. Many studies have been done on simulation of wind turbine wake. The methods are divided into three categories, including analytical, numerical and experimental methods that each of them has its own advantages and drawbacks. One of the most famous and basic models is the one presented by Jensen in 1983 [2]. In this case, by using a constant induction factor, the velocity was calculated immediately after the turbine, then the mass conservation law was used to estimate the magnitude of velocity and wake shape at different intervals. According to his model, Katic et al. [3] presented a model in which turbine characteristics such as rotor radius and hub height were considered, then used it to calculate the power of a wind farm. Based on the preceding models, Frandsen et al. [4] considered the axial induction factor and thrust coefficient and provided a model for wake simulation based on momentum theory.

In all of the models described above, a constant induction factor in the wake equations was used. But in fact this is a rough assumption because the induction factor changes along the blade. Ghadirian et al. [5] used blade element momentum method (BEM) to obtain the distribution of the induction factor in the span wise direction, after that by

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Nomenclature

A	rotor area, m^2
a	axial induction factor, dimensionless
a'	tangential induction factor, dimensionless
C_d	drag coefficient, dimensionless
C_l	lift coefficient, dimensionless
C_n	normal force coefficient, dimensionless
C_t	tangential force coefficient, dimensionless
D	rotor diameter, m
F	Prandtl's tip loss factor, dimensionless
$\dot{m}$	mass flow rate, kg s^{-1}
r	radius of the segment, m
u	velocity at rotor plane, m s^{-1}
u_1	velocity behind the turbine, m s^{-1}
V_0	undisturbed wind speed, m s^{-1}

Greek symbols

α	angle of attack, rad
β	twist angle, rad
ρ	air density, kg m^{-3}
σ	solidity, dimensionless
ϕ	inflow angle, rad
ω	rotational angular velocity, s^{-1}

Subscripts/superscripts

d	disc
e	end of the segment
p	pitch
s	start of the segment
loc	local
seg	segment
up	upstream

using mass conservation law and equalizing the flows from each of the sections with the total flow, obtained a single induction factor that was more in consistent with reality, then used this value in sequential equations. Hamedi et al. [6] used the concept of BEM to obtain the distribution of the induction factor along the blade, then calculated the velocity profile just behind the turbine and by using self-similarity and turbulence modeling, estimated the shape of the wake downstream. In BEM method [7], by using the momentum and also blade element theories, the local phenomena which occurs on blades are taken into account. This method has been used to study different performance parameters in order to optimize aerodynamics of a turbine operating at turbulent flow [8], obtain the optimize pitch angle [9], obtain the optimize chord and twist distribution [10], and also consider economic aspects [11]. One drawback of this method is steady state simulation and neglecting the unsteadiness due to gravity, tower shadow, wind shear, and turbulence [12]. There are also some methods proposed for considering the unsteady fatigue loads on the blades in yawed [13] and different atmospheric conditions [14].

In all of the analytic wake models described above, an approximate solution has been obtained for the problem by simplifying the equations governing the fluid flow. In order to obtain more precise results, Navier-Stokes equations should be solved in a computational domain. One of the most accurate models is full rotor simulation that is used in many studies such as [15,16]. It is worth mentioning that computational cost of this simulation is extremely high because of resolving boundary layer around the blades.

As a simple and low cost way, actuator disc (AD) method can be introduced. In this investigation, the wind turbine is considered as a porous permeable disc that absorbs wind momentum. Neglecting boundary layer region around the blade leads to a low cost but an efficient way. Newman [17], simulated a wind turbine using the concept of AD and examined the effect of different turbine parameters on the power coefficient. Sørensen et al. [18] have done a two dimensional simulation by solving Navier-Stokes and AD equations simultaneously. Mikellsen [19] studied the turbine performance in different operational conditions, such as yaw and different cone angles. The obtained results show that AD method, despite its simplifications, is able to model the interaction between turbine and its surrounding. Some researchers used AD simulation as the input for full rotor simulation in order to decrease the simulation time [20,21].

In offshore conditions the aerodynamic of the atmospheric boundary layer (ABL) is different from onshore and the performance of the floating turbines [22] are influenced by sea state [23]. The performance of the AD is evaluated in offshore condition and the results show that it is also practical for simulating offshore wind farms [24–26].

Another numerical technique that does not need resolving the boundary layer around the blades is actuator line (AL) method. This method needs unsteady state simulation [27,28] and is computationally expensive in comparison to AD method. Unlike AD, individual tip vortices are simulated using AL approach. It is preferred when near wake characteristics are studying but when the case is a wind farm including a large number of turbines, AL imposes high computational cost. Recently, a new method named virtual blade model (VBM) is introduced by Bianchini et al. [29,30] that simulates the wind turbine by body forces in which is not computationally complex in comparison to AL. The BEM method is also used in VBM in order to compute the loads.

One drawback of all the AD models is considering an uniform distribution of the induction factor and thrust coefficient across the disc. In order to consider the non-uniform distribution of the thrust coefficient on the disc surface, Javaheri [31] presented a model in which in hub section, the thrust coefficient and axial induction factor are considered to be zero. Also the blade element method can be used in order to modify an AD for wind farm simulation [32]. Naderi and Torabi [33] calculated radial distribution of the induction factor and thrust coefficient by combining the concept of AD and BEM and provided a modified AD. They also derived an induction factor that was a function of hub drag coefficient in order to model the effects of hub on wake shape.

In all the above AD models, the velocity of a point in upstream is considered as an input velocity to the turbine, or by using the velocity at rotor plane and the constant induction factor, an upstream velocity for the turbine is calculated. This simplification leads to high inaccuracy when different turbines are interacting together and the error increases as the number of turbines and their interactions increase.

In order to consider the details of formation and extension of the wake, it is necessary to use accurate turbulence models. Many models can be used to simulate wakes that are classified into two main categories including Reynolds averaged Navier Stokes (RANS) [33,34] and large eddy simulation (LES) [32]. Various aspects of wake have been examined in many studies by using these turbulence modeling methods [35,36].

In wind farms, when turbines are opposed to wake, their behavior is not similar. Empirical [37] and numerical data [26,32] show that turbines in second row encounter a high velocity deficit, and inlet velocity to the next turbines changes with an oscillation in a small range and sometimes increases. Castellani et al. [38] concluded that the AD