Applied Energy 226 (2018) 1187–1207

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Review and evaluation of wake loss models for wind energy applications

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HIGHLIGHTS

- 6 analytical wake loss models evaluated (3 for first time) with data from 3 wind farms.
- The 3 wind farms are a combination of offshore, inland, regular, and irregular layouts.
- Validation for wind directions aligned and non-aligned with the turbine rows.

ARTICLE INFO

Keywords:
Wake losses
Analytical wake loss models
Wind energy
Wind farms

ABSTRACT

Choosing an appropriate wake loss model (WLM) is a critical task in predicting power production of a wind farm and performing a wind farm layout optimization. Due to their efficient computational performance, analytical WLMs, also called kinematic models, are the most likely candidates for such applications. This paper examines the performance of six well-known analytical WLMs, i.e., Jensen, Larsen, Frandsen, Bastankah and Porté-Agel (BPA), Xie and Archer (XA), and Geometric Model (GM), by comparing their absolute error, bias, correlation coefficient, and ability to predict power production within one standard deviation of the mean observed values at three major commercial wind farms: Lillgrund (offshore, in Sweden), Anholt (offshore, in Denmark) and Nørrekær (inland, in Denmark). The three wind farms are chosen to cover many aspects of wind farms, such as offshore and inland conditions, regular and irregular layouts, and closely- to widely-spaced turbines. The conclusions of this review and the recommendations that are put forward provide practical guidelines for using analytical WLMs effectively in future wind energy applications. Overall, the Jensen and XA models stand out for their consistently strong performance and for rarely (Jensen) or never (XA) ranking last for all wind directions at all farms and are therefore the recommended models in general.

1. Introduction

As efforts continue worldwide to transition to renewable electricity in order to reduce the effects of fossil fuel consumption on air pollution, climate change, energy independence, and political stability, the construction of wind farms continues at record pace. Denmark reached a new record in 2015, producing enough wind energy to cover 42% of its electricity demand utilizing a combination of onshore and offshore wind [1]. The United Kingdom completed the London Array offshore wind farm in 2013, with an installed capacity of 630 megawatts (MW, 10^6 W) and with plans for additional large farms offshore of Scotland [2]. The United States saw new onshore wind installations exceed the construction of all other forms of electricity in 2016, with 8.7 gigawatts (GW, 10^9 W) of new installed capacity, bringing the total installed wind capacity to 82 GW, surpassing hydropower for the first time [3]. Additionally in 2016, the Block Island Wind Farm became the first offshore wind farm to be completed in the US, providing 30 MW of clean wind energy to the residents of Block Island, Rhode Island, previously confined to expensive and polluting electricity from diesel generators [4]. China is continuing to develop its renewable energy portfolio and is on pace to become the world's leader in new wind installations with ambitious plans to install 205 and 5 GW of onshore and offshore wind, respectively, by 2020 [5].

Despite the growth of wind energy in recent years, challenges remain [6–8]. One significant challenge, particularly for offshore wind, continues to be understanding and minimizing wake losses within a

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https://doi.org/10.1016/j.apenergy.2018.05.085
Received 23 February 2018; Received in revised form 14 May 2018; Accepted 21 May 2018

wind farm. A wind turbine wake is the plume-like region downwind of a wind turbine characterized by reduced wind speed and increased turbulence intensity. Wakes from upstream turbines can severely affect the performance of downwind turbines, causing wake losses typically in the range of 10–20% of the power generated by the undisturbed, front-row turbines [9,10], but as high as 70% for wind directions that are perfectly aligned with columns of wind turbines, for wind speeds lower than the rated wind speed of the turbines, and for tightly-spaced layouts, like at the Lillgrund offshore wind farm in Sweden [11–14].

Wake losses in a wind farm are challenging to predict because they are the result of complex, non-linear phenomena that are not perfectly understood. First the wind hits the blades of a turbine and puts them in motion, at a rate that depends on many meteorological, aerodynamic, and control factors, such as wind speed, wind shear, turbulence intensity, aerodynamic properties of the airfoils in the blades, and pitch angle of each blade. Each of these factors alone is difficult to simulate, let alone in combination with the others. Next, the rotor turns the gearbox and eventually the generator produces electrical power, after non-linear frictional losses at all stages, at an optimal rate that is different for each turbine model. Meanwhile, the flow leaving the turbine is weaker than upfront and the blade rotation adds turbulence to it, in a manner that depends on the initial wind speed and turbulence, the rate of rotation of the blades, and the yaw angle of the turbine. The resulting wake expands laterally and vertically, meanders, and eventually dissipates, in an almost chaotic fashion controlled by ambient turbulence, atmospheric stability, and the presence of other wakes overlapping with the original one. Not surprisingly, predicting all these factors accurately is an almost impossible task, which explains why many wake loss models (WLMs hereafter) have been proposed in the literature, with increasing complexity, as reviewed next.

WLMs can be divided into two categories. Analytical (or kinematic) WLMs provide an analytical solution to the wind speed deficit or relative power of a downwind turbine with respect to the upstream turbine. WLMs based on computational fluid dynamics (CFD), also known as field models, solve numerically the Navier-Stokes equations governing the entire flow field in a wind farm.

The most famous and widely used analytical model is Jensen [15,16], which provides an equation for the wake deficit, i.e., the wind speed deficit in the wake of a turbine, assuming an axial-symmetric expansion of the wake downstream described via a constant wake decay constant (k_w). In its original formulation, the wake deficit is only a function of axial distance from the upstream turbine. Larsen developed a semi-analytical model [17] from asymptotic expressions of Prandtl's rotational symmetric turbulent boundary layer equations. Frandsen's model [18], adopted in the Storpark Analytical Model, aims at predicting the wind speed deficit in large offshore wind farms with a rectangular site area and equal spacing between the wind turbines. More recently, two Gaussian-like models have been developed, one by Bastankah and Porté-Agel [19], in which the wake is assumed to have a Gaussian shape with the same expansion rate in the vertical and horizontal, and the other by Xie and Archer [20], in which the wake expansion is postulated to be different in the horizontal and in the vertical. Last, the Geometric Model by Ghaisas et al. [13] is a new hybrid model that predicts directly the relative power of downwind turbines based on simple geometric properties of the wind farm. These six WLMs are the focus of this paper and will be described in detail in the next section.

A widely used CFD-based model is the eddy viscosity model (EVM) [21], which solves an axial-symmetric formulation of the time-averaged Navier-Stokes equations with an eddy viscosity closure. Studies have shown that, since all standard CFD-based WLMs, including the EVM, assume that the wind turbines have no effect on the mean properties of the atmospheric boundary layer, wake losses in large wind farms are generally under-estimated, or, in other words, power production is over-estimated [22–24]. Correction methods have been developed, such as the Deep-Array Wake Model (DAWM) in Openwind [22] and the Large Array Wind Farm (LAWF) model in Wind-Farmer [23]. These corrections, combined with the original models, have proven to be somewhat effective [25]. A fast linearized field model, FUGA, combined with an actuator disk model to simulate the wind turbine rotor, was developed by Ott et al. [26]. FUGA-predicted wakes at the Horns Rev 1 and Nysted offshore wind farms in Denmark were in good agreement with measurements. The dynamic wake meander (DWM) model [27] can model both power production and loads on wind turbines in wind farms. The general idea is that wake meandering is governed by large-scale turbulence structures in the atmosphere. The DWM model was proven accurate at predicting single-turbine wake development [28].

Another group of more sophisticated CFD-based models are large-eddy simulation (LES) models, which have recently been used to study turbine wakes with great spatial and temporal resolution [29–33,20]. Generally, LES models include either an actuator disk or an actuator line model for the turbine rotor/blades and compare well with wind tunnel measurements [30] and observations [13]. However, LES models require large computational resources, of the order of weeks to simulate a few minutes on hundreds of computer cores.

Studying wake losses in a wind farm has become increasingly important in wind energy research and has led to increasingly complex models, from fast, analytical models to simplified CFD-based to high-fidelity LES, with more than exponentially increasing computational requirements. Since one of the most important applications of wake loss models is the identification of the optimal layout of a future wind farm which minimizes wake losses and therefore yields the highest power, using slow, CFD-based models is not practically feasible. For a given wind farm area and spatial resolution, the number of possible layouts increases rapidly with the number of turbines [34] and each layout needs to be evaluated for all wind directions, each with its own observed frequency. For a medium-sized wind farm of 50 turbines, the number of combinations to assess easily exceeds a million. Even if each layout will take a few minutes to be evaluated for all wind directions with a CFD-based linearized model such as FUGA, finding the global optimum will take millions of minutes, i.e., years. Considering that LES take much longer than a few minutes, the problem is effectively intractable with CFD-based models. Analytical models, despite being simpler and at times less accurate than CFD-based models, have such a quick execution time that they are the only practical solution for optimization problems. Thus the focus of this study is on analytical WLMs.

This is not the first study that compares the performance of analytical WLMs, as numerous assessments can be found in the literature. Sorensen and Nielsen [9] compared the performance of three WLMs (Jensen, Larsen, and EVM) at the Horns Rev 1 offshore wind farm and concluded that Jensen with a wake decay coefficient of 0.04 was best. In 2006, Barthelmie et al. [35] used sodar-derived profiles to conduct an extensive analysis of the performance of over 10 WLMs (including Larsen and EVM, among others) at the Vindeby offshore wind farm for single wakes and for directions of perfect alignment and concluded that it was not possible "to establish any of the models as having individually superior performance with respect to the measurements." In 2009, Barthelmie et al. [10] used data from two offshore wind farms (Nysted and Horns Rev 1) to compare Jensen and two CFD-based WLMs, with a focus on directions of perfect alignment between the turbine rows and the wind direction. In general Jensen performed worst and significantly underpredicted the power deficit. Gaumond et al. [36] compared three WLMs (Jensen, Larsen, and FUGA) at both Horns Rev 1 and Lillgrund and concluded that all three were able to accurately predict wind power with a 1.5% error for wide wind direction sectors of 30°. The three models, however, underpredicted power production of a row of wind turbines when narrow sectors of 3° or 5° were used. Andersen et al. [12] used CFD simulations based on the actuator line model for idealized cases (single turbine, a long row of turbines, and an infinite wind farm) to provide fitted estimates of the wake expansion coefficients for the Jensen and Frandsen models. González et al. [34] reviewed the wind farm layout optimization problem, with emphasis on