Determining the Wind Speed Distribution within a Wind Farm considering Site Wind Characteristics and Wake Effects

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ABSTRACT

This paper introduces a wind speed model for simulating the distribution of wind speeds within a wind farm. The model combines a macro scale wind speed time series (WSTS) model based on a continuous Markov process with a wake flow model, based on the Jensen model, to produce wind speeds upwind of every wind turbine. This model has been designed for use in the testing of turbine coordinated control algorithms and for use in detailed reliability analysis. An example analysis was carried out to investigate the Annual Energy Not Produced (AENP) due to wake effects on a single string wind farm. It was found that the wakes accounted for a 20.2% reduction in energy production compared to the wakeless scenario, highlighting the need to model these wake effects.

I.   INTRODUCTION

The stochastic nature of the wind and effect of wakes from upstream wind turbines provides unique fuel characteristics for wind farms. For reliability analysis of offshore wind farms the need to capture these characteristics is paramount, as the wind resource affects the power available to each wind turbine at any given time. By including wind resource characteristics and wake affects in the farm, the effect of failed assets and farm layout on Levelised Cost of Energy (LCoE) can be more accurately quantified. The modelling of these wind speed characteristics is also essential for evaluation and testing of coordinated control algorithms. The variations in wind speed will affect the performance of wind turbines when operated with coordinated control.

To produce the distributed wind speeds within a wind farm that are suitable for both reliability assessment and the testing of coordinated control algorithms, work on reproducing wind speed time series (WSTS) based on original wind speed data [1] has been combined with a wake flow model developed in [2].

This paper outlines the characteristics of this combined wind speed model. Section II gives details on the WSTS model and wake flow model, and how the models are combined to produce a whole farm model. Section III outlines an example analysis that this whole farm model can be used for. Section IV details the results of the example analysis and important conclusions from this analysis for reliability analysis and coordinated control, and Section V summarises the key findings from this paper.

II.   WHOLE FARM WIND SPEED MODEL

This section outlines the key components of the whole farm wind model; the WSTS model for determining the macro-wind speed at given time period, the wake flow model which is based on the Jensen model, and how the two models are combined.

Firstly, to decide what model to use to generate the WSTS, the metrics in [1] were used to assess the quality of the model. The metrics are designed to determine the quality of the WSTS for reliability analysis, so here it has been assumed that the WSTS will also be adequate for use in testing the coordinated control algorithms. The results in [1] have determined that of the models tested so far, a continuous Markov Process model is the most appropriate for this whole farm wind speed model. The specific details of this model can be found in [1].

Secondly, a wake flow model has been developed in [2]. The model is based on Jensen wake flow model [3] with some modifications. In the original Jensen model [3], the wind flow is assumed to be ideal with the same turbulence intensity in the whole wind farm. In this model, the wake decay coefficient varies according to the turbulence intensity in the wind farm. This way the effect of turbulence is incorporated for calculating wind speed deficits. A correction factor is applied to the wind speeds for power as power is directly proportional to the cube of wind speed. Wind direction is considered to be parallel to the array of turbines and therefore the turbines are in full wakes. The effects of multiple wakes are considered on downstream turbines. Details of this model can be found in [2].

The two models were combined to produce the whole farm wind model. A look-up table (LUT) was produced, which shows the wind speed deficit at every wind turbine for every macro-scale wind speed experienced at a site. A

WSTS is produced for the site for a given period of time from the WSTS model. Using this WSTS and the LUT of wind speeds, a WSTS was produced for each wind turbine in the farm for the life time of the farm.

For this whole farm wind model, there are some simplifying assumptions. Firstly, it has been assumed that macro-wind speed for the whole site remains constant in a given time period, and the only variation is due to the turbines' wakes effects. The wind direction also remains constant, and faces the front of the farm.

Therefore, a whole wind farm model has been produced by combining a WSTS model based on a continuous Markov Process with a wake flow model that is based on the Jensen model, considering the effects of multiple wakes.

III.   ILLUSTRATION

This Section details an example analysis carried out using this whole farm wind model. The Annual Energy produced (AEP), Annual Energy Not Produced (AENP) and annual revenue loss over the lifetime of a wind farm were calculated for both wake and wake-less scenarios.

To calculate the AEP due to wake effects, the energy produced at each turbine is computed for wake-less and wake scenarios using (1).

$$E_{T(i)} = \sum_{k=1}^{N-1} 0.5 C_p \rho \pi r^2 u_{t,T(i),k}^{3} (t_{k+1} - t_k) \qquad (1)$$

Where $E_{T(i)}$ is the energy produced by turbine i in the array (Wh), k is the time array step, N is the total number of time array steps, C_p is the coefficient of power, ρ is the air density (kg/m^3), r is the blade length (m), $u_{t,T(i),k}$ is the equivalent velocity at turbine i at k (m/s), and t_k is the time at k (hours). The equivalent velocity is calculated by modifying the actual wind speed with limits to represent the cut-in, cut-out and rated wind speeds (2).

$$u_t = \begin{cases} 0, & u < u_{in} \\ u, & u_{in} \leq u < u_{rated} \\ u_{rated}, & u_{rated} \leq u < u_{out} \\ 0, & u \geq u_{out} \end{cases} \qquad (2)$$

Where u is the actual wind speed (m/s), u_{in} is the cut-in wind speed (m/s), u_{rated} is the rated wind speed (m/s), and u_{out} is the cut-out wind speed (m/s). The AEP is calculated by diving by the simulation time.

The energy not produced (ENP) is calculated using (3).

$$ENP = N_T E_{T(1)} - \sum_{i=1}^{N_T} E_{T(i)} \qquad (3)$$

Where N_T is the number of turbines.

AEP and AENP are calculated by dividing by the number of simulation years. To calculate annual revenue loss, the AENP for the is multiplied by both £140/MWh and £100/MWh, representing current and future strike prices [4].

To carry out this analysis, a model wind farm was required. The wind farm in this example was a single string of 5 wind turbines in a row, in line with the wind direction, with 7 diameter (7D) array spacing. The performance parameters of the turbine and characteristics of the air are detailed in Table 1.

Parameter	Value	Parameter	Value
N_T	5	C_p	0.36
Distance between turbines	420 m	u_{in}	4 m/s
r	30 m	u_{rated}	13 m/s
Wind farm lifetime	25 years	u_{out}	25 m/s
Coefficient of thrust (C_t)	0.4	ρ	1.225 kg/m^3

Table 1: Wind farm and wind turbine operating parameters.

For this analysis, the original wind speed data was taken from the meteorological mast at the Egmond aan Zee wind farm site [5]. The data used was wind speeds from a height of 70 m, at 10 minute intervals from 01/07/2005 to 30/06/2006, and has been cleaned to produce a complete data set. This data set was used as the data to develop the continuous Markov process transition rate matrix. A 25-year WSTS was produced to simulate the wind profile over the lifetime of the farm.

It has been assumed that the turbines have perfect reliability for this analysis, and that the propagation time of wake effects in the farm are negligible compared to the sampling time of the WSTS. Therefore, the wake effects are assumed to occur simultaneously at all wind turbines.

The example analysis investigates the energy and revenue loss of a 5 turbine string array wind farm due to wake effects with unidirectional wind speed over a 25 year life time using the combined WSTS-wake flow model.

IV. RESULTS AND DISCUSSION

This section presents the results of this example analysis. Table 2 details the results of the energy analysis, Figure 1 gives an example trace of the WSTS for each of the turbines for a month, and Figure 2 shows the distribution of energy production and energy loss throughout the wind farm.

Parameter	Value	Parameter	Value
AEP	23.39 GWh	AENP (percentage of AEP wakeless)	20.2%
AEP (wakeless)	29.32 GWh	Annual revenue loss (current)	£0.83M
AENP	5.93 GWh	Annual revenue loss (future)	£0.59M

Table 2: Results of example analysis.
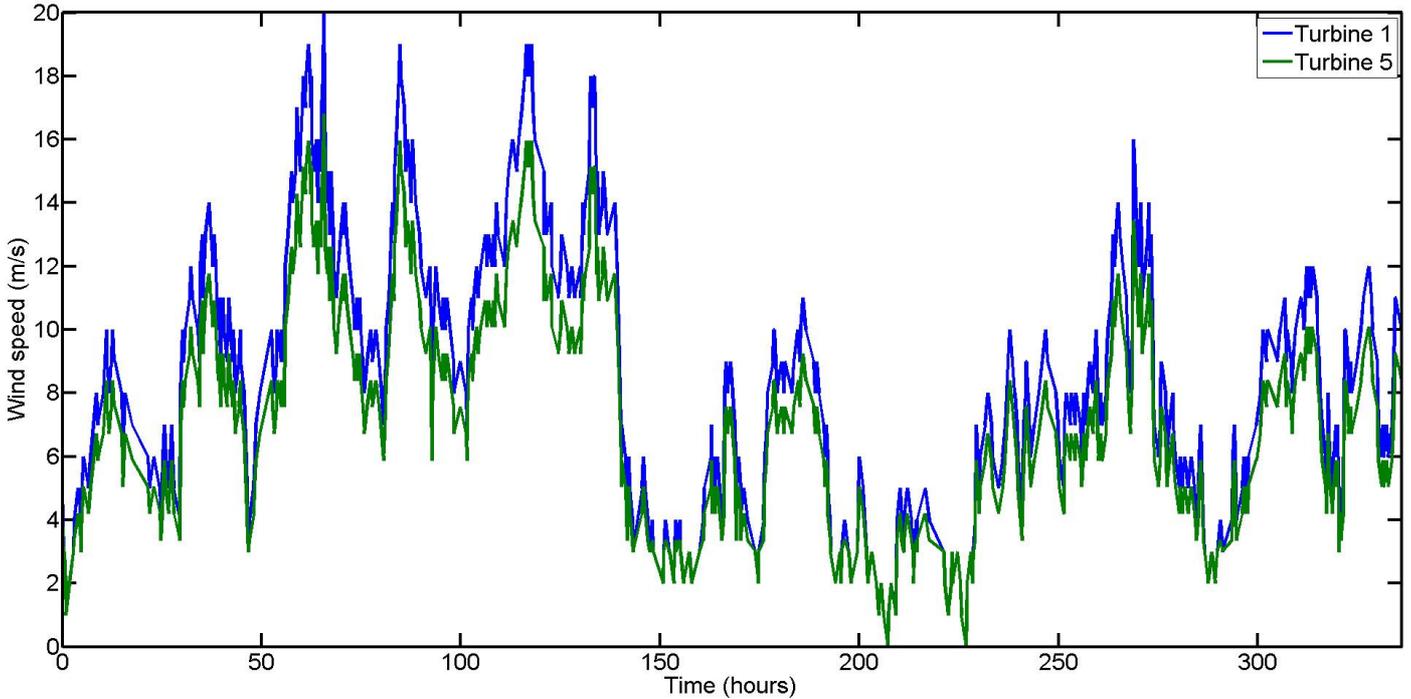
Figure 1: WSTS for 2 weeks for turbines 1 and 5.
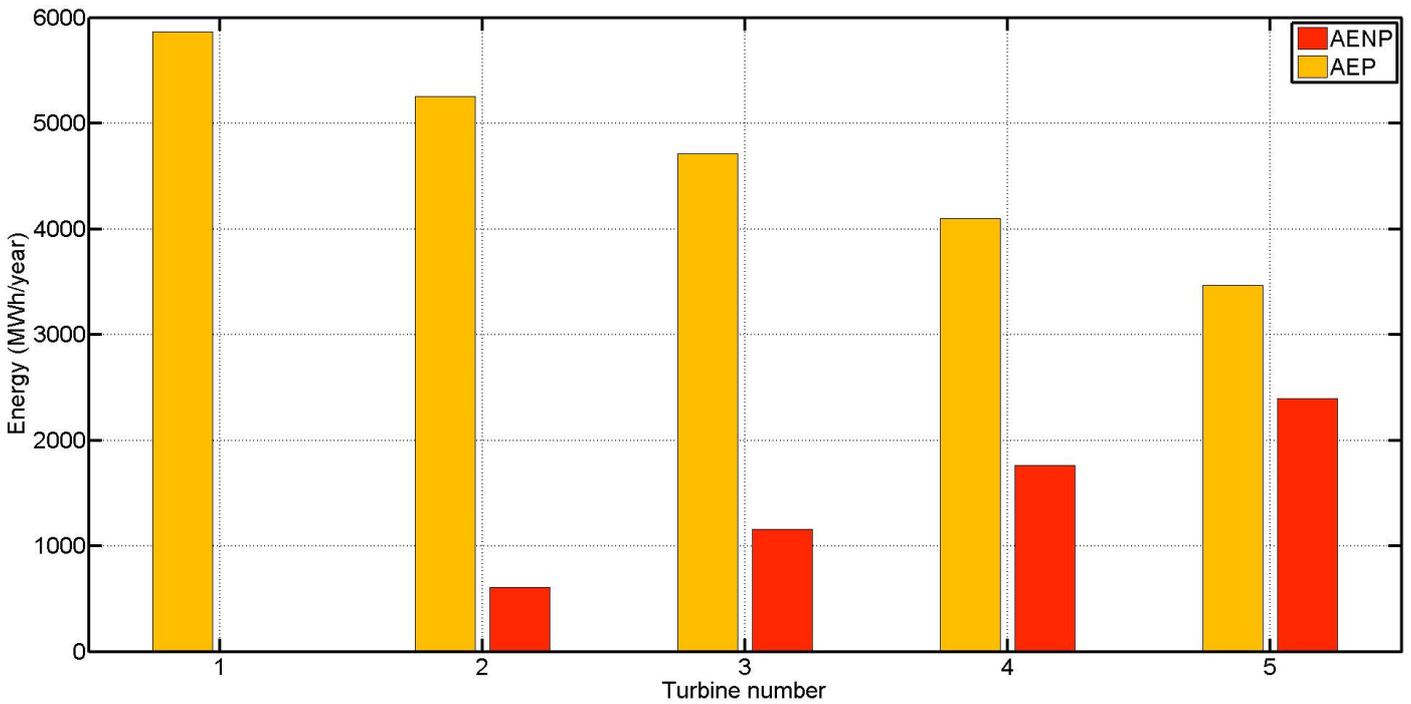
Figure 2: Distribution of energy production and energy loss throughout the wind farm.

Table 2 reveals that the effect of wakes has a large impact on the energy output of the wind farm, with the wakes accounting for a 20.2% reduction in energy production when compared to the wakeless scenario. These results are in line with the values found in [6]. Figure 2 shows that this energy loss, as expected, increases with array length. Interestingly, the wake effects on turbine 5 cause a 40.8% reduction in turbine 5's energy production. This is due to cumulative effect of each of the wakes of the turbines in front of turbine 5. Indeed, Figure 1 displays a significant reduction in wind speed from turbine 1 to turbine 5, particularly at high winds. This has the greatest impact when the wind speed is reduced from the rated wind speed to a much lower speed. Therefore, there is potential for a reduction in energy extraction at the leading turbines to increase the overall energy production of the wind farm by increasing the wind speeds at the downwind turbines.

In reality, a single string wind farm with the turbines in a row would be positioned so that the turbine wakes did not shadow downwind turbines in the prevailing wind direction and therefore the AENP due to wakes would be lower than described. However, an array of wind turbines with a number of strings in a grid will suffer similar magnitude wake losses, depending on current wind direction and distance between turbines. To adapt this model for a grid of turbines, the distribution of wind speeds across the front of the wind farm needs to be investigated.

These results provide two key conclusions. Firstly, the impact of wakes on energy production and annual revenue loss in even a simple wind farm highlight the potential benefits coordinated control can bring to a wind farm operator. By controlling the wind turbines in the array to maximise energy extraction by minimising wake effects, an increase in annual revenue can be achieved for a small investment and design change. This whole farm wind speed model can be used to quantify these potential benefits once the algorithms are developed. The transitions between wind speeds can also test the robustness of the co-ordinated control algorithms.

Secondly, the results highlight the importance of including wake effects in reliability analysis. Neglecting to accurately portray wake effects in the wind farm can lead to an over-estimation of the energy production of a wind farm by a significant margin. In turn, the effect of a failure of a wind turbine may be over-estimated; a failure of a downwind turbine will be lower than that of an upwind turbine, and the reduction in energy production due to failure of an upwind turbine could be smaller than anticipated due to the improved performance of the downwind turbines. This combined whole farm wind speed model can provide the basis for such a reliability analysis.

The AENP for this 5 turbine wind farm was 20.2% due to wakes, with a significant impact on turbine 5's energy production. This highlights the need to model wake flows both in reliability analysis and the testing and evaluation of coordinated control algorithms. The model developed in this paper is able to carry out these analyses.

V.   CONCLUDING REMARKS

This paper introduces a wind speed model for a whole wind farm that combines a macro scale WSTS model with a wake flow model to generate the 10 minute average wind speeds at every wind turbine in a farm for the life time of the farm. The WSTS model is based on a continuous Markov process that has been tested for its suitability, whilst the wake flow is based on a modified Jensen model with varying turbulence intensity. The wake flow model produces a LUT of wind speeds at every time interval. A WSTS is produced for the upwind turbine in the array, and the LUT used to produce the wind speeds for each of the downwind turbines.

An example analysis was carried that investigated the AENP due to wake effects on a single string, 5 turbine example wind farm, with the wind always facing parallel to the string direction. It was found that the AENP was 5.93 GWh; a 20.2% reduction in energy production compared to a wakeless scenario. This high AENP highlights the large impact wakes can have on the energy production of a farm.

The whole farm model allows for more accurate calculation of energy production in the farm in reliability analysis. The wind farm model can also be used to test the robustness of coordinated control algorithms and quantify their benefits on the farm energy production. In future, the model will be expanded to include the distribution of wind speeds across the front of an entire wind farm, the effect of turbine failures on wake interaction, and the modelling of wind direction.

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