Onshore Wind Farm Fast Wake Estimation Method: Critical Analysis of the Jensen Model

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Introduction

Wind energy is the most rapidly expanding source of renewable energy in the UK and has supplied 5% of the country's electricity requirements since 2010. With finite space available for future development, investors and manufacturers are constantly looking for new methods to increase the efficiency of both active and planned wind farms.

Wind turbine wake effects are a common cause of energy loss within a wind farm; capable of reducing a trailing turbine's output by up to 30%. Through the use of wake estimation models, wind farms can be designed and operated to reduce the wake effects experienced by turbines.

The Jensen model is a fast wake estimation model, derived from the momentum equation, capable of providing wind speed and wake radius values at distances downstream of a turbine. The simplicity and low computation time of the model have made it highly popular in the commercial market. This paper critically reviews the Jensen model for on-shore wind farms. This critical review demonstrates that the Jensen model is appropriate as a rapid wake estimator that can be used as part of an on-line wind farm control system for wake optimisation.

Approach

The majority of the research carried out using the Jensen model has involved comparisons with other wake estimation models and has been focused primarily on offshore wind farms due to the greater scale of both space and turbine size. The lack of onshore research has meant there is little understanding of the Jensen model's capabilities in locations with high roughness values or non-uniform terrain.

This report aims to critically analyse the accuracy and appropriateness of the Jensen model for operation on an onshore wind farm. As a data driven analysis, no comparison will be made with other computational methods. Therefore other wake models (e.g. Larsen and Lissaman [Renkema, 2007]) and turbulence models (e.g. Frandsen and Danish Recommendation [Fransden & Thogersen, 1999]) are superfluous.

Traditionally, Wind Farms operate with a "greedy" approach (each turbine operating at its individual maximum output). Ahmad et al [2015] and Annoni et al [2014] both show that the de-rating of individual turbines within a turbine array can generate an increase in total power output.

In order for such a control system to be incorporated into a wind farm a method of estimating turbine wake speeds is required. The Jensen model is often considered for real time control systems due to its simplicity and speed; this report will evaluate its accuracy and adaptability.

Method & Results

The aim of this research was to compare the Jensen model estimates to field data. This required finding a wind farm where the wind turbines were placed sufficiently close to each other that the wakes would not dissipate between turbines. The Brazos (Texas) wind farm presents such a case. This wind farm typically experiences wind from the south, and as such has a large north-south spacing, but a dense (ca 3-5 diameter) east-west spacing. By filtering the SCADA data for time segments where the wind came from the east, it was possible to study the wake effects on densely populated wind farms.

Jensen Model

The Jensen wake model is a simple fast wake estimation model with the aim of calculating power losses within turbine arrays due to wake interference [Jensen, 1983]. The model generates a linear wake based on the momentum equation. Ultimately, the Jensen wake model can be expressed in terms of the wake decay constant, k, turbine radius, r_0, the free wind speed, u_0, the turbine thrust coefficient, C_T, and is expressed as a function of distance downstream of the turbine, x, shown in (1).

$$v(x)=u_0\left[1-\left(\frac{1-\sqrt{1-C_T}}{1+(kx/r_0)^2}\right)\right] \tag{1}$$

Due to the Jensen model's dependency on the ambient wind speed it cannot accurately model an individual turbine that is not experiencing free flow conditions (e.g. in the wake of another turbine). This is due to a fundamental principal of the model whereby, even with varied input parameters (k and C_T) the wake speed will always tend towards the initial/ambient wind speed. This is similar to actual turbines as the free flow air surrounding the wake is one of several factors that helps return the wake to ambient conditions.

To enable the Jensen model to compute the response of a turbine experiencing wake effects or to model conditions where two or more wakes have crossed it is assumed that the kinetic energy deficit of the combined wakes is the sum of the kinetic energy deficits of the individual wakes at the same point, as shown in (2).

$$\left(1-\frac{v}{u_0}\right)^2=\left(1-\frac{v_1}{u_0}\right)^2+\left(1-\frac{v_2}{u_0}\right)^2+\cdots \tag{2}$$

Where v_1 and v_2 are the individual wake speeds at distance x related to turbines 1 and 2 respectively.

Due to the squaring of the values (2) will result in a gradual plateauing effect, whereby additional turbines or wakes further downwind will have a reduced influence on the total wind speed.

Wind Farm data

The objective of this paper is to carry out a critical data driven analysis of the Jensen model. To achieve this, four turbine rows were identified (Table 1 for details). These were sets of turbines sited in east-west alignment. Recorded data was supplied the Brazos wind farm, situated in Northern Texas, consisting of 160 Mitsubishi turbines each rated at one megawatt with rotor diameters of 62m.

Table 1: Turbine Row Summary

Row	No. Turbines	Turbine Spacing (m)	Reason for selection
A1	7	185	Control
A2	5	120	Shorter Spacing
A3	5	120	Rough Terrain
A4	5	185, 315, 120,120	Varied Turbine Spacing

Results

The results are summarised in Table 2. Each test row has a locally calibrated value of *k*, and from this calibration, a very high fidelity (<1% error) is noted in the Jensen average wind speed estimation at the down wind turbines.

The local wake decay constant figures are roughly double the general value recommended for flat land in commercial programmes (*k*=0.07); however, using the surface roughness value of 0.03m (appropriate for flat terrain with grass or very low vegetation), a global wake decay constant of 0.15 was calculated.

The *k* value for row A3 appears anomalous, being almost four times the recommended default value and twice the calculated value. On inspection, the aforementioned cliff edge runs in front of the first turbine within the row. The rapid change in terrain is very likely to cause more turbulent conditions, which are accounted for in the higher value of *k*.

Considering the wind speed along a row of down wind turbines, one striking result is that the wind speed is able to recover above the Jensen estimate. Figure 1 illustrates the differences between the Jensen estimates and the observed average wind speeds for the four selected rows.

Table 2: Observed down stream wind speed v Jensen estimate

	Wind Speed (m/s)				*Wake Decay Constant* , k
	1st Turbine	2nd Turbine			
		Observed	Comp.	% error	
A1	5.6	4.48	4.52	0.9	0.13
A2	5.88	4.66	4.65	0.2	0.17
A3	5.4	4.6	4.61	0.2	0.28
A4	5.7	4.65	4.65	0	0.135

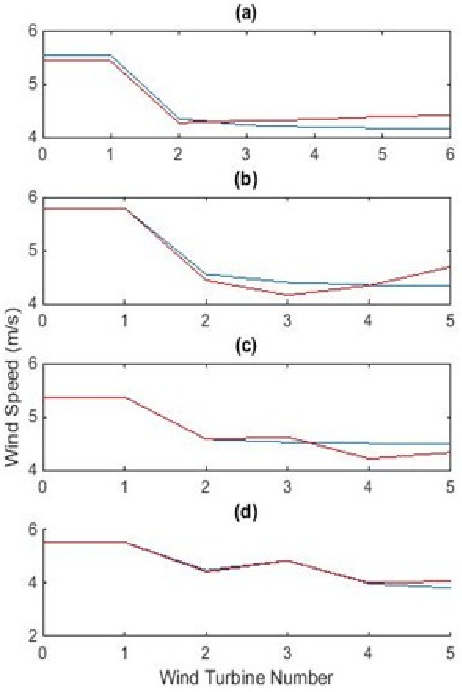

Figure 1: Wind speed comparison: Observed (red) v Jensen (blue) for test rows A1-4

Conclusions

The Jensen model was successfully used to estimate the average wake speeds experienced within a number of onshore turbine arrays. This showed the model was capable of being applied to areas with high terrain roughness values.

The Jensen model was successfully used to estimate the average wake speeds experienced within both a two-turbine and extended-turbine row. Calculations calibrated to two-turbine arrays achieved the highest levels of accuracy (<1% error) whilst the estimations run using global parameters achieved lower accuracy (<10% error) but with improved computation time.

However, the Jensen model was unable to predict unique patterns within row responses, even after a varied thrust coefficient equation was incorporated. Furthermore, as all wake estimations have been compared to average values the Jensen model should not be considered capable of predicting the wind speed at a specific time. It is thought for further accuracy, varied wake decay constants and turbulence models should be considered.

These negatives do not invalidate the model as a practical tool. Instead, the Jensen model has demonstrated its ability to accurately estimate the wakes of onshore wind turbines.

Learning Outcomes

1. The Jensen wake model has sufficient fidelity on average for wind energy estimation.
2. High ground roughness and turbulence levels increase wake recovery speed: a dynamic control system will therefore benefit off-shore farms more than on-shore.
3. The Jensen model is adequate for use as part of a dynamic control system to maximise wind farm production.
4. With extended rows there is an initial observed drop in wind speed after the first turbine, but then often there appears to be a smaller observed loss in wind speed than Jensen predicts, including at times an increase.

References

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