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Validation of turbulence models through SCADA data

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Abstract. This analysis compares engineering turbulence models to SCADA measurements from operating wind farms. The investigated models are S. Frandsen, G.C. Larsen and D.C. Quarton, which all overestimate the wake added turbulence intensity. The model closest to the SCADA measurements is the model of G.C. Larsen, which confirms the findings of T. Sørensen et.al in [1].

1. Introduction

The wake induced turbulences calculated in the planning phase of a wind farm have a great influence on the layout and sector management of the farm. If these turbulences are overestimated, the highest possible energy yield will not be reached. If they are underestimated the resulting fatigue loads exceed the forecasted ones due to the wake induced turbulences, resulting in a shorter life time of the turbine. Thus, it is important to use a validate model which is representative for the turbines inside the calculated wind farm.

The turbulence models used in engineering have been calibrated with wind turbines which are already obsolete. Hence, it is questionable if these models are producing results that are applicable for modern multi megawatt wind turbines. In this analysis, the most common engineering turbulence models will be compared with Supervisory Control and Data Acquisition (SCADA) data from operating onshore wind farms in the two to three megawatt class.

The validation data is obtained from three wind farms in the Midwest region of the United States and one wind farm in the South Central region of the United States. All wind farms are IEC III Class sites and show an equally distributed low ambient turbulence with similar average annual wind speeds. All the terrain is flat, has no significant incline and no forest or higher buildings nearby the wind farm.

In this analysis wake effects from neighboring turbines, including multiple wake situations, will be used in the validation process of the engineering turbulence models.

2. Validation

In this study three of the most common engineering turbulence models will be examined. All of them are either part of the “European Wind Turbine Standards II” (EWTS II, [2]) or the IEC 61400-1



guideline [3]. Furthermore, all models are implemented in industry wide used site assessment software tools such as DNV GL WindFarmer [4] or EMD windPRO [5].

Below the formula for the calculation of the wake added turbulence intensity (TI) I_{add} for each model is shown:

- S. Frandsen, published 2006 [6], included in [3], implemented in [4] and [5]:

$$I_{add} = \frac{1}{1.5 + \frac{0.8 \cdot s}{\sqrt{c_T(v_{Hub})}}} \quad (1)$$

with c_T the thrust coefficient, v_{Hub} the wind speed at hub height and s the downstream distance normalized by rotor diameter.

- G.C. Larsen, published 1998 [7], included in [2], implemented in [5]:

$$I_{add} = 0.29 \cdot s^{-\frac{1}{3}} \cdot \sqrt{1 - \sqrt{1 - c_T(v_{Hub})}} \quad (2)$$

- D.C. Quarton with modified parameters from [8], included in [2], implemented in [4] and [5]:

$$I_{add} = 5.7 \cdot c_T^{0.7}(v_{Hub}) \cdot I_{amb}^{0.68} \cdot \left(\frac{x}{x_n}\right)^{-0.96} \quad (3)$$

with x the downstream distance, x_n the beginning of the far wake section and I_{amb} the ambient turbulence.

For all models the total turbulence intensity I_T is calculated as proposed in [9]:

$$I_T = \sqrt{I_{amb}^2 + I_{add}^2} \quad (4)$$

2.1. Validation method

In an optimal measuring campaign, the turbulence intensity of each turbine would be measured in front of the rotor. These measurements are not available, hence this validation is based on SCADA data where the wind is measured on the nacelle behind the rotor by nacelle anemometers. As a result, the absolute values of the turbulence intensities cannot be compared, but the increase in turbulence intensity between the up- and downstream turbine can. A schematic of this method is shown in Figure 1.

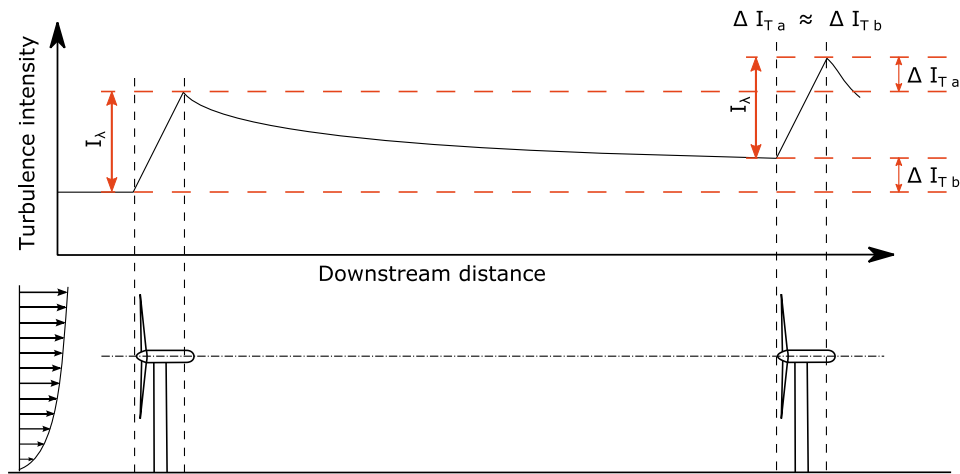


Figure 1. Schematic: Validation method

To use this approach, it is important to show that the increase in turbulence intensity between two turbines is equal when measured in front of the rotor to the increase measured behind the turbines. In the first step it is determined whether measurements upwind of the rotors are equal for turbines of the same type at free flow. Therefore, the difference of the measured turbulence intensity at free flow from two neighboring turbines was examined at different wind speeds.

The evaluation was done for a wind farm which layout is shown in Figure 2. The main wind direction is south, the ambient turbulence intensity is low and equally distributed. All turbines in this farm are Nordex N100 2.5 MW with a hub height of 100 m and a rotor diameter of 100 m. In Figure 3 the mean absolute difference between the turbulence intensity measurements of two nearby turbine is shown as well as the measuring accuracy of the ultra-sonic anemometer of the wind turbines SCADA system. The difference between two nearby turbines is taken to assure that both turbines experience similar wind conditions. The evaluation shows that the absolute difference of two nearby measurements at free flow ($180^\circ \pm 7.5^\circ$) is within the measuring accuracy of the anemometer. This leads to the conclusion that the influence of the nacelle and the rotor on the turbulence intensity measurement is negligible for turbines of the same type.

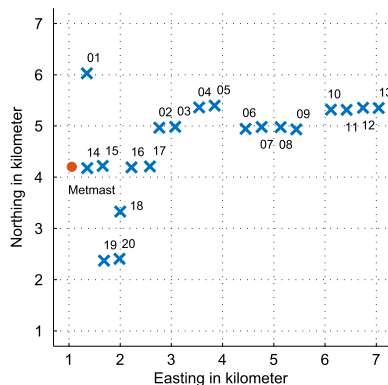


Figure 2. Wind farm layout

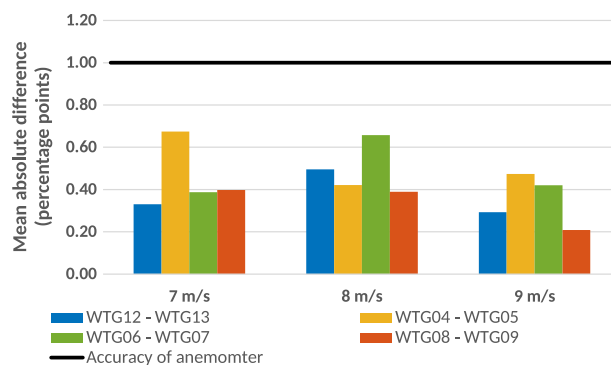


Figure 3. Comparability of nacelle turbulence intensity measurement

In the second step it is necessary to show that the increase of turbulence intensity measured in front and behind the rotor does not strongly depend on the wind speed. Behind the turbine, the velocity of the wind decreases whereas the turbulence increases. Therefore, the turbulence intensity measured by the met mast shown in Figure 2 is compared to the turbulence intensity measured by turbine 14 at a wind direction interval of $270^\circ \pm 7.5^\circ$. The results are shown in Figure 4. As you can see from the qualitative course of both turbulence intensity measurements as well as from the quotient of both curves referenced to the right-hand y-axis, the difference between the measurement on the met mast and the turbine nacelle can in good approximation be described as a constant factor at all wind speeds. Thus, the difference between the total turbulence intensities measured from the SCADA systems of two nearby turbines is assumed approximately equal to the turbulence intensity difference in front of their rotors.

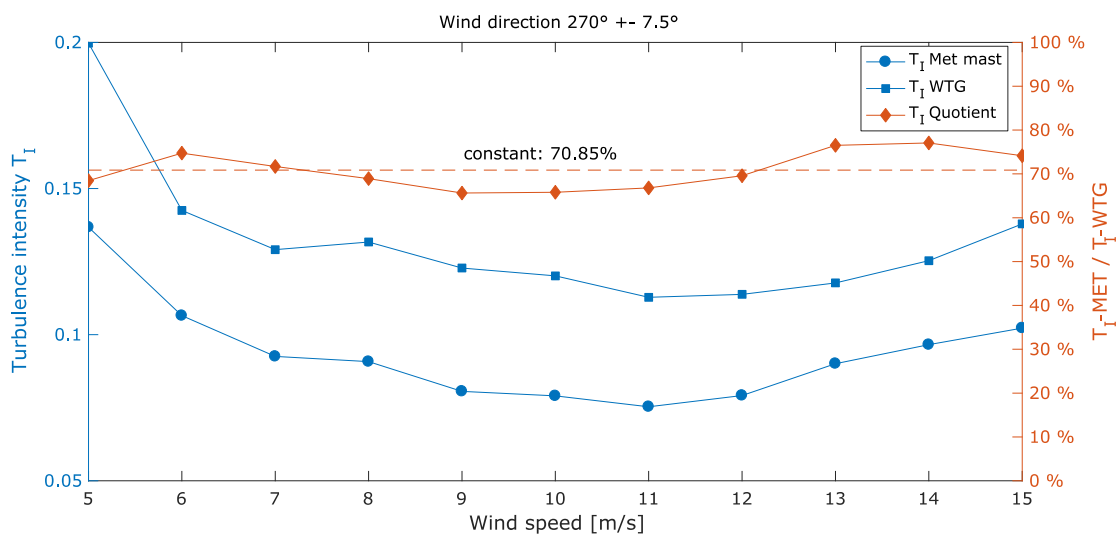


Figure 4. Comparison of TI measured by met mast and SCADA

The difference in total turbulence intensity of the models for a single wake situation is calculated as shown below.

$$\Delta I_{T-Model} = \sqrt{I_{amb}^2 + I_{add}^2} - I_{amb} \quad (5)$$

2.2. Results – Single wake situation

As a representative example for all measurements, only turbine pair 4 - 5 of the single wake measurements will be discussed. As pictured in Figure 5 the full wake situation between 4 and 5 is analyzed at a wind direction of $263^\circ \pm 7.5^\circ$. The downstream distance is approximately three rotor diameters. The observed wind speed range is 5 to 15 m/s binned in 1 m/s steps. Higher wind speed could not be considered because of a low data availability.

The measurements show a slight decline in the turbulence intensity difference over wind speed due to the higher extinction of the wake induced turbulences at increasing wind speeds. The measurement

shows significant lower turbulence intensity compared to all models, so all analyzed models overestimate the turbulence intensity as pictured in Figure 6. The model closest to the measurements is the G.C. Larsen model. The D.C. Quarton model extremely overestimates at wind speeds under 10 m/s. Also the model does not follow the measuring trend. The S. Frandsen model continuously overestimates the measurements by a factor of about four.

This was observed at all examined single wake situations in all analyzed wind farms, the measured difference in total turbulence intensity was always lower than the calculated difference from the models. Overall, the G.C. Larsen model showed the best results for a single wake situation.

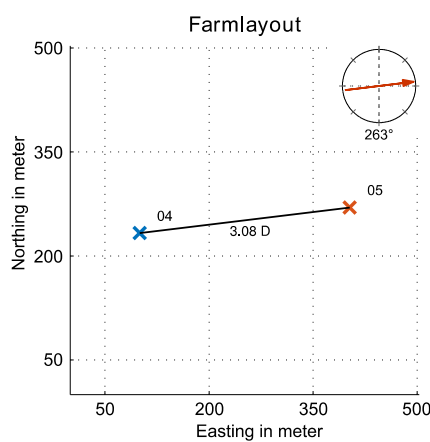


Figure 5. Single wake situation

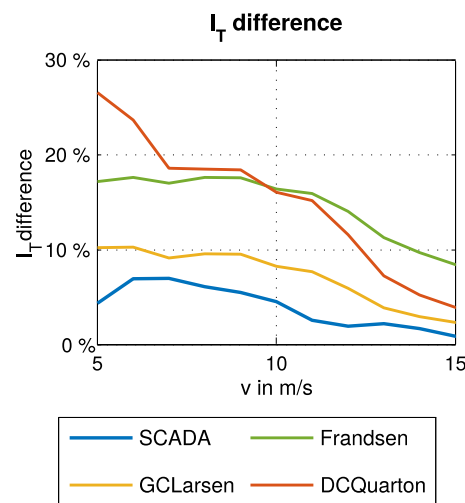


Figure 6. Single wake WTG 4-5 model vs. meas.

The results of all examined turbine pairs from the four different measuring sites are shown in Figure 7. It shows the difference in turbulence intensity over the downstream distance at a given wind speed of 7 m/s. As already said only the G.C. Larsen model estimates the measurement fairly, the remaining models highly overestimate for downstream distances lower than 7 rotor diameters.

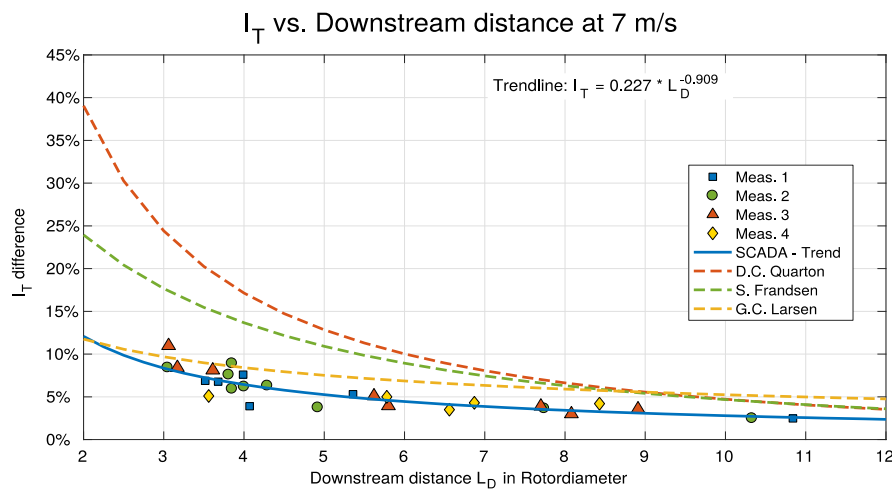


Figure 7. All measurements I_T over downstream distance

2.3. Results - Multiple wake situation

Furthermore, multiple wake situations are analyzed. In the turbulence intensity models multiple wakes are considered as increase of ambient turbulence intensity. The calculation for a double wake situation is shown in formula (6), a generalized formula is given in (7).

$$\Delta I_{T-Model} = \sqrt{\left(\sqrt{I_{amb}^2 + I_{add}^2[s_0]}\right)^2 + I_{add}^2[s_1]} - I_{amb} \tag{6}$$

$$\Delta I_{T-Model} = \sqrt{I_{amb}^2 + \sum_{i=0}^n I_{add}^2[s_i]} - I_{amb} \tag{7}$$

For the investigation of a double wake situation the turbines 7, 8 and 9 from the wind farm shown in Figure 2 are examined. An enlarged section of the windfarm layout is given in Figure 8. At a wind direction of $94^\circ \pm 7.5^\circ$ the turbines are nearly in a perfect row and the deviation of the centerline is less than 5 meters.

The results are displayed in Figure 9. At the left-hand side, the single wake situation from turbine 9 to 8 is shown. On the right-hand side, the double wake situation from turbine 9 to 7 is shown. Again, all models overestimate the measurement. This is true for single and double wake situations. It is notable that the measured turbulence intensity difference is only slightly higher in a double wake situation than in a single wake situation. Here not only the models overestimate the wake added turbulence intensity also the summation formula (7) increases the conservative effect of the models. Hence the models greatly overestimate the turbulence intensity in double wake situations.

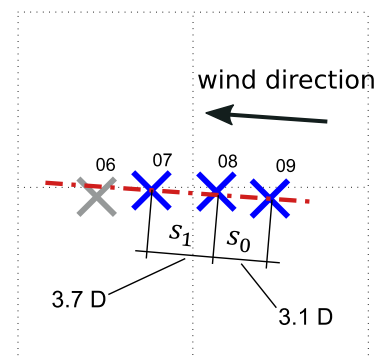


Figure 8. Enlarged layout snippet of double wake situation

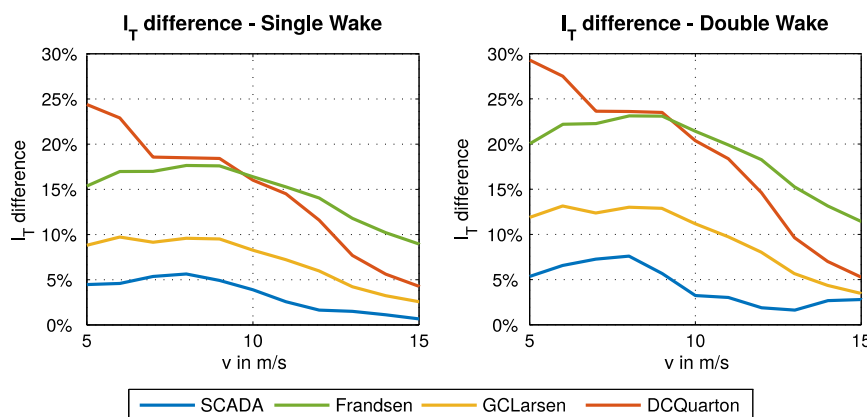


Figure 9. Single wake and double wake: Model vs. measurement

3. Conclusion

In this study a method was developed to validate engineering turbulence models without any cost extensive measuring campaigns by using the turbine SCADA data. A method was developed which generates a validation for all given models over all wind speeds and wind directions.

All investigated models overestimate the turbulence intensity to a large extent. This study shows that the widely used model of S. Frandsen can be ranked conservative for the examined wind farms. The closest representation of the measurements was achieved with the G.C. Larsen model. The overestimation of the D.C. Quarton model as already shown in [1] is also true for turbines of the multi megawatt class. To get the most realistic results it would be necessary to recalibrate the parameters of the models, which is also recommended by S. Frandsen in [6]. As long as no model parameter is recalibrated, it is suggested to use the G.C. Larsen model to estimate the wake added turbulence intensity. All models require an individual parameterization to perform best, where the most complex model is not necessarily the most accurate, in accordance to the results in [1]. This study also confirms the preliminary validation results of T. Sørensen et. al. in [1], nevertheless the turbines used in [1] are not fully comparable to the turbines in this study. Similar results in terms of energy deviation were found to be true in [10]. Here also the G.C. Larsen model showed the best results, but all investigated models were found to be conservative.

As it was shown that the S. Frandsen model behaves very conservative, it is recommended to recalculate existing wind farms in terms of turbulence. This could lead to less restrictive sector management settings which will increase the wind farms annual energy production. New projects will benefit from this results since the turbine layout could be denser or turbines could be placed in regions where it was not possible before. All results are preliminary so far, since it needs to be examined how the G.C. Larsen model or a new parameterized model perform in terms of the wind turbine loads.

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