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Does wind turbine rotor size impact the effect of turbulence on power production?

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SUMMARY: (10 pt)

Atmospheric turbulence occurs on a spectrum of spatial scales. Small eddies are associated with fluctuations of high frequency and larger eddies with lower frequencies. Turbulence has important impacts on wind energy, particularly within fatigue loads, but also on the power output of wind turbines.
In this study we investigate the effect of turbulence on wind turbine power output, and we show how the rotor absorbs the smaller spatial scales of turbulence acting as a low-pass filter on temporal fluctuations. This spatial filter effect is well-known within wind loads on structures and is modeled by the Background factor (cf. Eurocode EN1991-1-4) accounting for the non-coherence of a turbulent wind field across a structure. However, in the IEC 61400-12 standard for wind turbine power curve verification this spatial filter-effect is omitted, and turbulent wind fields are implicitly assumed to be fully coherent. The resulting error increases with the rotor area and is around 50% for the largest modern rotors around 200m.
We present a new method to efficiently predict the resulting filter-effect as a function of rotor size. The new method is validated both using aero-elastic simulations and using observations of concurrent wind turbine power production and wind measurements.

Keywords: Turbulence, Power Curve, Coherence

1. INTRODUCTION

Atmospheric turbulence is a four-dimensional phenomenon that develops in time and the three spatial dimensions on a broad spectrum of spatial scales. Eddies of small spatial scale are associated with high frequency fluctuations and larger scale eddies are associated to lower frequency fluctuations. The impacts of turbulence are important in several aspects of wind energy, particularly in structural fatigue loads and component lifetime. But turbulence also impacts the power output of wind turbines.

Here we investigate the effect of turbulence on the power output of modern wind turbines. We analyse how the interaction between the wind turbine rotor and turbulence results in a net effect where the turbine acts as a filter and the rotor absorbs the smaller scale turbulence. In frequency domain this corresponds to a low-pass filter, damping the higher frequency turbulent fluctuations. This spatial filtering effect is well-known in the field of wind loads on structures where it is represented by the so-called background factor e.g. (EN1991-1-4: 2005). This background factor accounts for the non-coherence of the turbulent wind field across the exposed area of the considered structure. However, for verification of wind turbine power production this effect appears to have been overlooked and is omitted in the IEC 61400-12 standard (IEC61400-

12: 2022) for wind turbine power curve verification. Hence, the turbulent wind field is implicitly assumed to be fully coherent. The magnitude of the resulting error due to non-coherence increases with the size of the area swept by the rotor as an increasing part of the turbulence spectrum is dampened. Fig. 1 illustrates this effect comparing the output of aero-elastic simulations with predictions using the method in IEC 61400-12. Results are shown for a turbulence intensity of TI=0.3 and four different wind turbine rotor-diameters (RD) of 50m, 70m, 126m and 178m. Note the pronounced difference between the TI=0.3 power curves for the largest rotor (RD=178) and wind speeds above 10m/s. By assuming a fully coherent wind field the IEC61400-12 method (dashed grey curve) significantly overestimates the reduction of power relative to the aero-elastic simulation (blue curve) which accounts for spatial coherence.

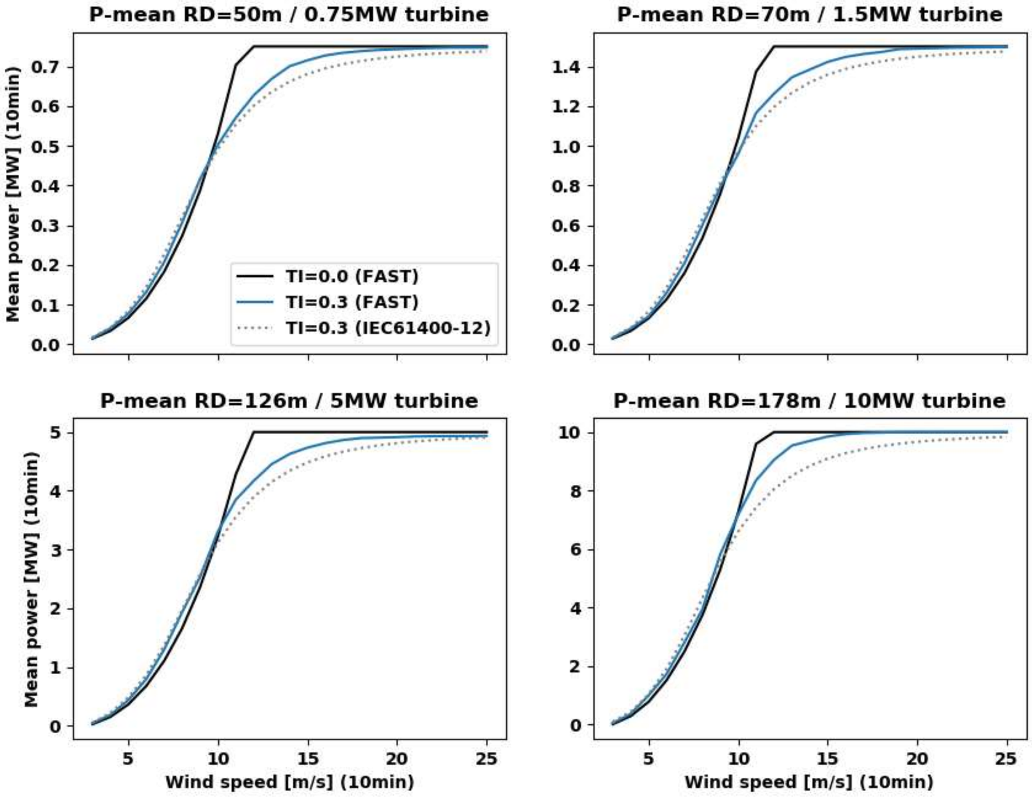

Figure 1. Plots comparing the power output at a turbulence intensity of 0.3 predicted using advanced aero-elastic simulations (FAST) and using the method described in IEC61400-12. The power at zero TI is also shown for FAST.

In this study we present a theoretical analysis of the rotor filter-effect and develop a method to predict the resulting low-pass filter-effect of turbulent fluctuations as a function of wind turbine rotor size. Finally, we validate the theoretical method both using aero-elastic simulations and using high quality observations of concurrent wind turbine power production and turbulence measurements at an adjacent mast.

2. METHOD

The theoretical method to predict the rotor filter-effect developed in this study makes use of well-established engineering methods. The basis of the method is the background factor approach presented in e.g. Eurocode EN1991-1-4 (EN1991-1-4: 2005) which we use to predict the net effect of a non-coherent wind field across the rotor swept area. This factor has a value between zero and one where one represents a fully coherent turbulent wind field, which implicitly is the current assumption in the IEC61400-12 standard (IEC61400-12: 2022). As input to this calculation, we rely on the spatial coherence model and the Kaimal spectrum defined in the IEC61400-1 standard (IEC61400-1: 2019) which are ordinarily used for turbulence models in aero-elastic load simulations.

As a first line of validation the predicted filter-effect is validated using aero-elastic simulations based on the tools Turbsim and OpenFAST by NREL, using four different generic turbine models with rotor sizes ranging from 50m up to 178m.

Validation of the developed method using observed data relies on a measurement setup as that required in the IEC61400-12 standard (IEC61400-12: 2022). A meteorological mast that measures the wind and turbulence just upstream of a wind turbine. For each 10min sample of measured wind speed mean and standard deviation (turbulence) we can predict the expected 10min mean and standard deviation of power output of the turbine. This is done for both the turbulence method in IEC61400-12 (IEC61400-12: 2022) and the method developed in this study. These predictions are then compared to the actual observed mean and standard deviations of power to assess the accuracy of each method and to validate the presented theoretical calculations.

3. RESULTS

Our results show that the low-pass filter-effect of the rotor on a turbulent wind field leads to an apparent reduction of the turbulence in the incoming wind field translating to a reduced power variability relative to a fully coherent wind field. This reduced variability of power affects the 10min averaged power output due to non-linearity of the wind turbine power curve. (cf. Fig. 1)

The main result is that the net filter-effect can be simply modelled as a reduction factor on the 10min wind speed standard deviation of the incoming wind field similar to the Background factor in (EN1991-1-4: 2005). For rotor sizes between 50m and 178m the reduction factor varies from ca. 0.77 to 0.55 when using the IEC61400-1 (IEC61400-1: 2019) coherence function and Kaimal spectrum. The factor depends slightly on average wind speed as shown in Fig. 2.

These theoretically predicted values are very close to the results we observe for the aero-elastic simulations using Turbsim/OpenFAST (cf. Fig. 1) for the four relevant generic turbine models with different rotor sizes. The results using the method developed in this study also closely reproduce the actual wind turbine power output measured from the Vestas V52 turbine at Risø, Denmark.

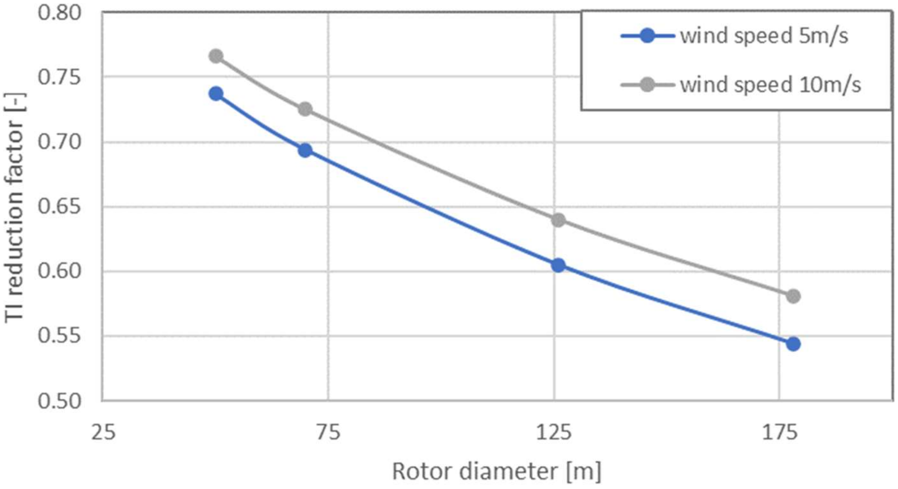

Figure 2. Plot showing the net reduction of 10min wind standard deviation (i.e. turbulence) by the rotor filter-effect at 5m/s and 10m/s, using the theoretical method developed in this study.

The rotor-size dependent filter-effect on power fluctuations also translates to a change of 10min averaged power where the turbine power curve is non-linear. Where the power reaches rated power the power curve is concave down and the power fluctuations due to turbulence lead to a reduction of 10min averaged power. Including the rotor-filter effect on the incoming turbulence reduces the resulting standard deviation of power so that the resulting power reduction is less than predicted by the IEC61400-12 standard (IEC61400-12: 2022). Hence, the IEC correction method overestimates the correction of 10min mean power values due to turbulence. The larger the rotor, the larger the overestimation as illustrated in Fig. 2.

4. CONCLUSIONS

The method for turbulence correction of power values in the IEC61400-12 standard omits the effect that a turbulent wind field is not fully coherent, which leads to overestimated corrections of 10min power. The effect of non-coherence is significant and may be included using the method developed in this study, which rests on a solid foundation of engineering methods defined in the standards Eurocode EN1991-1-4 and IEC61400-1. The method has been thoroughly validated using both aero-elastic simulations and observed turbine power production data.

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