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Effects of Changing Atmospheric Conditions on Wind Turbine Performance

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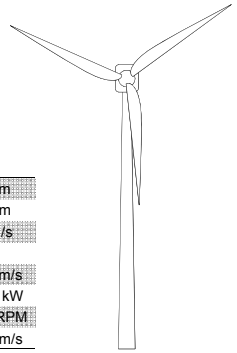
1. Introduction

Multi-megawatt, utility-scale wind turbines operate in a turbulent, thermally-driven atmosphere where wind speed and air temperature vary with height. These changes impact turbine power production and loads in ways that are not well understood.

To better understand the response of a generic turbine to turbulent inflow conditions, we use the turbulent flow simulator TurbSim [1] to force a turbine model in the aeroelastic simulator FAST [2]. The WindPACT 1.5-MW baseline turbine that we model is similar in size and power output to many of the machines currently installed in the United States (***Figure 1***, [3]).



Hub height	84 m
Rotor diameter	70 m
Cut-in wind speed	3 m/s
Tip speed ratio	7
Rated wind speed	11.5 m/s
Rated power	1500 kW
Rated RPM	20.5 RPM
Cut-out wind speed	27.6 m/s

Figure 1. *The WindPACT 1.5 MW turbine [3]*

2. Simulations

Using TurbSim, 1,800 wind fields with random combinations of wind speed, turbulence intensity, and wind speed shear were generated. Wind direction was not varied. These wind fields are used as inputs to the FAST turbine model to obtain time series of turbine power and loads. This enables a data set of turbine power and loads as a function of turbulence intensity *Ti*, mean wind speed *U*, and shear exponent *α*, which describes the variation of wind speed with height *z*:

$$Ti = \frac{\sigma(u)}{U} \qquad \frac{U_1}{U_2} = \left[\frac{z_1}{z_2}\right]^{\alpha}$$

The damage equivalent load or DEL is used to characterize the load acting on different components in the wind turbine. It is a function of the sum of the cyclical loads (*L*) over *N* cycles, and the material properties (Fiberglass, *m* = 8):

$$\mathrm{DEL} = \left[\sum_{i=1}^{N} L_i{}^m C_i\right]^{1/m}$$

3. Turbine Impacts

The 1,800 simulations describe a multidimensional space where different combinations of wind speed, shear, and turbulence give widely varying mean-output power over 10 minutes (***Figure 2***).

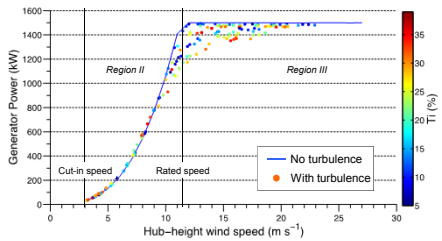


Figure 2. *Turbine power curve from simulations with different turbulence intensities. Points show data for 0.15 < α < 0.25.*

At mean wind speeds less than rated speed (11.5 m/s), power is a complex function of shear and turbulence. At speeds greater than rated speed, shear is less influential, and the power captured in 10 minutes drops as the turbulence increases (***Figure 3***). The DEL at the blade root is a function of turbulence at all speeds, and doubles as turbulence intensity increases from 10% to 30%. An increase in DEL indicates an increased risk of failure and reduced reliability.

3. Implications and Applications

It is usually assumed that the power produced by a turbine is only a function of the wind speed. This is the basis of the power curve that is used by the wind energy industry. However, the power curve is likely a function of the conditions at which the turbine was tested (***Figure 2***) and as suggested by recent work [4].

Machine learning tools can create models from observations that can then predict the power produced under a range of operating conditions. One method is an ensemble regression tree [5], visualized in **Figure 4**.

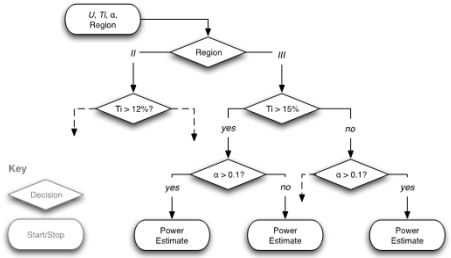


Figure 4. *Visualization of a single member of a regression tree ensemble that uses wind speed, turbine operating region, shear, and turbulence to predict turbine output power. Other trees in the ensemble can have very different forms.*

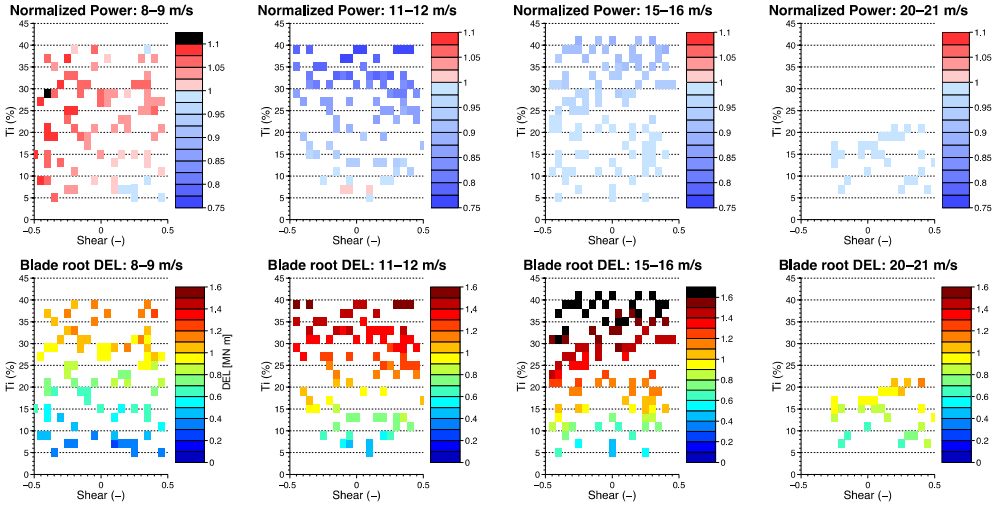


Figure 3. *Variation of generator power output (top row) and blade root damage equivalent load (DEL, bottom row) with shear and turbulence intensity. Power is normalized by the power curve with no turbulence and α = 0.2 from Figure 2.*

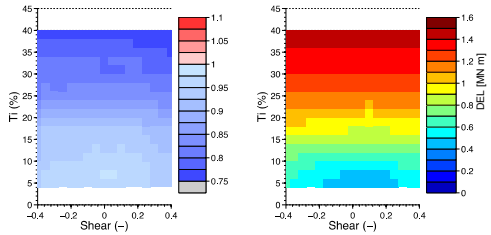


Figure 5. *Model-derived normalized power and blade root DEL at 11.5 m/s as shear and turbulence intensity change.*

The regression model can be used to estimate the power generated for any forcing conditions (***Figure 5***). The model can be generated from all observations, including turbine test data. The new model of the turbine could be forced with site data to generate a site-specific power curve, or time series of power output. Better estimates of long-term power production can reduce uncertainty in project financing, thereby reducing the cost of electricity to the consumer.

So far, the regression model has been trained on uniform wind fields without low-level jets, Kelvin-Helmholtz instabilities [1], or changes in wind direction in the flow field. Future tests will include these flow features, and may require a more complex set of forcing variables. We will also compare the model to observations of inflow conditions and turbine performance at the National Wind Technology Center.

4. Conclusions

Simulations using the turbulent flow-field simulator TurbSim and turbine aeroelastic simulator FAST show that the response of a wind turbine to forcing may be more complex than is captured by the power curve. The power is most obviously affected by changes in wind speed at the hub height, and then by turbulence, and lastly by shear. At wind speeds greater than rated speed, increased turbulence reduces power capture and increases loads. The tools used for this study can be applied to any wind turbine for which structural and aerodynamic data are known.

An ensemble regression tree model of the turbine performance has been created with the simulation data. This model can also be created from field data, to predict turbine performance in a range of forcing conditions.

References

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This work was supported by the Department of Energy's Wind and Water Power Program

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American Geophysical Union Fall Meeting | San Francisco, CA | 3-7 December 2012

NREL/PO-5000-57084