An evaluation of power performance for a small wind turbine in turbulent wind regimes

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Why study turbulence?

- Increased attention towards engineering and economic feasibility in lower wind speed regimes [Ewing et al (2008)]
- Progressive damage and shortened turbine lifetime via stochastic loads [Saranyasootorn & Manuel (2008)]
- Increased interest in turbulence for future academic study [Web of Science]
  - 180 publications in 2014 (top)
  - 1400 cited articles in 2014 (bottom)
Wind Turbine & Site
Methodology

• Collect site characteristics data from wind turbine location
• Determine relationship between $P$ and $TI$
• Quantify statistical distribution of in situ $TI$ frequency
• Verify/compare results with IEC standards, Albers (1997) and Sunderland et al (2013)
The turbine power and turbulence intensity were quantified over 15 months (6/13-9/14). Excluding anomalies like turbine maintenance, power exhibits strong statistical correlation with turbulence intensity.
Seasonal Variation of Power & Turbulence Intensity

- **P_out v. TI (Summer 2013, 2014)**
  - Power (kW) vs. TI
  - Data points showing seasonal variation

- **P_out v. TI (Fall 2013)**
  - Similar to Summer data

- **P_out v. TI (Winter 13-14)**
  - Significant increase in power and turbulence intensity

- **P_out v. TI (Spring 2014)**
  - Further increase, possibly indicating higher turbulence intensity
Common industrial practice requires a Weibull distribution for frequency of wind speed [Woolmington et al (2014)]. However, an empirical distribution match for turbulence intensity is more difficult.
Wind speed dependence for the turbine power curve enables statistical correlation between frequency of occurrence for power and $T_l$. 
The culmination of these turbulence intensities at constant velocities enable “binning” of turbine power output. With smaller wind speeds, the power output increases for increased $TI$, exhibiting periods of overdrive.
Turbulence intensity tends to follow a Gamma distribution \((k=12, \theta=0.014)\) at constant wind velocity.

\[
f(x; k, \theta) = \frac{x^{k-1} e^{-x/\theta}}{\theta^k \Gamma(k)}; \quad x, k, \theta > 0
\]
Relative Error Between Gamma Function and Observed $T_I$

<table>
<thead>
<tr>
<th>Wind Speed (m/s)</th>
<th>Min Error (%)</th>
<th>Max Error (%)</th>
<th>Mean Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.00±0.25</td>
<td>0.00</td>
<td>1.66</td>
<td>0.45</td>
</tr>
<tr>
<td>7.50±0.25</td>
<td>0.00</td>
<td>1.67</td>
<td>0.42</td>
</tr>
<tr>
<td>10.0±0.25</td>
<td>0.00</td>
<td>3.18</td>
<td>0.79</td>
</tr>
</tbody>
</table>
Example of TI Integration into Wind Turbine Power Curve
Conclusions & Future Work

• The gamma function is a good indicator to estimate power performance incorporating $T/I$.

• Power output increased by as much as 60% for lower wind speeds at higher $T/I$, but decreased power by as much as 17% for high wind speeds and $T/I$.

• A more standardized approach for $T/I$ integration into the power curve was tested and correlated well with results from Sunderland et al. (2013) and Albers (1997).

• Over-performance is possible for low wind speed regimes with high $T/I$.

• This process can be integrated into (or verified by) industry accepted programs like WT_Perf and FAST for computer simulations predicting stochastic loads due to turbulence and their effects on power production for any turbine size in any location.
Acknowledgments

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• Aerospace & Energy Engineering Departments
• Penn State Center for Sustainability
References


3. Web of Science


Questions?
Quantifying Power and Turbulence

- Turbine power \( (P) \) is a function of the cube of the velocity \( (v) \), air density \( (\rho) \) and rotor area \( (A) \) [Manwell et al (2010)]

\[
P = C_P \frac{1}{2} \rho A v^3
\]

- Turbulence intensity \( (TI) \) is the ratio of the standard deviation \( (\sigma) \) to the mean wind speed \( (V) \) [Wang et al (2014)]

\[
TI = \frac{\sigma}{V}
\]

- It can therefore be quantified that turbine power can related to turbulence intensity

\[
P = f(TI)
\]
Fig. 5. Albers normalisation of the Skystream 3.7 (2.4 kW) power curve in terms of varying TI and wind speed.
Figure 6: same as Figure 4 but normalisation to 5% turbulence intensity (blue) and filtering to turbulence range 2.5%-7.5% (red).