A Novel Approach to Design and Simulation of Horizontal Axis Wind Turbine in Islanded Network

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Abstract: In this paper the design and simulation of a wind turbine with horizontal axis is indicated. The wind turbine simulation system includes wind speed simulation, mathematical models of wind turbines, modeling of rotor blade characteristics, modeling of tower effect and emulation of rotor inertia. The wind turbine simulator should take a simulated wind profile as the input and convert it to an output of electrical power. In this paper, a new procedure to simulating the wind with one Hertz resolution in a long period of time is presented. The results of the simulation in MATLAB/SIMULINK are compared to actual data to justify the validity of the proposed wind generator.

Key words: wind turbine, horizontal axis, wind model

INTRODUCTION

Wind power has become one of the most attractive energy resources for electricity production as it is virtually pollution-free (if noise is not considered as pollution). As a result, a great deal of research has been focused on the development of new turbine design to reduce the costs of wind power and to make wind turbines more economical and efficient. The investigation of wind power system involves high performance wind turbine simulators, especially for the development of optimal control solutions.

At present, wind turbine simulators have become a necessary tool for research laboratories to enhance the quality of the wind energy conversion system.

In order to accurately reproduce wind speeds over a time scale longer than about 10 minutes while retaining an accurate resolution of about 1 second, both the turbulence and the long term wind components need to be modeled. Unfortunately, there is no single model that can accurately cover both short term fluctuations and long term changes (Nichita 2002). As stated by Nichita (2002), a method for modeling long term wind called the Van der Hoven model is accurate for long range simulation but provides an inaccurate representation of turbulence. On the other hand, Nichita (2002) states that modeling turbulence can be achieved using the Von Karmen power spectrum, but it fails to provide accurate results once time horizons on the scale of tens of minutes are reached. Another technique of modeling turbulence alone is the Shinozuka method (Jeffries 1991).

MATERIALS AND METHODS

The torque generated by wind blow is described by the following relations:

\[ \lambda = \frac{\omega_m R}{V_{\text{WIND}}} \]  
\[ P_{\text{MW}} = \frac{1}{2} \rho \pi R^2 C_p V_{\text{WIND}}^3 \]  
\[ T_{\text{MW}} = \frac{P_{\text{MW}}}{\omega_m} = \frac{1}{2} \rho \pi R^3 C_p \frac{\omega_m^3}{\lambda^3} \]

where \( V_{\text{WIND}} \) is wind speed, \( R \) is the blades radius, \( P \) is the air density, \( \omega_m \) is rotor angular speed and \( \lambda \) is
the tip speed ratio (TSR). $C_p$ is the power conversion factor which can be defined as turbine power in proportion with wind power and is related to blades aerodynamic characteristics. Resulted mechanical torque is applied as the input torque to the wind generator and makes generator to operate. Power conversion factor is expressed as the function of tip speed ratio $\lambda$ as follow:

$$C_p = (0.44 - 0.0167\beta)\sin\frac{\pi(\lambda - 2)}{13 - 0.3\beta} - 0.00184(\lambda - 2)\beta$$

where $B$ is blade's pitch angle. For a turbine with constant pitch, $\beta$ is considered as a constant value, Figure 1 is $C_p$ variations in terms of $\lambda$ for different $\beta$ values. In this paper $\beta$ is considered zero where the $C_p$ value would be 0.48 then.

![Fig. 1: $C_p$ in terms of $\lambda$ for different $\beta$ values.](image)

To get around the problem of modeling long term wind with a high resolution, Nichita used a method where he combined both the Van der Hoven and Von Karmen models. The Van der Hoven model is used to generate a new wind speed data point every 10 minutes or so. This Van der Hoven point is then taken as the average wind speed over the 10 minute interval that is filled with Von Karmen generated wind data. Since the Von Karmen psd has average velocity as a variable, this moving average generated by the Van der Hoven equation gives both accurate short- and long-term wind modeling. The only problem with this is the heavy computational time involved as described by Nichita (2002), but this can be alleviated with faster computers.

For the wind model used in this paper, the Shinozuka model was chosen as the method for simulating turbulence. For the problem of generating long term wind data, it is hypothesized that the Shinozuka method could in fact be used for both the turbulence and the long term fluctuations based on the premise that short term fluctuations is a relative idea. If one was looking at several hours’ worth of wind data, then a scale of seconds could be considered as short term fluctuations; this of course is the traditional view of what turbulence is. If, however, one was looking at several days’ worth of wind data, then the smallest time scale of concern may be on the scale of minutes or even tens of minutes. This lower resolution might be acceptable since the entire set of wind data covers several days, and literally thousands of these ten minute intervals. If this is the case, then small samples of these once-every-ten-minute points would be turbulence in the presence of days of data. If true, then the Shinozuka turbulence method will work to describe small numbers of these points.

This concept is similar to that of fractals in nature. For example, a pine tree, when examined closely, has needles as its smallest significant part, with cells making up those needles. When examined from afar, the smaller branches are the smallest significant part, with the needles making up the branches. When examined from even farther, the trees are the small parts making up the forest. Which parts are small and which are large is all relative to the size of the system being examined; this is the very concept behind using the Shinozuka turbulence method for both the long and short term models.

The task of combining the models into a coherent long term wind profile of high resolution is based on the variable average ideas outlined in Nichita’s paper (2002). The Shinozuka method is used to create a data point once every 10 minutes for any number of hours. This data point is then used to fill every 10 minute interval with second by second data points, again using the Shinozuka method. This results in hours of data points at a resolution of one second per point with long term average and turbulence information that is
specified by the user. The method results in accurate wind modeling that holds true if the user is looking at hours of data or at a few seconds.

RESULTS AND DISCUSSION

As hypothesized above, turbulence depends on the size of the system. For a second-by-second simulation of wind over a long period of time, there needs to be two separate time horizons at work, similar to the method used by Nichita (2002). Since the wind engineering standard for measuring turbulence intensity is 10 minutes (Manwell 2002), that was chosen as the larger time horizon. The smaller, is of course, one second. This means that if, for example, 5 hours of data were to be generated the simulator would first generate a data point every 10 minutes using the Shinozuka formula and the Von Karmen psd, creating 30 points that will become the “moving average.” These 30 points will adhere to the statistical properties as governed by the inputs which are long term mean, average turbulence intensity, integral length scale of both large- and small-scale turbulence, and the number of hours to simulate.

The next level of the program takes each of the 30 data points and creates 10 minutes worth second-by-second data, or 600 points for each of the 30 averages. These points are created using the Shinozuka formula with Von Karmen psd and will adhere to the behavior given by the inputted turbulence intensity and length scale, but each set of 600 will have its own average pulled from its corresponding point in the set of 30. This method of nesting turbulence simulation follows the idea of relativity in that if you look at the 5 hour simulation as a whole, the 10 minute intervals are fairly small parts and can be generated using the same turbulence model as the second-by-second points that make up the small parts within the 10 minute intervals.

To analyze the performance of this simulator, synthesized data was compared to measured data. Table 1 shows the numerical comparison for a simulation of ten hours of data. The mean and turbulence intensity of the simulated data is very accurate, as well is the length of the short term turbulence scale. The average power output of the wind is also right where it should be. The length scale of the long term turbulence is a bit off due to the fact with ten hours of data there are only sixty points of long term turbulence. With so few points whose values are semi-random, small differences from the desired values are magnified. This minor discrepancy is physically ok, as can be seen in Figure 2, where the graph of the simulated wind is very similar to that of the measured wind.

![Graphical comparison of simulation to measured data for ten hours.](image)

**Table 1:** Comparison of wind simulator to real data for ten hours of data.

<table>
<thead>
<tr>
<th>Data</th>
<th>Mean (m/s)</th>
<th>Turbulence Intensity</th>
<th>Long Term Length Scale (m)</th>
<th>Short Term Length Scale (m)</th>
<th>Average Power (W)</th>
<th>Computational Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured</td>
<td>9.1654</td>
<td>0.3860</td>
<td>39.7265</td>
<td>107.5495</td>
<td>2037.0</td>
<td>26.687</td>
</tr>
<tr>
<td>Simulation</td>
<td>9.1795</td>
<td>0.3521</td>
<td>16.2258</td>
<td>95.6062</td>
<td>1942.3</td>
<td>25.546</td>
</tr>
</tbody>
</table>

**Conclusions:**

Upon examining the test results of synthesized data points and measured data points, it is seen that this model is acceptable to use in producing a realistic wind profile for an input to a wind turbine system. The method is proven to produce different results every time due to the randomness of the signal’s phases, it adheres to the statistical inputs extracted from the measured data, and it produces very realistic power input.
It is also computationally light, with 1 data point created approximately every 700 μs (the simulation time is obviously relative to computer speed, and these tests were done on a mid-range computer). Due to the random nature of the phase angle generation, this method does produce some undesirable results from time to time. This occurs very infrequently, and the result is a physically improbable graph of the wind speed. The statistical results are still accurate, but graphically it sometimes looks “off”, with unwanted medium-frequency oscillations. This doesn’t necessarily mean what was simulated could never happen, it simply means that compared to what was measured at the test site the oddly simulated profile looks improbable. Despite these rare occurrences, the wind generator consistently produced wind speed data that adhered to the desired physical properties. It will interface desirably with the wind turbine dynamics to produce output electrical power, thus completing a complete software simulation of a horizontal axis wind turbine.

REFERENCES