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ABSTRACT

It is a common practice to use wind speeds at hub height in determining wind turbine power curves. Although the possible influence of other variables (such as turbulence and wind shear) is generally neglected in power curve measurements, we discovered the importance of other variables in an analysis of power curves for three 2.5 MW wind turbines. When the power curves were stratified by turbulence intensity, the observed power output for a given hub-height wind speed increased substantially with turbulence intensity. Such a large sensitivity to turbulence was not expected, and further analyses were conducted to determine if other factors accompanying the change in turbulence level could cause or contribute to the observed sensitivity of the power curves to turbulence.

In summary, the sensitivity of the observed power curves was largely due to two factors: 1) an actual sensitivity to turbulence in determining the power curve and 2) the deviation of the disk-averaged velocity from the hub-height velocity under low turbulence conditions that were most prevalent at the site. An examination of the wind shear profiles over the height of the rotor disk revealed that low turbulence conditions were characterized by strong shear in the lower half of the rotor disk and weak or negative shear in the upper half.

Implications of this analysis are that significant errors in power curve measurements can result if the effects of wind shear and turbulence are ignored.

1. INTRODUCTION

A wind turbine power curve is defined here as the observed power output of a wind turbine plotted against a wind speed, measured on a tower located in the vicinity of the wind turbine. Standards documents (1,2) are available that provide recommended methods for performing such power curve measurements. It is common practice to use wind speeds at hub height for power curve measurements. The possible influence of other variables (such as turbulence and wind shear) has generally been neglected in power curve measurements. The importance of other variables, however, was discovered in an analysis of the power curves for three 2.5-MW MOD-2 wind turbines.

The wind turbines were operating at the Goodnoe Hills site in Washington State. The three machines were located on a relatively flat and broad ridge, as shown in Fig. 1. The hub height of the MOD-2 was 61 m (200 ft) and the rotor diameter was 91 m (300 ft). The three wind turbines were installed in a triangular pattern with spacings of approximately 5, 7, and 10 rotor diameters (D) between machines. Wind speed and direction and other meteorological data were collected at various levels on two meteorological towers: a 61-m tower operated by the Bonneville Power Administration (BPA) and 107-m tower operated by PNL. A centralized data logging system monitored data collected from both the meteorological towers and the three wind turbines. The data recorded were 1-min averages and standard deviations based on 1-s samples, collected from April to October of 1985.

2. DATA ANALYSIS

Analysis of these data (3) showed that the prevailing strong winds (>6 m/s) at the site were predominantly from the west, and wind directions were between 250° and 310° more than 70% of the time. Thus, turbine 1 and the PNL tower were frequently in the wake of turbines 2 and 3 (see Fig. 1). For the prevailing westerly wind directions, the

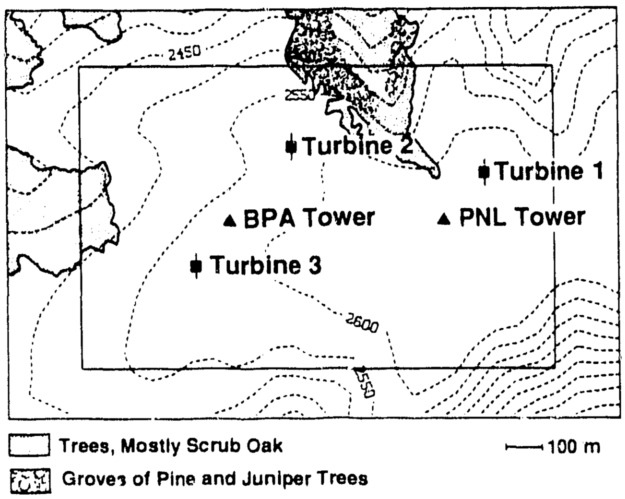

Fig. 1: Goodnoe Hills site showing locations of the wind turbines and meteorological towers

BPA tower was not influenced by the wind turbine wakes; therefore, it served as the upwind tower for measurement of the ambient wind conditions. Wind speed data collected at the 59-m level of the BPA tower were used for the power curve measurements. Wind directions between 240° and 320° were used, because the BPA tower and wind turbines 2 and 3 were completely free of turbine wake influences at these directions. For turbine 1, power data were used only from periods when the turbine was free of wake influences from an upwind turbine.

The average power output at each wind turbine was first examined as a function of wind speed only, then the power curves were stratified as a function of turbulence intensity. (Turbulence intensity is defined here as the standard deviation of the 1-s samples of wind speed for a 1-min average divided by the mean speed for the same period.) When the power curves were stratified by turbulence intensity, the results were startling. For a given wind speed, the mean power output at each wind turbine increased substantially with turbulence intensity. Fig. 2 shows the power curves stratified by turbulence intensity for turbine 2, based on about 577 hours of data from the period June 1 through August 31, 1985. The differences in power output between lowest and highest turbulence intensity were generally in the range of 300 to 400 kW for wind speeds between 7 and 13 m/s. For turbines 1 and 3, these large differences in the power output with turbulence intensity were also observed and were very similar to those for turbine 2.

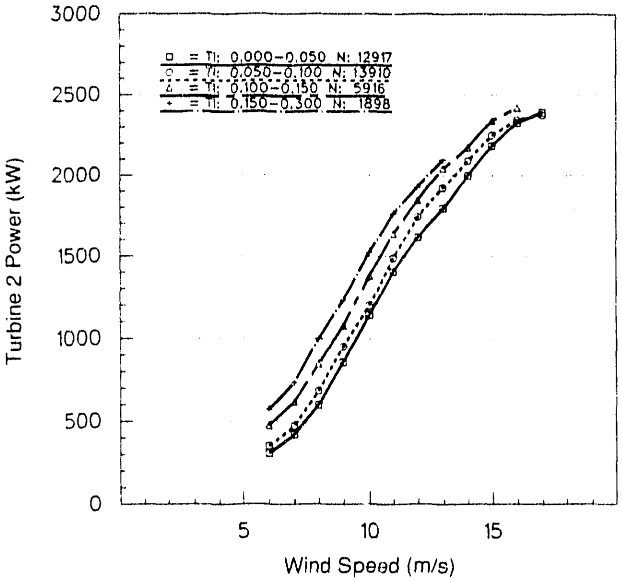

Fig. 2: Power curves stratified by turbulence intensity, based on BPA tower hub-height winds (1-min averages)

Faced with these surprising results--the sensitivity of the observed power curves to turbulence--we formulated some questions in an effort to find possible explanations. Are such large increases in power output possible from the effects of turbulence alone? If not, then how much of an increase is expected due to turbulence effects? What is the source of the error causing the large sensitivity of the observed power output with turbulence intensity?

In an effort to answer these questions, we reviewed studies by other investigators for relevant information on the effects of turbulence on wind turbine power output and also information on the effects of additional factors as well. Two of the most recent, comprehensive studies on power curve measurements identified were the Risø report, "Accuracy of Power Curve Measurements" (4), and the paper by Frandsen, "On Uncertainties in Power Performance Measurements" (5). These two documents include discussions of the work by numerous other investigators. First, we examined existing information on the effects of turbulence on power curves.

3. EFFECTS OF TURBULENCE ON POWER CURVES

The potential effects of turbulence on wind turbine power curves are discussed in the Risø report (4), where it is concluded that the power curve could depend on turbulence, but little is known about the power curve change with turbulence. However, the Risø report recommends that power curve measurements at a test site include a measure of the turbulence level to permit a possible correction to the power curve in estimating the power production at a different site, which may have considerably different turbulence levels than the test site. A method for precisely estimating the change in the power curve with turbulence could not be recommended.

However, a simple method exists for estimating an upper bound of the increase in power due to turbulence effects. If it is assumed that power, P, is proportional to the cube of the wind speed, u^3, then the average power can be estimated by

$$\overline{P} = P(\bar{u}) \left[1 + 3 \left(\frac{\sigma}{\bar{u}} \right)^2 \right] . \qquad (1)$$

$P(\bar{u})$ is the power in the mean wind and $\sigma/\bar{u}$ is the turbulence intensity. Because the power output from real wind turbines does not vary as u^3, but rather varies as u^k where $k < 3$, and for other important reasons, the term $3(\sigma/\bar{u})^2$ represents an estimate of the upper bound of the fractional increase in power due to turbulence effects. Actual increases in power due to turbulence could be considerably less than this upper bound.

In the power curves in Fig. 2, the highest turbulence intensity bin is 0.15 to 0.30, with a median of 0.225. For this turbulence intensity, the percent increase in power due to turbulence is estimated (i.e., the upper bound) to be 15%. For the lowest turbulence intensity bin of 0.00 to 0.05, the estimated increase in power due to turbulence is insignificant (<0.5%), which indicates the power at this low turbulence level is essentially the same as that in the mean wind.

To estimate the turbulence increase when the turbine has its greatest aerodynamic efficiency, we use the wind speed at which the turbine's power coefficient is at a maximum, which occurs at about 10 m/s for the MOD-2. At this wind speed, the observed increase in power due to turbulence is about 380 kW, or 33%. Therefore, the observed increase (33%) is much larger than the upper bound estimated above (15%).

4. SEARCHING FOR THE SOURCE OF THE ERROR IN THE POWER CURVES

In an effort to isolate the cause of the large error in the power curve sensitivity to turbulence intensity, we conducted further analyses to determine if other factors accompanying the change in turbulence level could cause or contribute to the large sensitivity to turbulence. The Risø report (4) examined many possible sources of error in power curve measurements. The report identified three main error groups: 1) machine conditions and power sensor errors, 2) wind sensor errors, and 3) representativeness of measured wind speed. The third group was determined to be the biggest source of error. This group includes terrain effects, turbulence effects, and statistical effects. Terrain effects were considered to constitute the largest potential source of error. Here, terrain effects have to do with how well the wind speed at the reference anemometer represents the wind speed at the turbine. Statistical effects include data sampling rates, averaging times, and binning methods.

Since terrain effects were determined to be the most likely cause for such a large error in the observed power curve sensitivity to turbulence, we decided to focus our initial attention on terrain effects. The possible effects of machine conditions, power sensor errors, and wind sensor errors were difficult to evaluate and, based on previous studies (4,5), were considered to be minor in comparison to terrain effects.

4.1 Terrain Effects

At the Goodnoe Hills site, terrain effects on the spatial variability of the wind flow have been analyzed from data collected at a height of 32 m at 7 portable towers, in addition to the BPA and PNL towers (6). These data indicated that the mean wind speeds, averaged over all wind directions, were uniform across the site; largest differences were less than 5%. However, considerable spatial variability was observed when the wind data were stratified by wind direction, and we discovered that most of this variability was caused by changes in surface roughness. Therefore, it was initially suspected that the sensitivity of the power curves to turbulence could be possibly caused by differences in wind speed and turbulence with direction at the turbine and BPA tower, although these effects appeared to be minimal at hub-height level. However, when the power curve data were stratified by wind direction, the sensitivity of the power curves to turbulence was still observed for a given wind direction. Thus, it was evident that the flow variability with direction was not the major factor responsible for the sensitivity of the power curves to turbulence.

4.2 Effects of Averaging Time

Another potential error source examined was the effect of different averaging times on the power curve sensitivity to turbulence intensity. We compared the results of 1-, 5-, and 10-min averaging times. (The IEA has recommended the use of 10-min averaging times). Because turbulence intensity generally increases with the length of the averaging time, it is not possible to get a true comparison using the same classes of turbulence intensity. For example, using 1-min averages, turbulence intensity values greater than 0.1 occurred 23% of the time; however, using 10-min averages, turbulence intensities greater than 0.1 occurred more than 50% of the time. The comparison of the power curves for the three different averaging times did not show any significant differences. For a 10-min averaging time, the power curve change with turbulence intensity was only slightly less than that for a 1-min averaging time.

4.3 Effects of Different Measures of Turbulence

Although we expected a similar behavior of the sensitivity of the power curve to turbulence for other measures of atmospheric turbulence (besides turbulence intensity), we nevertheless examined the power curves stratified by two other measures of turbulence: standard deviation of wind speed and standard deviation of wind direction. Similar results were obtained; that is, power output increased substantially as the level of turbulence increased.

4.4 Effects of Different Measurement Locations and Sensors

From the analysis of the power curves based on the wind data measured at the BPA tower, no explanation could be found for the large sensitivity of the power curves to turbulence. Therefore, we shifted our focus from the BPA tower to the PNL tower. Although the PNL tower was in the wake of either turbine 2 or turbine 3 for much of the wind direction sector of 240° to 320° used in the analysis of the power curves, we observed that the PNL tower was free of wake influences in the wind direction sector of 265° to 285° (6). Sufficient non-wake data were available (about 365 hours) from the PNL tower to permit an analysis of the power curves stratified by turbulence intensity, based on wind data from the 61-m (hub-height) level of the PNL tower. These power curves were compared with those previously produced using wind data from the BPA tower. This comparison of the power curves, based on wind data from two towers located about 700 m apart, allowed us the opportunity to evaluate not only the effect of the different measurement sites on the power curves but also the effect of different types of measurement sensors. The wind instrumentation on the BPA tower was a Belfort Aerovane with a distance constant of 4.6 m, whereas the wind instrumentation on the PNL tower was a Climatronics cup and vane system with a distance constant of 2.4 m.

Fig. 3 shows the power curves for turbine 2 stratified by turbulence intensity using the PNL tower hub-height wind data for wake-free directions. These power curves also show the large sensitivity to turbulence, as the power output is substantially greater at high turbulence intensities than at low turbulence intensities. Insufficient data were available for the highest turbulence bin (0.15-0.30), which occurred less than 1% of the time. Measured turbulence intensities at the hub-height level of the PNL tower were, on the average, about 10 to 15% lower than those measured at the hub-height

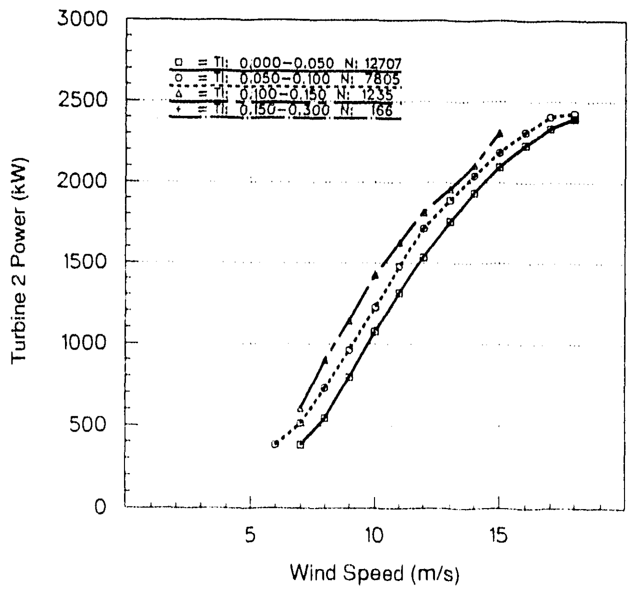

Fig. 3: Power curves stratified by turbulence intensity, based on PNL tower hub-height winds (1-min averages)

level of the BPA tower. Whether this difference in the measured turbulence intensities is real or largely due to the differences in response characteristics of the sensors is not known.

4.5 Effects of Disk-Average vs. Hub-Height Velocities

Five levels of wind sensors spanning the height of the rotor disk (15 m to 107 m) at the PNL tower permitted the opportunity to examine the wind shear profiles and to estimate the disk-average velocity. All wind sensors on the PNL tower were of identical type as that used at the hub-height level. Wake-free data from the wind direction sector 265° to 285° were selected. The disk-average velocity was approximated by the average of the wind speeds for the five height levels. Fig. 4 shows the power curves, stratified by turbulence intensity, for turbine 2 using the disk-average velocities from the PNL tower. In comparing Fig. 4 with Fig. 3, it is apparent that most of previous sensitivity of the power curves to turbulence intensity was caused by the deviation of the hub-height velocity from the disk-average velocity at low turbulence intensities. The power curves for high turbulence intensities (0.10-0.15) are nearly identical for hub-height and disk-average velocities, whereas the power curves for low turbulence intensities (0.00-0.05) are substantially different. For low turbulence intensities, the power output for disk-average velocities is considerably greater than that for hub-height velocities, which indicates that hub-height velocities overestimate disk-average velocities at low turbulence intensities (at this site).

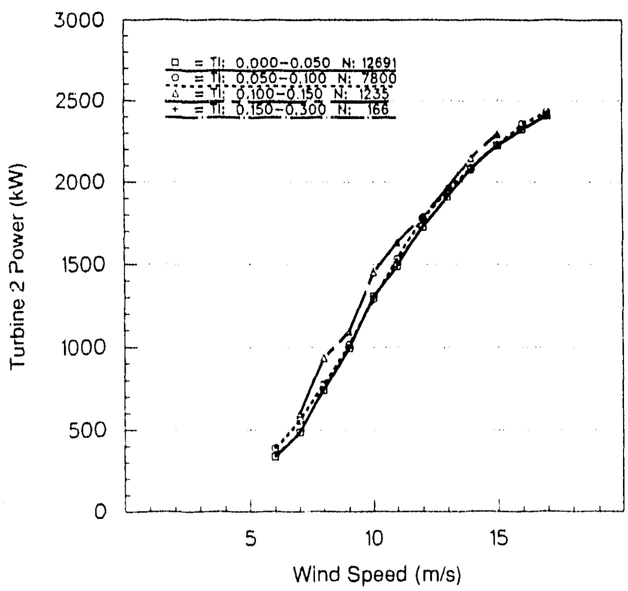

Fig. 4: Power curves stratified by turbulence intensity, based on PNL tower disk-average wind speeds (1-min averages)

However, turbulence effects on the power curves are still evident when disk-average velocities are used, as is apparent in Fig. 4. For disk-average velocities, differences in power output between low and high turbulence are mostly in the range of 100 to 150 kW (compared to differences of 300 to 400 kW for hub-height velocities). The observed power increase of 100 to 150 kW due to turbulence is more in agreement with the increase that would be estimated from Equation (1).

The analysis of the power curves, based on disk-average velocities, was also performed for 5-min and 10-min averaging times, and the results were similar to those for 1-min averaging times.

Fig. 5 shows the frequency distributions of the difference between hub-height and disk-average wind speeds, stratified by turbulence intensity. For low turbulence conditions, hub-height velocities overestimate disk-average velocities frequently by as much as 1 m/s or more. For high turbulence conditions, hub-height velocities represent disk-average velocities quite well, as the mean of the wind speed differences is near 0 m/s.

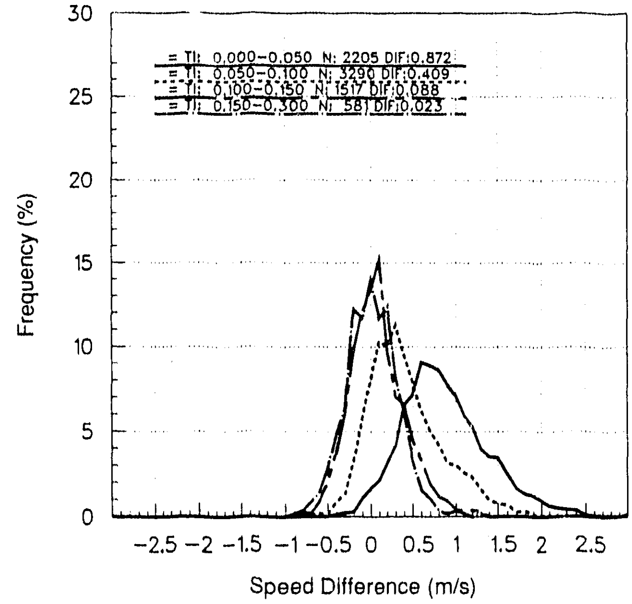

Fig. 5: Frequency distributions of hub-height minus disk-average wind speeds, as a function of turbulence intensity (5-min averages)

Fig. 6 shows the mean wind shear profiles, over the height of the rotor disk, stratified by turbulence intensity measured at hub-height level. It is apparent that the mean wind shear profiles are substantially different for low and high turbulence intensities. Low turbulence conditions are characterized by strong shear in the lower half of the rotor disk and weak or negative shear in the upper half. An examination of wind shear profiles for Goodnoe Hills (7) reveals that this shear profile occurs predominantly at night when low turbulence conditions are most prevalent.

5. CONCLUSIONS

A detailed analysis of the power curves, determined from hub-height winds, for three large wind turbines was performed to explain the large sensitivity of the observed power curves to turbulence. We discovered that this sensitivity was largely due to two factors: 1) an actual sensitivity to turbulence in determining the power curve and 2) the deviation of the disk-averaged velocity from the hub-height velocity under low turbulence conditions. These low-turbulence conditions were characterized by strong shear in the lower half of the rotor disk and weak or negative shear in the upper half of the rotor disk.

Implications are that significant errors in power curve measurements can result if effects of wind shear and turbulence are ignored. Hub-height wind speed generally becomes less representative of the disk-average wind speed with increasing rotor diameter. Therefore, the potential for significant

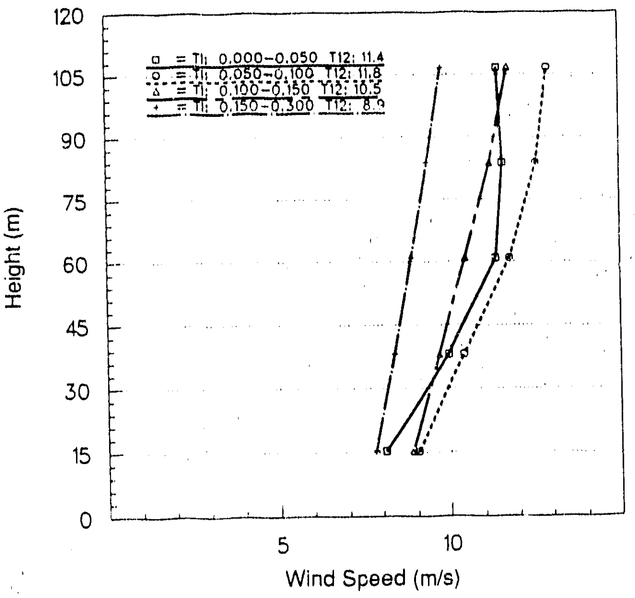

Fig. 6: Mean wind shear profiles over the height of the rotor disk, stratified by turbulence intensity (5-min averages)

errors in the power curve measurements (due to wind shear profile effects) is more likely for large machines than small machines.

Although several levels of wind data spanning the entire height of the rotor disk are obviously preferable over hub-height data alone, these additional data are often not available because of the additional expense required to collect these data. Moreover, current standards on performance testing for wind turbines, such as those published by AWEA (1) and IEA (2), specify only the collection of wind data at or near the hub-height level.

However, if only hub-height wind data and a measure of the atmospheric turbulence are available for power curve measurements, an analysis of the sensitivity of the observed power curves to turbulence intensity could be used as an indicator of the likelihood of influences due to wind shear effects and/or terrain effects related to the spatial variability of the wind flow. Further stratification by wind direction sector could indicate whether most of the power curve sensitivity to turbulence is more likely caused by wind shear or by terrain effects.

These types of analyses would serve as further indicators to assess the accuracy of power curve measurements, as well as their applicability to other sites.

Acknowlegments

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