

Evaluation of Wind Shear Patterns at Midwest Wind Energy Facilities

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EVALUATION OF WIND SHEAR PATTERNS AT MIDWEST WIND ENERGY FACILITIES

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Abstract

The U.S. Department of Energy-Electric Power Research Institute (DOE-EPRI) Wind Turbine Verification Program (TVP) has included several wind energy facilities in the Midwestern United States, including projects in Big Spring, Texas; Algona, Iowa; Springview, Nebraska; Glenmore, Wisconsin; and Fort Davis, Texas. At several of these projects, a strong diurnal shear pattern has been observed. During the day, low and sometimes negative shear has been measured. During night hours, very high positive shear is frequently observed. Wind shear is quantified as the exponent in the Power Law equation that relates wind speeds at two different heights. At some projects, the annual average shear peaks above 0.5 during early morning hours, with 10-minute and hourly average shear measurements frequently exceeding 0.75.

These high nighttime shear values are of concern due to the potential for high stresses across the rotor as the wind speeds are significantly different across the blades, particularly for newer turbines with large rotor diameters. The resulting loads on turbine components could result in failures. A significant number of nighttime faults have been observed at some TVP projects. The assumed causes of these faults have included high wind speeds and the lack of on-site nighttime operators to resolve problems, but incidences of some fault types also appear to be more frequent during periods of high wind shear. In addition, several Midwest projects have experienced significant component failures, such as gearbox bearing failures, that could be influenced by wind-shear-induced loads.

Conversely, the effects of high nighttime wind shear could benefit wind generated energy production in the Midwest by providing a source of greater hub-height wind speeds, particularly for multi-megawatt turbines that utilize tall towers. Sites that were characterized as possessing low wind speeds based on 40-m or 50-m (131-ft or 164-ft) meteorological data may be more productive than previously believed. Harnessing the high wind shear effects offers an opportunity to increase energy production and possibly lower the cost of energy, provided the turbines can successfully withstand long-term operations in such conditions.

This paper presents an overview of the observed wind shear at each of the Midwest TVP projects, focusing on diurnal patterns and the frequency of very high nighttime shear at the sites. Turbine fault incidence is examined to determine the presence or absence of a correlation to periods of high shear. Implications of shear-related failures are discussed for other Midwest projects that use megawatt-scale turbines.

In addition, this paper discusses the importance of accurate shear estimates for project development. At the majority of the TVP projects, initial long-term hub-height wind speed estimates were determined based on wind speed and shear measurements from lower height (i.e., 40 m (131 ft)) meteorological towers. Failure to accurately describe wind shear at hub height can produce significant errors in energy production estimates.

Introduction

Data used for the analysis of wind shear in this paper were obtained from five TVP projects located in the Midwestern United States. As illustrated in Figure 1, the project locations ranged from Wisconsin to Texas. Large spatial distribution of the projects facilitated analysis of wind speed data from a variety of climates located east of the Rocky Mountains. The projects also covered a region slated to see a significant increase in wind energy development in the coming years. These projects utilize turbines manufactured by Tacke, Zond, and Vestas that range in size from 500 kW to 1,650 kW and employ hub heights of 40 m, 50 m, 60 m, 65 m, and 80 m (131 ft, 164 ft, 197 ft, 213 ft, and 262 ft). At the Wisconsin TVP project, a nearby communications tower was instrumented with meteorological sensors, providing wind speed data at a range of heights up to 123 m (404 ft).

In addition to the five TVP projects, the National Renewable Energy Laboratory (NREL) provided analysis of wind speed data collected in cooperation with GE Wind at a communication tower near Lamar, Colorado. Measured data at this tower were collected from sensors installed at heights up to 113 m (370 ft).

NREL also provided 10-minute samples of high-speed data collected at 40 Hz from their long-term inflow and structural testing (LIST) towers located at the National Wind Technology Center. The LIST towers measure wind speed at five locations across a 42-m rotor diameter (top, bottom, left, right, and center). The high-speed data were used as an input into an ADAMS model of a three bladed, upwind, turbine with a rotor diameter of 70 m (229 ft) to evaluate the impacts of high shear events on the peak and fatigue loads experienced by the turbine.

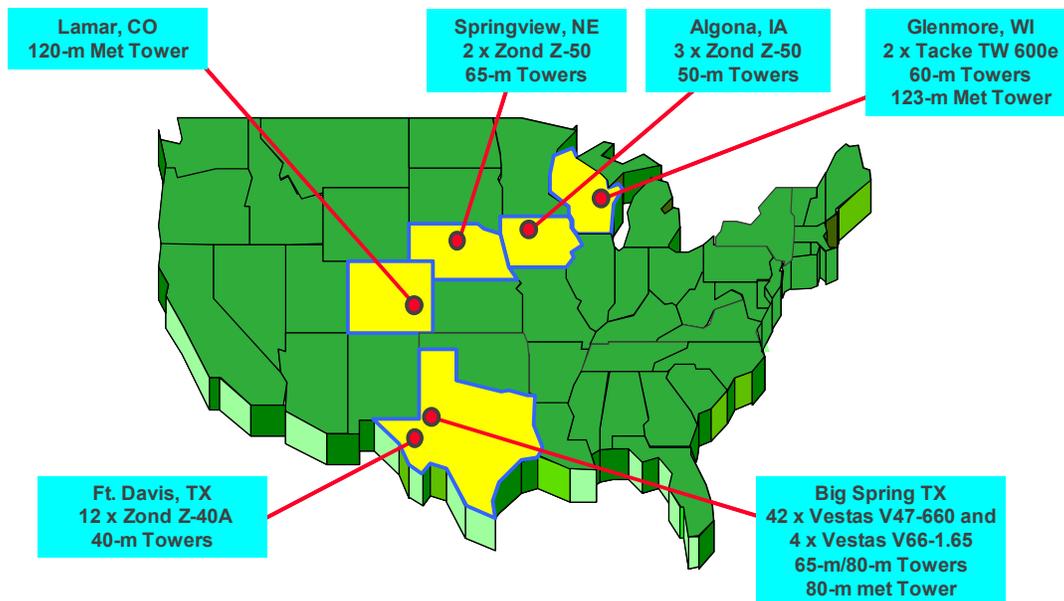


Figure 1. Locations of Meteorological Tower Data

Methodology and Data Used

For the purpose of this paper, long-term sets of validated data were analyzed to determine the timing, magnitude, and frequency of wind shear and high wind shear events at five TVP projects. The data validation procedure included identification and elimination of all data exhibiting erroneous results due to icing, data collection equipment failures, tower shadow, waking from nearby turbines, or other problems. No data replacement was performed on the data sets, so shear calculations were performed only where valid upper and lower wind speed measurements were available for a given time interval. In addition, wind speeds below turbine cut-in wind speeds (typically less than 4 m/s) were excluded from the calculation of wind shear. Average wind speed data were used to calculate average wind shear exponents based on the power law equation:

$$V_2/V_1 = (H_2/H_1)^\alpha$$

or

$$\alpha = \ln(V_2/V_1)/\ln(H_2/H_1)$$

Where V_1 is the wind speed at height H_1 , α is the wind shear exponent, and V_2 is the wind speed at height H_2

At the TVP projects, data collection was generally performed using the project SCADA systems; data for the Wisconsin project were collected using a separate data logger at the communications tower. Parameters measured by the SCADA system include turbine production and performance, faults, and meteorological data from associated met towers. SCADA data were collected on a 10-minute average basis. At the Wisconsin tower, 10-minute average data were collected, but validation was performed on an hourly average basis; consequently, only hourly average shear exponents were calculated. In addition, only hourly average data were available for the first year (1999) at the Iowa TVP project. At the NREL/GE Wind tower, wind speed data were collected on a 5-minute average basis. Table 1 presents a summary of the data sets used in this paper.

Table 1. Data Summary

Name	Sensor Heights	Duration of Data	Annual Average Wind Shear
TVP Projects			
Big Spring, Texas	40 m – 80 m	September 1999 – August 2000	0.21
Ft. Davis, Texas	25 m – 40 m	July 1998 – June 1999	0.11
Iowa	25 m – 50 m	January 1999 – March 2001	0.33
Nebraska	40 m – 65 m	October 1999 – March 2001	0.22
Wisconsin	37 m – 123 m	December 1999 – September 2001	0.28
NREL Towers			
Lamar, Colorado	52 m – 113 m	October 2001 – March 2002	0.20
NWTC – LIST	15 m, 37 m, 58 m	Several 10-minute intervals at 40 Hz	–

Comparison of Diurnal Wind Shear

Figure 2 presents a comparison of the diurnal wind shear observed during the corresponding period of data evaluation at five of the TVP projects. From these data, it is apparent that a strong nighttime peaking pattern is present at all the projects. With the exception of Ft. Davis, Texas, the wind shear values at night (between 10:00 p.m. and 6:00 a.m.) ranged from 0.26 to 0.44. However, during the day, the wind shear values ranged from 0.09 to 0.19 (excluding Ft. Davis). Given these significant differences between night and day, Table 1 illustrates that the sites exhibit relatively common (for the Midwest) annual average wind shear values from 0.2 to 0.33.

The elevation at Ft. Davis is 1,860 m (6,100 ft) above sea level, which is significantly higher than the next highest site (Big Spring, Texas, at 850 m [2,800 ft]). However, the measurement heights at Ft. Davis are lower than the other projects, which may help to explain the lower overall magnitude of wind shear at this site.

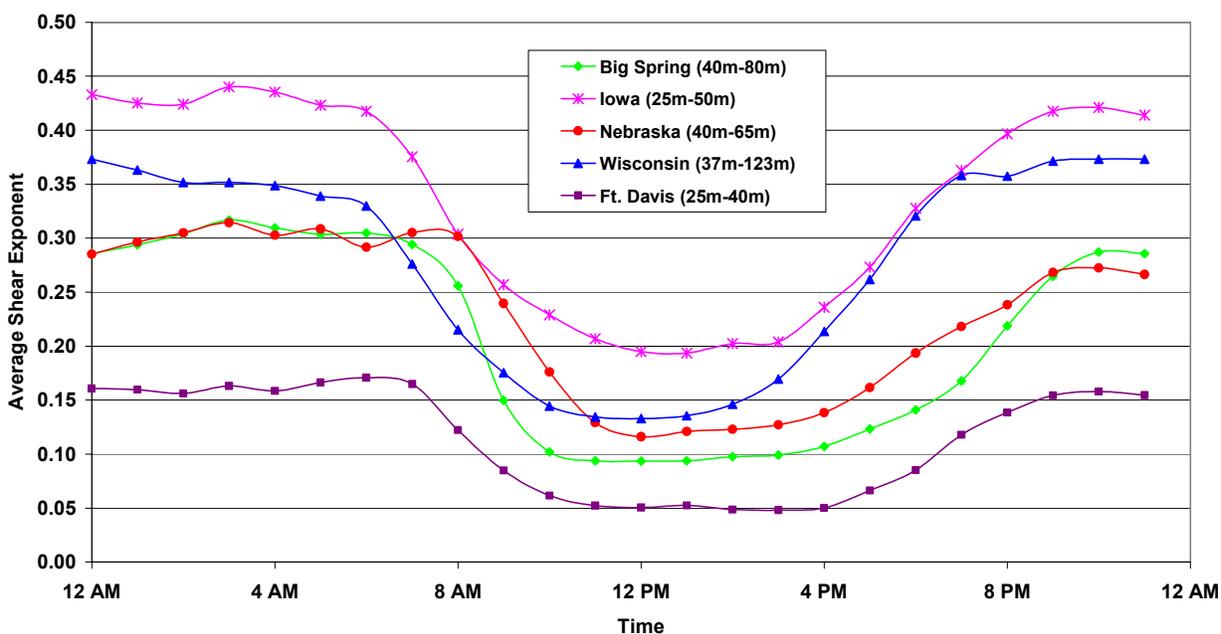


Figure 2. Comparison of Diurnal Wind Shear at TVP Projects

Most wind resource assessment activities utilize 40-m or 50-m towers with sensors installed at intermediate levels (10 m, 20 m, or 26 m for example). Shear observed over these lower heights is commonly extrapolated up to estimate hub-height wind speeds. This assumption may be reasonable in the case of sub-megawatt turbines, such as those with rotor diameters between 44 m and 52 m and installed with hub heights of 50 m to 65 m.

However, this extrapolation may not be appropriate for multi-megawatt turbines (with rotor diameters greater than 52 m) and installed with hub heights greater than 65 m. Figure 3 illustrates an example of this situation using diurnal wind speed data at different measurement intervals on the same met tower from Big Spring, Texas. In Figure 3, the annual average wind shear between 10 m–40 m and 40 m–80 m was approximately 0.2 for each interval. However, the magnitude of the diurnal variation between high

nighttime shear and low daytime shear between 40 m and 80 m was greater than between 10 m and 40 m. Consequently, the site conditions characterized by data obtained between 10 m and 40 m do not resemble the actual conditions encountered by the rotor.

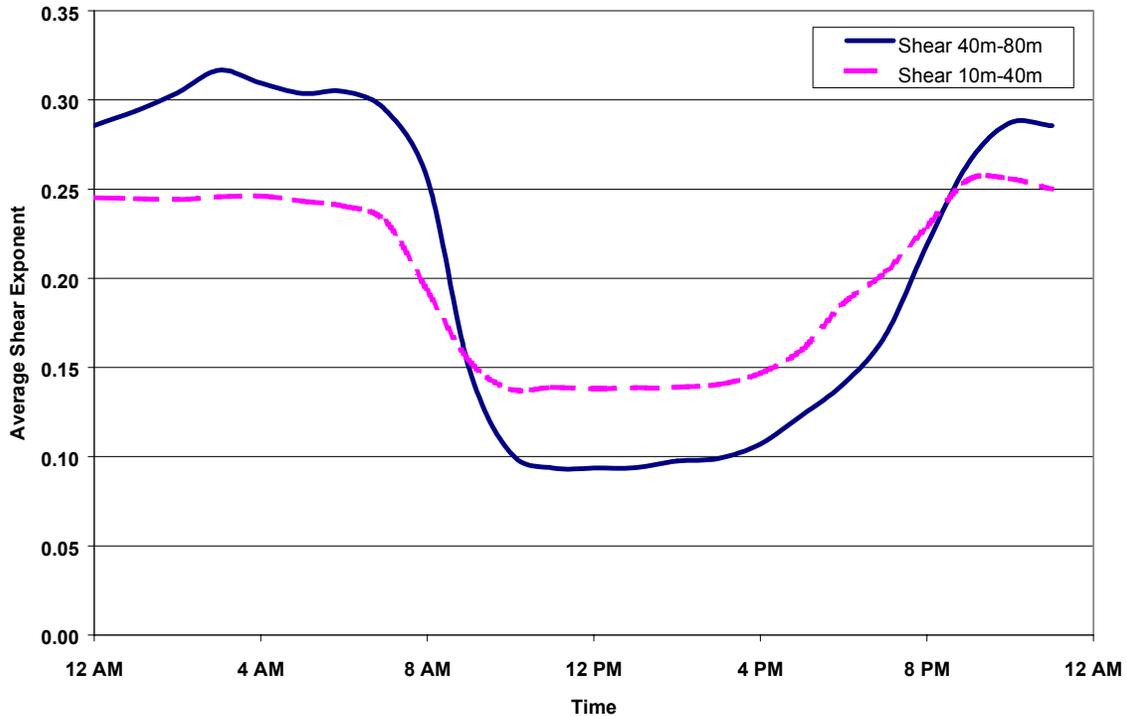


Figure 3. Comparison of Diurnal Wind Shear at Big Spring, Texas

Another example illustrating the differences between wind data collected for development purposes and wind data collected at the rotor is associated with prediction of energy delivery. In Figure 4, the 40-m diurnal wind speed pattern from Big Spring was adjusted to a hub height of 80 m by applying the annual average wind shear value of 0.2. Diurnal annual average capacity factors for a typical wind turbine were then calculated. The resulting values are shown in Figure 4 as sheared capacity factors. The actual diurnal average capacity factor calculated from 80-m wind speed data is also shown for comparison. The sheared capacity factor values under-predicted peak power output at night and over-predicted low power output during the day, both by about 5% of capacity. In this case, if a power marketer or utility grid manager were using the 10 m–40 m wind speed data to schedule project output, the predicted daytime output (when Texas utilities experience peak loads) would be overestimated while the nighttime output (corresponding to off-peak grid load) would be underestimated. This could result in the need for additional unplanned reserve energy sources to make up for the shortfall during daytime peak load hours. It is important to note that the calculated annual energy production using the sheared capacity factor data was essentially equal to the actual annual average energy production, although timing of the energy delivery was different.

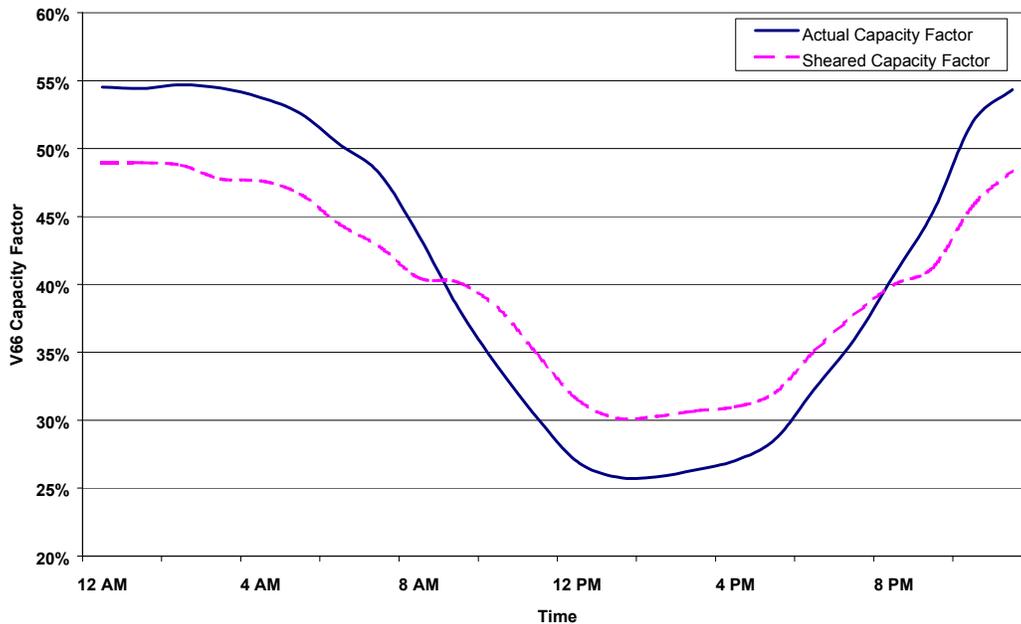


Figure 4. Calculated Versus Actual Diurnal Capacity Factors at Big Spring, Texas

Distribution of Nighttime Wind Shear at TVP Projects

Figure 5 presents the distribution of nighttime wind shear at the five TVP projects, where nighttime is defined as the hours between 10:00 p.m. and 6:00 a.m. This figure also indicates the amount of time the turbines operated in periods of high shear (defined as shear exponents greater than 0.5) during the measurement periods.

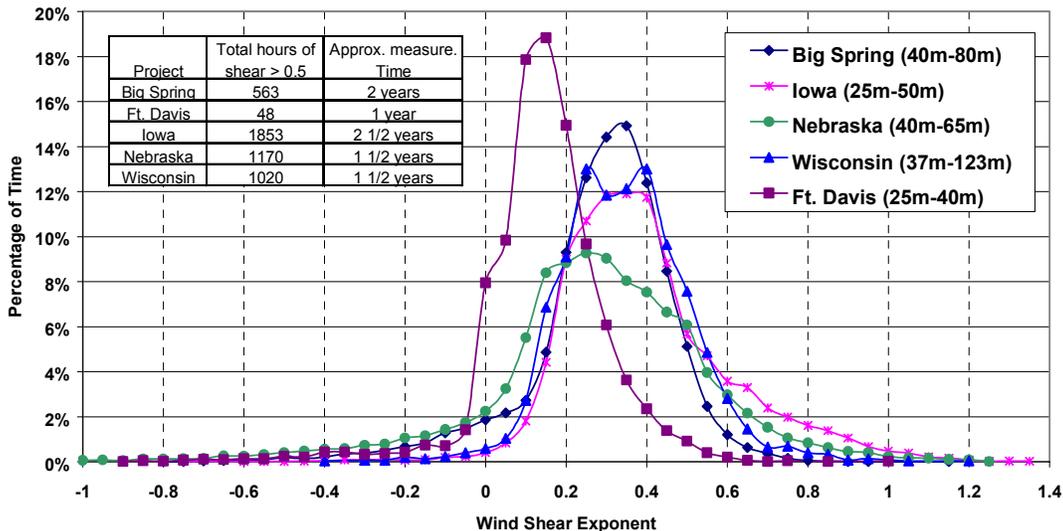


Figure 5. Distribution of Nighttime Wind Shear at TVP Projects

During the 1.5 to 2.5 years of data collection at these TVP sites, the turbines have experienced between 48 and 1,853 hours of operating time in wind shear conditions exceeding 0.5. Although not frequent, each of the sites experienced short durations in wind shear conditions exceeding 0.8. Because 10-minute

average data are being used in most cases, it is very likely that short-term wind gusts within the 10-minute period are well in excess of 1.0.

Distribution of Wind Shear at Lamar, Colorado

Data collected by NREL in conjunction with GE Wind (formerly Enron Wind) from a tall tower in Lamar, Colorado, provide further analysis of wind shear distributions. Figure 6 presents wind shear distributions at two different intervals on the tower, 3 m–52 m and 52 m–113 m. Although the 3-m height is not commonly used in site assessment and project development activities, the 3 m–52 m height interval spans the region where most wind speed data are collected. The wind speed distribution for the 52 m–113 m interval corresponds to the region in which rotors on multi-megawatt turbines are operating. Data collected at the Lamar tower were averaged on a 5-minute basis as opposed to the 10-minute basis generally measured at the TVP projects. Data shown in this figure include all hours (i.e., daytime data were not excluded). Wind speeds lower than 3 m/s were excluded from analysis. The number of hours noted on the figures corresponds to the six-month period between October 2001 and March 2002.

During the six months of data collection, the average wind shear exponent across both height intervals was 0.2. However, the shape of the 52 m–113 m distribution is considerably different from that for the lower height interval. Significantly more time of high shear (greater than 0.5 shear exponent) and low shear is observed between 52 m–113 m than between 3 m–52 m. This figure further illustrates the difference that exists between shear measured at heights commonly evaluated during site assessment and shear at megawatt-scale turbine operational heights.

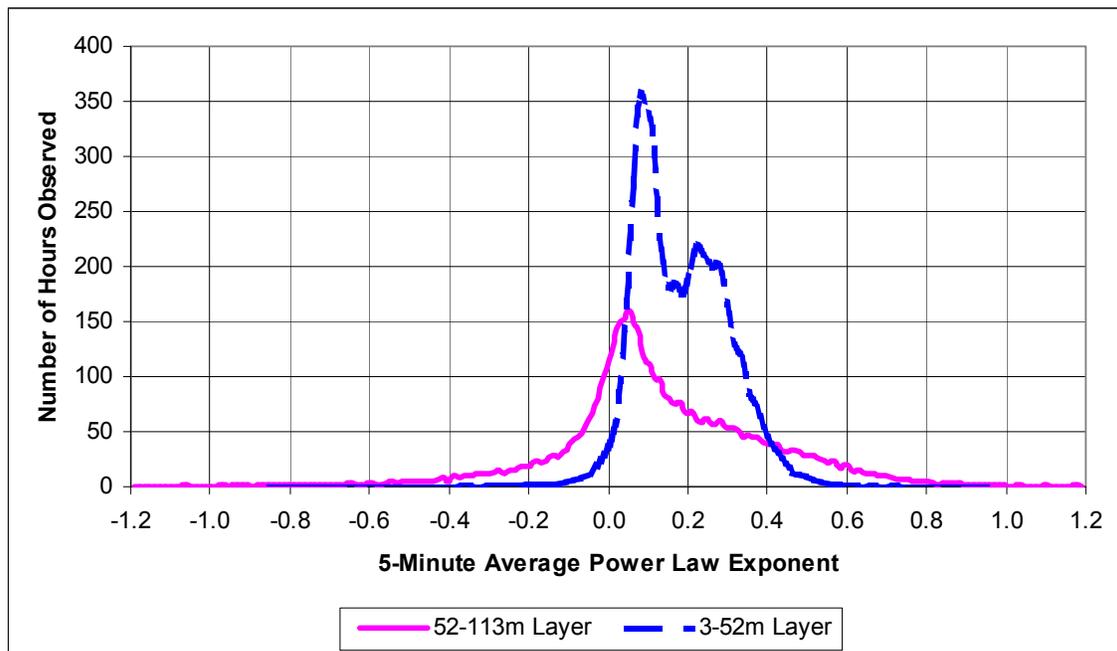


Figure 6. Distribution of Wind Shear at the NREL/GE Wind Lamar Tower

Similar patterns were observed at Big Spring, Texas. Figure 7 illustrates the distributions of shear from 10 m–40 m and from 40 m–80 m at the Big Spring TVP facility. Although the mean shear over each interval is approximately 0.2, significantly more extreme positive and negative shear is measured at the upper interval.

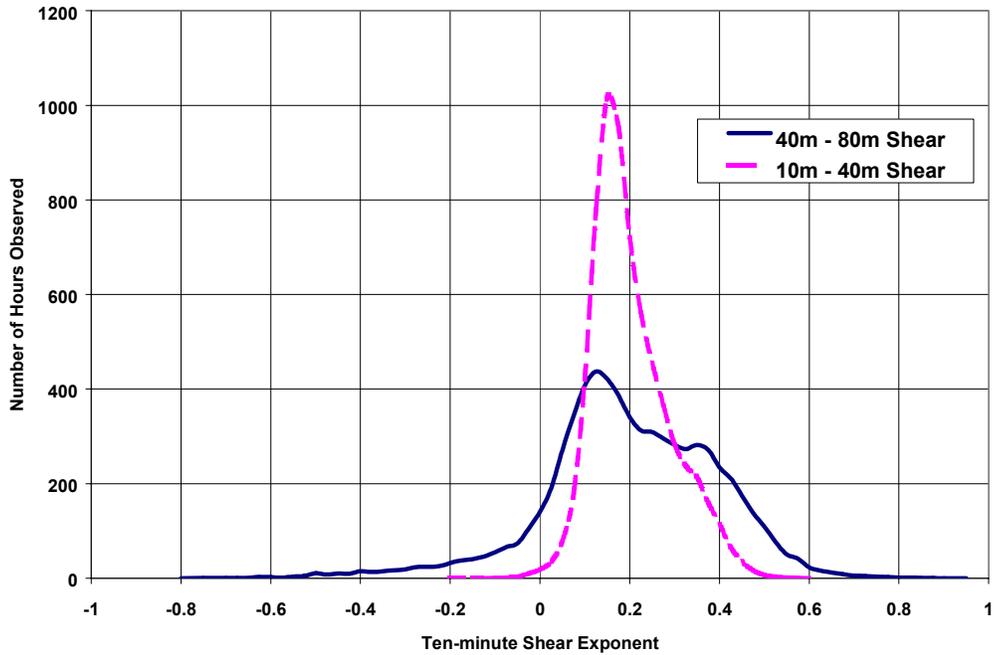


Figure 7. Distribution of Wind Shear at Big Spring, Texas

Example High Wind Shear Event from Wisconsin

Turbines at each of the observed projects are frequently exposed to prolonged high shear events over nighttime hours. An example of one of these events, measured at the Wisconsin tower on April 28–29, 2001, is presented in time-series format in Figure 8.

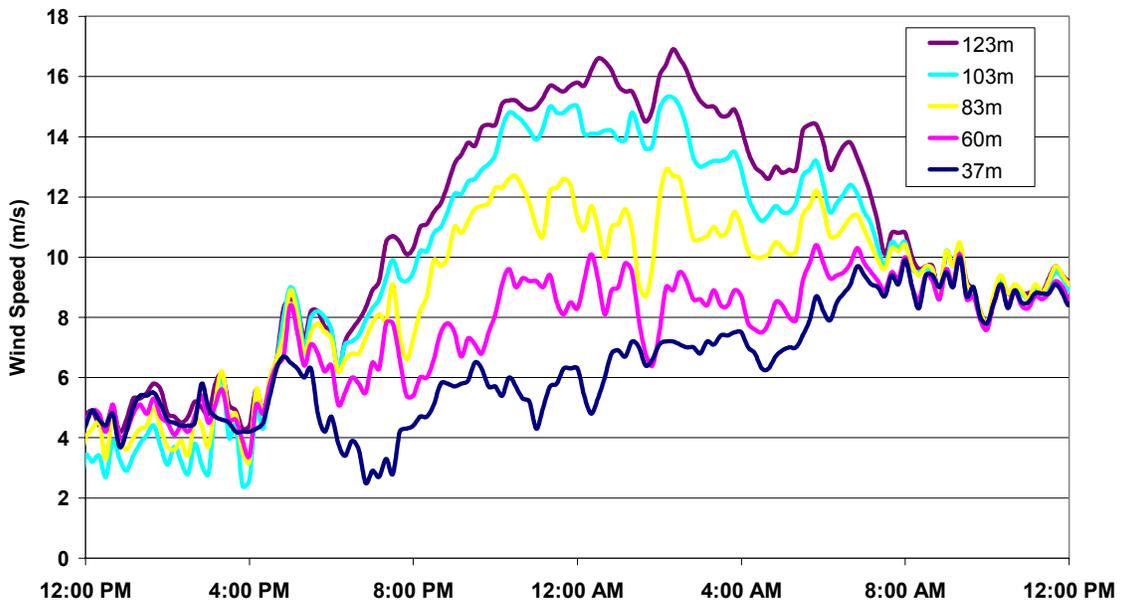


Figure 8. Prolonged High Wind Shear Event at the Wisconsin TVP Project

From Figure 8 it is apparent that sensors on a 40-m met tower would be incapable of documenting the extreme wind event that occurs at rotor operating heights. In this case, data from the 37-m sensor indicate a rather gradual increase in wind speed from about 8:00 p.m. to 8:00 a.m. However, a rotor from a multi-megawatt turbine operating through this wind event would experience prolonged operation in wind with the bottom-of-rotor wind speed approximately 6 m/s (37 m height) and the top-of-rotor wind speed 15 m/s (123 m height), corresponding to an approximate shear exponent of 0.75. During one 10-minute period just after midnight, the 37-m height wind speed dropped to 5 m/s while the 123-m height wind speed increased to approximately 16.7 m/s resulting in an average wind shear exponent of 1.0.

Wind Speed Profiles and Atmospheric Stability

The atmospheric phenomenon that causes periods of high wind shear at night has not been completely characterized but is believed to be associated with low-level nocturnal jets. As discussed in Det Norske Veritas (DNV) *Guidelines for Design of Wind Turbines* [1], atmospheric stability appears to cause the conditions necessary for periods of strong upper level turbulence. During the night, the atmosphere cools, resulting in formation of air layers with varying temperatures. It is during these highly stable conditions that formation of strong turbulence becomes triggered (the specific mechanism is not known). One of the byproducts of this strong turbulence is noticed in near-surface [within 200 m (656 ft) of the ground surface] wind speed data as high shear events. During the day, heating of the earth’s surface results in convective mixing of different air layers that releases some of the boundary layer friction. The convective air movements are noticeable in near-surface wind speed data as periods of low to even negative wind shear.

Wind speed profiles in highly stable atmospheres are characterized as continual wind speed increases as height increases (high wind shear). Wind speed profiles in unstable atmospheres result in relatively small increases of wind speed as height increases. These conditions are observed in both the Wisconsin and Big Spring met tower data. Figures 9 and 10 present the noon and midnight wind speed profiles for the Wisconsin and Big Spring TVP projects, respectively. Data used in these figures corresponds to the average wind speeds between 12 and 1 (a.m. and p.m. as appropriate).

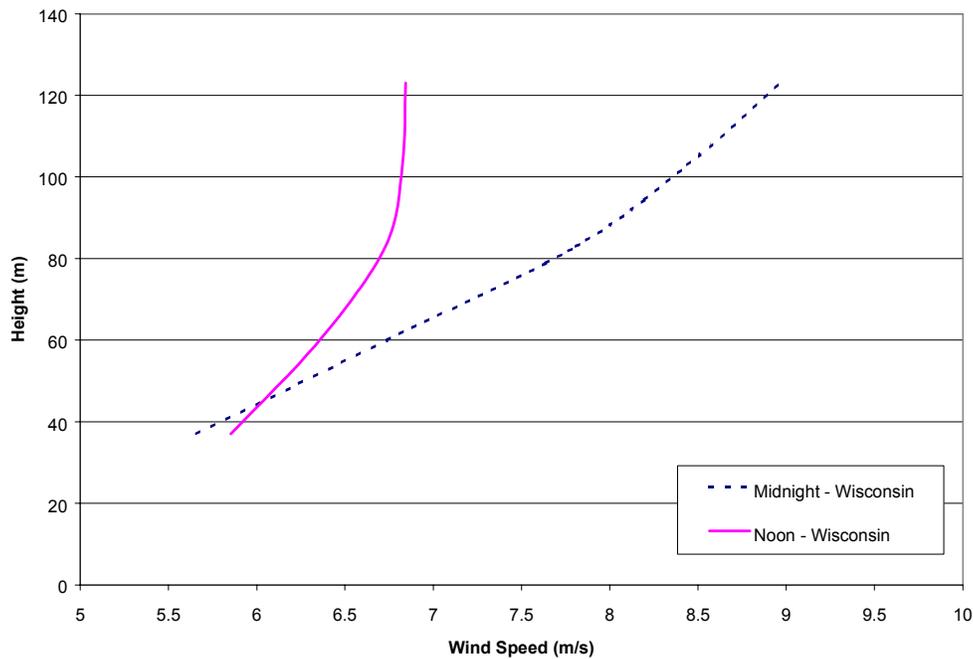


Figure 9. Day and Night Wind Speed Profiles at the Wisconsin TYP Project

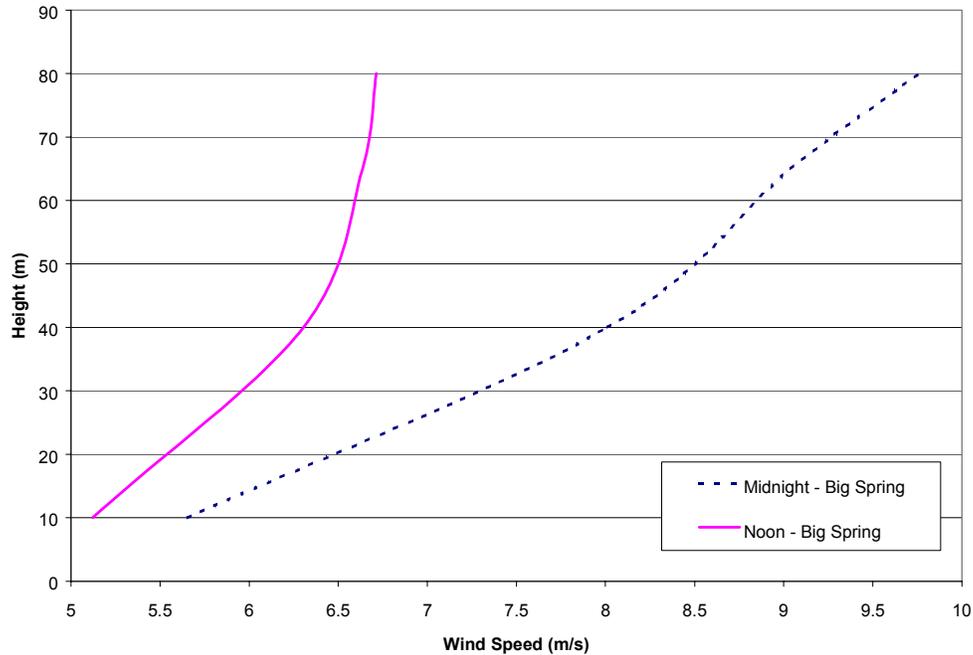


Figure 10. Day and Night Wind Speed Profiles at the Big Spring TVP Project

During the day, both sites exhibit rather flat wind speed profiles; however, at night the profiles become more aggressive.

Wind Turbine Design Specifications

One of the basic elements in the design of wind turbines is characterization of external conditions in which the turbines are intended to operate. Numerous wind conditions are used to encompass the range of potential operating environments the turbines may experience during their expected 20- to 30-year design life. The wind conditions are typically divided into two categories: normal and extreme. The International Electrotechnical Commission (IEC) has established the design standard generally followed by wind turbine manufacturers in the document *Wind Turbine Generator Systems – Part 1: Safety Requirements* [2]. Two internationally recognized wind turbine design certification bodies in the wind energy industry are Det Norske Veritas (DNV) and Germanischer Lloyd (GL). These certification bodies utilize guidelines that differ from the IEC standard. The external wind conditions associated with wind shear required (by IEC) or suggested (by DNV or GL [3]) in the design of wind turbines were summarized and compared to the observed wind conditions previously presented in this paper.

As shown in Table 2, the normal wind shear conditions identified in the design guidelines are similar to the range of wind shear observed at the TVP projects and the Lamar tower. In addition, the magnitude of extreme wind shear is also similar to the magnitude of extreme wind shear noted in Figures 5 and 6. However, there is a significant difference between the design guidelines and the observed data in relation to the duration of the extreme events and the frequency of their occurrences. The design guidelines assume that extreme wind shear events occur over a very short time frame (5 to 12 seconds) whereas measured data from the TVP projects indicate that turbines are consistently exposed to 10-minute average shear comparable to the extreme event shear conditions. In addition, turbines at the TVP projects have experienced extreme wind shear events at a higher rate than the once in 50 years assumed in the design standards. In some cases, turbines have experienced extreme shear conditions more frequently than once a night.

Table 2. Summary of Wind Turbine Design Certifications

	IEC	DNV	GL
Wind Shear Exponents for Normal Operating Conditions	$\alpha = 0.2$ For all Wind Speed Classes	Unstable Conditions $\alpha \sim 0.16$ Neutral Conditions $\alpha \sim 0.22$ Stable Conditions $\alpha \sim 0.35$	$\alpha = 0.16$ For Class I or II Sites
Comparable Wind Shear Exponents for Extreme Events ¹	Equivalent to a Shear Exponent $\alpha = 1.13$ in Steady Flow	Discussed but no Firm Recommendations	Equivalent to a Shear Exponent $\alpha = 0.55$ in Steady Flow
Frequency of Extreme Events	50-Year Return (Once in a Design Lifetime)		
Duration of Extreme Events	12 Seconds with Cosine Function Variation	Discusses Analysis Over 10-Second Periods	Average Over 5 Seconds
Load Cases Analyzed	Ultimate Loads During Power Production Ultimate Loads With Rotor Parked		

¹ Extreme values have been calculated assuming a 66-m rotor, an 80-m hub height, and a cut-out hub-height wind speed of 25 m/s.

ADAMS Modeling of Extreme Wind Shear Conditions

To estimate the effects of turbine operations in high-shear conditions, load modeling was performed using data from a variety of observed conditions at the Wisconsin and Big Spring TVP projects. Four representative 10-minute periods were selected. Table 3 summarizes the conditions observed in each.

Table 3. Sample Extreme Wind Shear Conditions Observed at TVP Projects

	Mean Hub-Height Wind Speed (m/s)	Mean Wind Shear Exponent	Standard Deviation Hub-Height Wind Speed (Gustiness) (m/s)	Standard Deviation of Wind Direction (Range of off-yaw operation) (degrees)
Simulated Wisconsin 1	10.2	0.95	1.64	5.71
Simulated Big Spring 1	15.5	0.56	0.74	2.58
Simulated Big Spring 2	14.1	0.61	1.88	7.18
Simulated Big Spring 3	17.1	0.64	1.60	6.43

Because wind speed data with a high sample rate are needed for model inputs and only 10-minute average data were available for the TVP projects, 40 Hz data collected at the NREL LIST tower were used as surrogate inputs. The LIST tower data were modified by linearly scaling the top-of-rotor, hub-height, and bottom-of-rotor wind speed measurements such that the 10-minute average of each LIST dataset equals the 10-minute average observed during the corresponding TVP data. (At Big Spring, where no top-of-rotor measurements were collected, it was assumed that the shear observed between 40 m and 80 m remained constant to the top of the rotor.) The three heights were set as appropriate for the model turbine described below. Other input parameters, including horizontal shear and variation from average wind direction, were not scaled. Each of the resulting datasets include 10 minutes of 40 Hz measurements with mean wind speeds and shear equal to those from the TVP projects.

The Model

To assess the impact of the observed high wind shear conditions on turbine design, it was decided to use an ADAMS™ (Automatic Dynamic Analysis of Mechanical Systems from Mechanical Dynamics, Inc. Ann Arbor, Michigan [4]) model to estimate turbine loads at various locations within a turbine. The model selected for this comparison was the 1.5 MW baseline configuration used in the WindPACT Rotor Design Study [5] because this model was available and because it was similar to the multi-megawatt machines recently installed in the field. The major features of the WindPACT 1.5 MW baseline turbine were:

- Rotor diameter = 70 m
- Maximum tip speed = 75 m/s
- Full-span pitch control, variable speed
- Hub height = 72 m

The AeroDyn_12 [6] routines were used for the aerodynamic loading.

Loading Calculations

The following inflow conditions were used with the model and the corresponding responses were noted.

- All IEC-defined extreme events at rated and cut-out wind speeds (with the exception of extreme winds on the stationary rotor).
- IEC-defined normal turbulent flow for Class 2a with mean wind speeds corresponding to the mean speeds measured at each of the four sites.
- Modified inflow constructed from the field data for each of the four cases presented in Table 3.

The responses were scanned for peak values, and the results from the turbulent inflows were translated into rainflow excursions for fatigue loading. The fatigue cycles were also used to calculate equivalent fatigue loads. The response of the model to the modified inflow field data was then compared with the corresponding response to standard IEC-defined inflow.

Peak Load Results

Figure 11 presents results of the peak load analysis at five locations within the turbine and tower structure. Loads calculated by the model for each of the modified inflow conditions have been normalized by the loads derived from the IEC-defined inflow conditions. The IEC peak loads were exceeded in root flap bending for two of the modified inflow cases. Shaft bending, yaw moment, and fore-aft tower base bending were all within 20% of the IEC peak loads for the Big Spring Case 3 modified inflow conditions. Shaft bending and fore-aft tower base bending were also within 20% of the IEC peak loads for the Wisconsin modified inflow conditions.

Note that the results for shaft bending are with respect to the rotating shaft and are measured at the connection between the shaft and the hub. In contrast, the pitching moment at the yaw bearing is referred to the fixed nacelle frame. The effect of a vertical wind shear will therefore be seen primarily as a once-per-revolution cyclic moment in the shaft but will be recorded as a constant moment at the yaw bearing.

Peak loads from the modified inflow field data that approach the IEC peak values are grounds for concern. This is because the IEC peak loads are values that are expected only once in the turbine design lifetime. Whereas, the modified inflow field data are representative of conditions that can exist for many hundreds of hours.

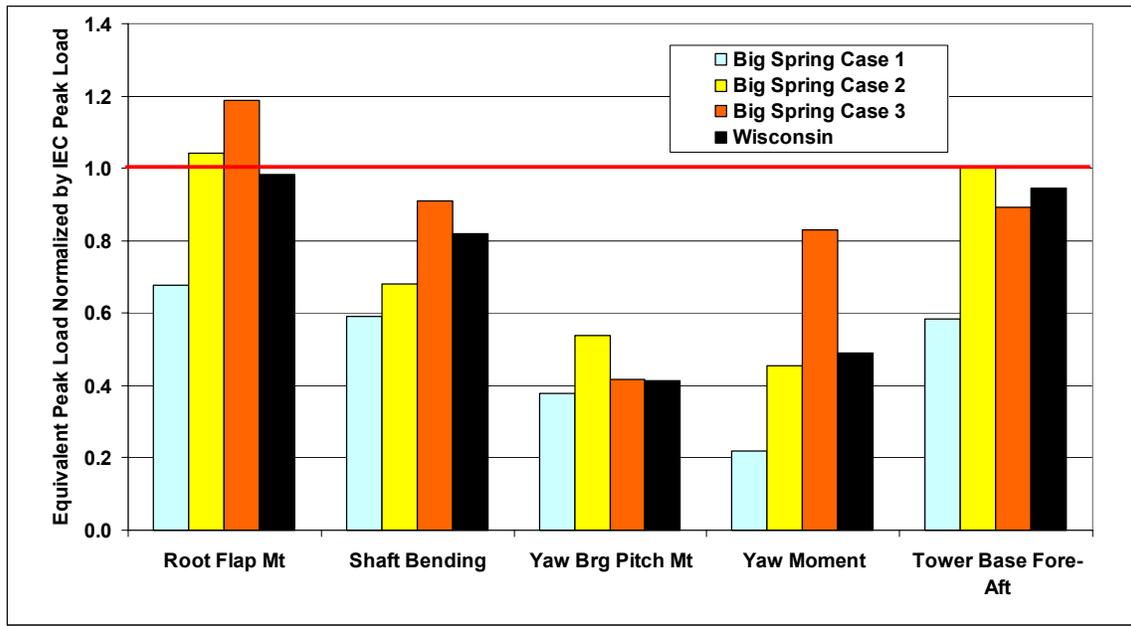


Figure 11. Peak Load Analysis Normalized by IEC Peak Load

Fatigue Load Results

Figure 12 presents the results of fatigue load analysis normalized by IEC fatigue loads. The IEC fatigue loads for root flap bending, shaft bending, and fore-aft tower base bending were exceeded for almost all of the modified inflow cases. Shaft bending and fore-aft tower base bending exceeded the IEC fatigue loads by more than 50%. Yaw bearing pitch moments and yaw moments did not prove to be heavily influenced by the high shear conditions. This result was unexpected as intuition suggests that these loads might be affected by high shear.

However, previous work by Malcolm in “Modal Response of 3-Bladed Wind Turbines” [7] indicates that high shear can result in a strong 3-per-revolution modal load and displacement within the turbine. High wind shear may be exciting this harmonic resulting in unexpected vertical and lateral forces within the nacelle. Further work to analyze this issue is currently being undertaken and will be published in the *ASME Journal of Solar Energy Engineering* special November 2002 Wind Issue.

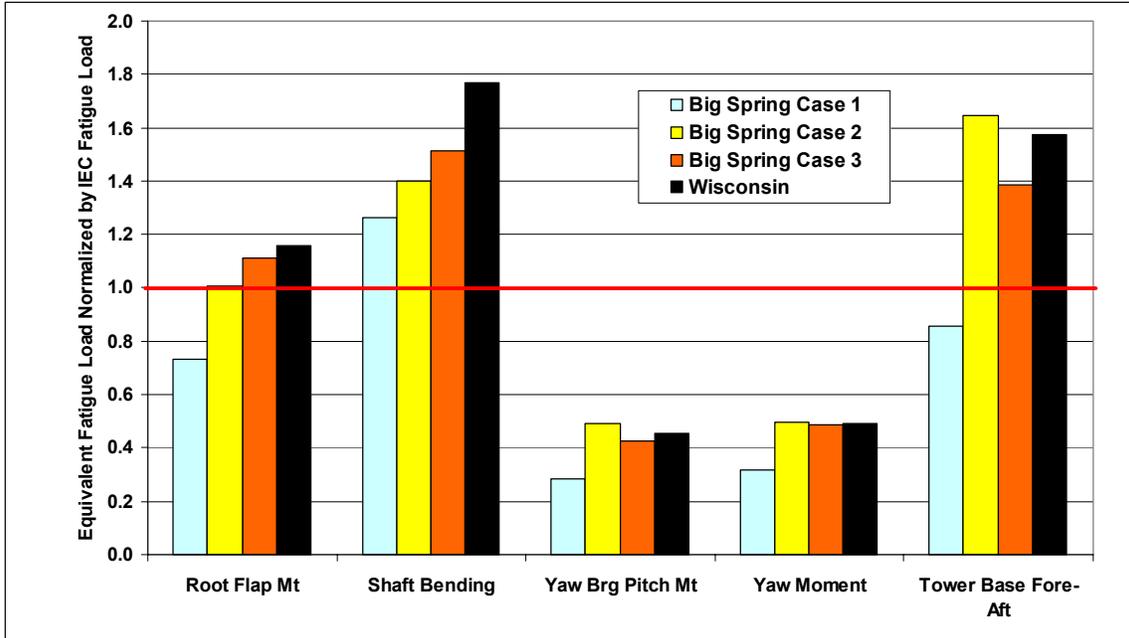


Figure 12. Fatigue Load Analysis Normalized by IEC Load

It is important to note that peak and fatigue loads may not be the final parameter used in the design of a given component. Other qualities such as stiffness may ultimately drive a particular component’s design. Exceeding the IEC conditions does not strictly imply that these components will fail. However, the resulting calculations indicate that the actual loading may be close to exceeding the safety margins utilized in component design.

Summary Discussion

At each of the TVP sites analyzed across the Midwest, high wind shear events were observed more frequently than anticipated in the turbine design standards and guidelines. Review of the turbine design standards and guidelines reveals that the current definitions of “external conditions” significantly underestimate the frequency and duration of extreme wind shear that is present in the Midwest. At several projects, the periods of prolonged high wind shear coincided with periods of high winds, suggesting that the effect of the wind shear could be more damaging than if it was occurring during periods of low winds. None of the design standards or guidelines address extreme wind shear as a fatigue issue.

Implications for Turbine Design and Operations

Although component failures in systems potentially affected by fatigue from high shear have occurred at all TVP projects, no conclusive correlation could be established between the high shear events and these component failures. At Big Spring, turbine fault time was observed to be more frequent during the hours of high wind shear, as shown in Figure 13. However, the fault time is influenced by many other factors, including increased wind speeds at night and slower operator response time. Although there seems to be a relationship between strong wind shear and fault time, it is not possible at this time to attribute faults to high shear with currently available data.

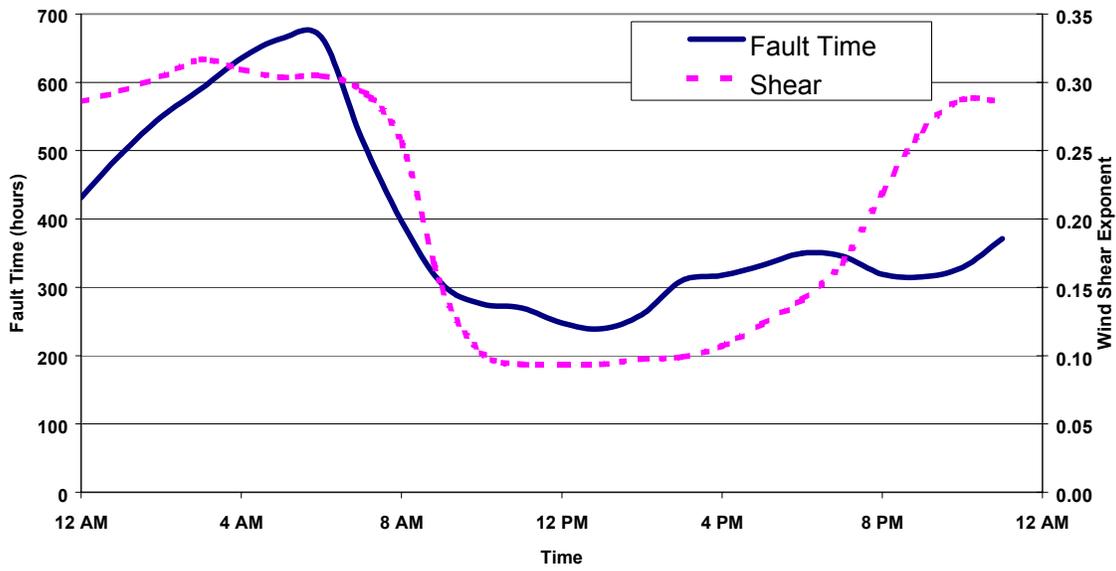


Figure 13. Diurnal Fault and Shear Patterns at Big Spring, Texas

More research and analysis is required to determine the most serious impacts of prolonged high shear in turbine components. Peak and fatigue load analysis of the major components under high shear conditions is needed; however, damaging harmonics could be excited by prolonged high wind shear within the turbine. Harmonics could result in excessive movement of drive train components or unanticipated vertical and lateral loads. Research into high wind shear should include collection of simultaneous wind, turbine fault and load measurements from conventional multi-megawatt turbines. At a minimum, wind speed measurements should be recorded at the rotor top, center, and bottom. High frequency sampling rates that are synchronized with load measurements would prove most useful. Nacelle and tower vibration measurements are also needed to assess drive train operating conditions.

The number of installed multi-megawatt turbines with rotor tips exceeding heights of 100 m has increased significantly during 2001, primarily in Texas. However, a significant data gap exists in the amount of wind speed, air temperature, and air pressure data available at heights greater than 50 m. Five or more dedicated 200 m towers (supplemented with existing tall communication towers where available) located in climatically different regions of the United States should be instrumented to collect the necessary atmospheric data. Tall towers located in areas where wind energy development already exists or is feasible would be the most likely choice. Any assessment of offshore wind resources should also consider collection of wind speed data up to top-of-rotor elevations.

Use of Doppler sonic detection and ranging (SODAR) systems to collect wind speed data at heights greater than 50 m has received a lot of interest in recent years; however, the data recovery tends to decrease with increasing height and their ability to accurately measure very high wind speeds has been questioned. Interferences such as precipitation also limit the usefulness of SODAR data at present. If these issues are researched and satisfactorily addressed, SODAR could be a significant tool in helping to perform cost-effective wind resource assessment at rotor heights. To perform such research, SODAR units should be deployed adjacent to instrumented tall communication towers to collect long-term wind speed and atmospheric stability measurements.

A turbulence model used to mathematically describe the high shear phenomenon for use within turbine design models does not exist. Existing turbulence models used by designers appear to be insufficient for conditions observed in the Midwest.

Due to their larger rotors and use of taller towers, multi-megawatt turbines will likely experience more time in harsh wind shear conditions than turbines with smaller rotors installed on 40- or 50-m towers. Manufacturers need to obtain a better understanding of the impacts associated with prolonged exposure to extreme shear and assess their design and control schemes. Utilizing hub-height (or greater) met tower data to detect the onset of extreme wind shear periods could be performed and interlinked with a project's SCADA system to allow automatic adjustment of the turbines' operation mode. The turbine control program could include a "safe mode" in which power production is maintained through the extreme shear event, although at a lower rating to reduce loads on the turbine.

Implications for Site Assessment, Project Development, and Energy Prediction

Project developers need to recognize the value associated with hub-height (or higher) wind resource assessment and provide analysis of wind shear to turbine manufacturers to obtain their guarantee of adequate turbine design for the site conditions. Not only should the IEC design classifications of a given turbine model be assessed and verified, but actual site wind conditions should be compared to the wind conditions identified in the corresponding IEC design classification. Discrepancies between site and design conditions should be documented and implications to the turbine design evaluated.

Wind shear analysis should be performed on a 10-minute average basis in addition to calculations of monthly and annual averages. Diurnal averages and frequency distributions of 10-minute average wind shear should be conducted to determine the frequency, timing, and magnitude of extreme wind shear events.

Initial site resource assessment activities should be performed for at least one year to ensure that any seasonal variations related to wind shear are observed. If only six or nine months of wind speed data are obtained at a particular site, extreme wind events may not be captured.

Energy estimates based on 40-m wind speed data that are shear adjusted to hub height may provide a good estimate of the annual energy production. However, this paper has shown that the timing of actual energy production during the day can be greater or less than that predicted by shear-adjusted 40-m wind speed data. This mischaracterization of the actual diurnal average energy pattern could create grid management problems, financial penalties, or reduce the value of wind energy if it is sold on the open market. Analysis of hub-height wind speed data would reduce such errors.

Conclusion

Prolonged periods of high wind shear, particularly when combined with frequent extreme shear events (i.e., shear exponents greater than 1), are of concern from a turbine design and project development standpoint. However, since high shear frequently implies high wind speeds at turbine hub heights, harnessing this high shear offers an opportunity to increase energy production (thereby lowering the cost of energy) provided that the turbines can successfully withstand long-term operations in such conditions. The nocturnal wind shear conditions that are present across the Midwest provide nighttime wind speeds that are greater than previously assumed. Increasing hub heights can provide access to these strong night winds. However, turbine designs need to take into account that conditions currently assumed to be extreme, rare events may actually be normal occurrences.

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13. ABSTRACT (Maximum 200 words) The U.S. Department of Energy-Electric Power Research Institute (DOE-EPRI) Wind Turbine Verification Program (TVP) has included several wind energy facilities in the Midwestern United States. At several of these projects, a strong diurnal shear pattern has been observed. During the day, low and sometimes negative shear has been measured. During night hours, very high positive shear is frequently observed. These high nighttime shear values are of concern due to the potential for high stresses across the rotor. The resulting loads on turbine components could result in failures. Conversely, the effects of high nighttime wind shear could benefit wind generated energy production in the Midwest by providing a source of greater hub-height wind speeds, particularly for multi-megawatt turbines that utilize tall towers. This paper presents an overview of the observed wind shear at each of the Midwest TVP projects, focusing on diurnal patterns and the frequency of very high nighttime shear at the sites. Turbine fault incidence is examined to determine the presence or absence of a correlation to periods of high shear. Implications of shear-related failures are discussed for other Midwest projects that use megawatt-scale turbines. In addition, this paper discusses the importance of accurate shear estimates for project development.			
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