Influence of Meteorological Variables on Measured Wind Turbine Power Curves

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Summary:
The influence of meteorological variables on measured power curves of multi megawatt wind turbines (WT's) has been investigated in the frame of certification measurements. The three investigated WT's are of type Enercon E-112 (6.0 MW and 4.5 MW rated power, 124 m hub height) and Enercon E-70 E4 (2.3 MW rated power, 65 m hub height) and are located in flat terrain.

At all three machines large effects of the turbulence intensity are observed. The measured power coefficients increase significantly with increasing turbulence intensity below rated power and decrease significantly with increasing turbulence intensity in the transition region to rated power. The effect has the same magnitude at all three investigated WT's.

After isolating turbulence and wind shear effects, nearly no effect of the vertical wind shear remains at the Enercon E-112 machines. At the Enercon E-70 E4 a significant wind shear effect is observed with the power coefficient decreasing with increasing wind shear below rated power. This is believed to be due to the low hub height of the investigated turbine.

A new approach for normalising the power curve data to a target turbulence intensity in respect to the effect of averaging the power curve data over 10-minutes has been developed. This Normal Distribution Model is capable to model the time averaging effect also at high turbulence intensities and in the transition region to rated power. It turns out that only a small part of the observed turbulence effects can be explained by the time averaging effect.

1 Introduction

The reported work is aimed to better understand the site dependency of wind turbine power curves and to further develop the procedures to measure and describe wind turbine power output characteristics, especially in the case of multi-megawatt machines.

The present standard for power curve testing IEC 61400-12-1 [1] describes the power curve of a wind turbine on the basis of the wind speed measured at hub height at one position in a distance of 2-4 rotor diameters of the wind turbine (WT) and averaged over a period of 10 minutes. This procedure is in use since about two decades and has formerly been developed with wind turbines in mind, which were an order of magnitude smaller than today's utility scale machines. Principle shortcomings of the procedure are:

- The wind speed is measured only at hub height. The question arises in how far this point measurement represents the wind conditions incident to the rotor of multi-megawatt machines, which covers an area in the size of a soccer field.
- Apart from the air density, no other secondary variables are taken into account for the evaluation of the measurements. However, there are investigations indicating the importance of such secondary variables like the turbulence intensity, the vertical wind speed gradient, the atmospheric stability, the vertical wind direction veer and the vertical flow inclination [2], [3], [4], [5], [6], [7], [8].
- At multi-megawatt turbines the distance between the wind turbine and the wind measurement of 2-4 rotor diameters is in the same range than the turbulence lengths scale of a few hundred meters. It is in question, how far the measured power curve is influenced by the travelling time and the large distance between the mast and the WT.

The performed work tackles part of these questions.

2 Measurements

The investigations are based on power curve measurements with the purpose of wind turbine type certification at two WT's of type Enercon E-112 with 6.0 MW and 4.5 MW rated power and 124 m hub height and one turbine of type Enercon E-70 E4 with 2.3 MW rated power and 65 m hub height. All investigated machines are gearless and have variable speed, pitch control and fully synchronous generators.

The measurement sites are characterised by flat terrain. The 6.0 MW-version of the Enercon E-112 (114 m rotor diameter) has been measured directly at the German North Sea shore near the city Emden. In the measurement sector the wind is coming mainly over the sea. The 4.5 MW-version of the Enercon E-112 (112.8 m rotor diameter) has been measured at the German inlands near the town Egeln. At the site Egeln a higher average turbulence intensity and vertical wind speed gradient is present than at the site Emden. The Enercon E-70 E4 (71 m rotor diameter) has been measured near the German North Sea Coast in flat terrain. Due to the lower hub height, this turbine is exposed to a higher average vertical wind speed gradient than the investigated E-112 turbines.

All measurements have been performed according to the IEC-standard 61400-12(-1). In addition to cup anemometers mounted at hub height, cup anemometers were also available near the lower rotor tip in case of the Enercon E-70 E4 (31 m measurement height) or near the hub height minus 2/3 of the rotor radius in case of the Enercon E-112 machines (83 m to 84 m measurement height). All cup anemometers are of type Thies First Class or Vector A100 X and have been calibrated according to MEASNET [9] and DKD. No site calibration has been performed prior to the power curve tests because of the flatness of the terrain and the open appearance of the measurement sites.

Only such operating periods without any changes of the wind turbines have been evaluated. The amount of measurement data available for the power curve analysis is shown in Table 1.

Site	Emden	Egeln	Westdorf
WT	E-112 6.0 MW	E-112 4.5 MW	E-70 E4 2.3 MW
Data Sets Available for Turbulence Classification	4697	3968	2527
Data Sets Available for Wind Shear Classification	4697	1608	2527

Table 1: number of 10-munte periods available from each measurement site

3 Data Analysis

The primary analysis has so far been put on the effect of the turbulence intensity and the vertical wind speed gradient (in the following called vertical wind shear) on the measured power curves. For this purpose the measurement data has been classified either only according to the measured turbulence intensity, or only according to the vertical wind shear as measured in the lower rotor half, or according to both variables. Then power curves have been evaluated within each data class in accord to the standard IEC 61400-12-1, and the bin-averaged power curves of the different data classes have been compared in order to evaluate the influence of different variables. For comparison, a reference power curve has also been evaluated for each wind turbine on the basis of the complete available data. This would be the normal power curve resulting from the power curve test in accord to IEC 61400-12-1. In addition, the dependency between the two variables turbulence intensity and vertical wind shear has been analysed. All compared power curves have been interpolated to the same central wind speed bins by means of linear interpolation.

The data classes have been chosen as compromise between available data and a high resolution of each variable. For a classification only according to the turbulence intensity the turbulence classes 0-5 %, 5-10 % and 10-15 % have been chosen. The turbulence intensity has been evaluated as ratio of the standard deviation and average wind speed within each 10-minute period on the basis of the measurements with the cup anemometer at the top of the met masts. No trend correction or correction for the data sampling rate has been applied.

The vertical wind shear has been defined from the wind speed measurements at hub height and the lower measurement height as follows:

$$G = \frac{v_H - v_z}{\frac{v_H + v_z}{2} \cdot (H - z)}$$

with

G: wind shear with dimension [1/m]

v_H: wind speed at hub height H

v_z: wind speed at lower height z.

A vertical wind shear of 0.001 1/m means an increase of the wind speed of 1 % over a height difference of 10 m. The definition has the advantage to provide comparable values for different heights above ground, for different height differences and to be independent from any assumed shape of the wind speed profile. The classes of the wind shear used for the data classification are shown in Table 2.

As expected, the analysis of the relation between the vertical wind shear and the turbulence intensity has shown a tendency of the vertical wind shear to decrease with increasing turbulence intensity (decreasing atmospheric stability) and vice versa. This relation is shown in Figure 1 for all three test sites. In order to be able to distinguish between turbulence effects and wind shear effects, a classification according to both variables has been performed in addition to the classification in accord to only one variable. For the analysis of the isolated turbulence effect / wind shear effect the power curve data has first been filtered to a small range of wind shear / turbulence intensity, and the remaining data has then been classified in accord to the turbulence intensity /wind shear. The applied data filtering and choice of data classification is given in the lower two rows of Table 2.

Site		Emden	Egeln	Westdorf
WT	[-]	E-112 6.0 MW	E-112 4.5 MW	E-70 E4 2.3 MW
turbulence classes (non-isolated analysis)	[%]	0-5, 5-10, 10-15	0-5, 5-10, 10-15	0-5, 5-10, 10-15
shear classes (non-isolated analysis)	[1/m]	0.000-0.002 0.002-0.004 0.002-0.006	0.000-0.002 0.002-0.004 0.002-0.006	0.000-0.0035 0.0035-0.007 0.007-0.0105
turbulence classes (shear fixed)	[%]	0-5, >5 (shear 0.000-0.002 1/m)	0-9, >9 (shear 0.002-0.004 1/m)	0-10, >10 (shear 0.0035-0.007 1/m)
shear classes (turbulence fixed)	[1/m]	0.000-0.002 >0.002 (turbulence 5-10%)	0.000-0.004 >0.004 (turbulence 5-10%)	0.000-0.005 >0.005 (turbulence 7.5-12.5%)

Table 2: chosen data classification

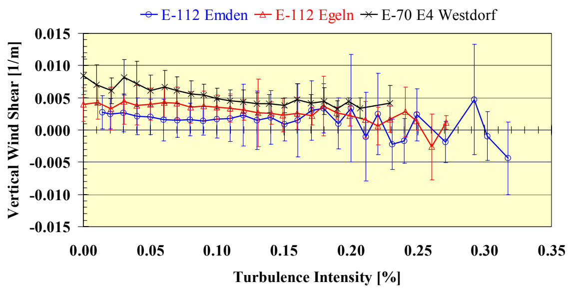

Figure 1: Relation between the vertical wind shear and the turbulence intensity. The lines show the bin averages and the bars denote the standard deviation per bin.

4 Results of Turbulence Analysis

All investigated turbines have shown a clear increase of the power output with increasing turbulence intensity below rated power and a decrease of power output with increasing turbulence intensity in the transition region to rated power. Similar results have been reported also in former investigations [2], [6], [7]. The effect is shown at the example of the Enercon E-112 6.0 MW as measured at the site Emden in Figure 2. At all three investigated WT's the turbulence effect does not significantly change its magnitude by the pre-filtering of the measurement data according to the vertical wind shear, i.e. by the isolation of the turbulence effect from possible wind shear effects. This is illustrated again in the example of the Enercon E-112 6.0 MW as measured in Emden in Figure 3.

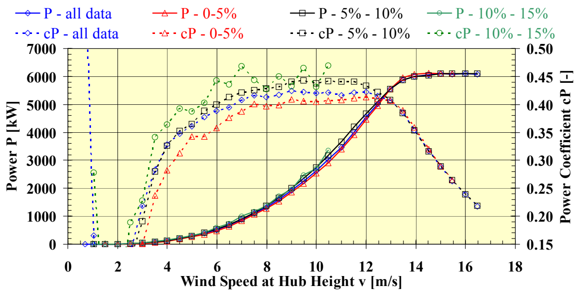

Figure 2: Effect of the turbulence intensity on the power curve measured at the E-112 6.0 MW in Emden (turbulence and wind shear effects not isolated).

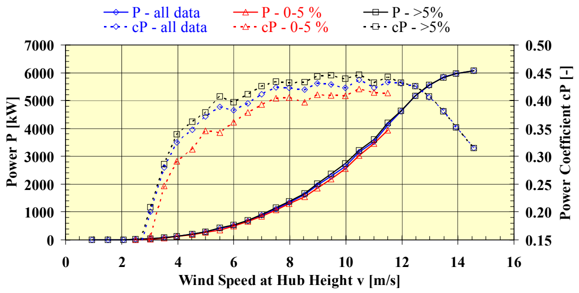

Figure 3: Effect of the turbulence intensity on the power curve measured at the E-112 6.0 MW in Emden after isolation of the turbulence effect from possible wind shear effects.

For each turbine the uncertainty of the comparison of the power curves of different turbulence classes has been evaluated. For this, it has been assumed that the category B uncertainties (systematic uncertainties) of the power curve measurements cancel out if the difference of power curves at the same machine is calculated, while it has been assumed that the category A uncertainties (statistical uncertainties) of the to be compared power curve measurements are independent from each other. Then, the probability that one power curve measured at a certain WT exceeds a power curve from another data class of the same WT can be calculated. This evaluation is shown in Figure 4 in case of the Enercon E-70 E4. The results shown in Figure 4 are related to the case of an isolation of the turbulence effect from a possible wind shear effect, i.e. the measurement data has been pre-filtered in accord to the vertical wind shear. The power curve evaluated for the high turbulence class exceeds the power curve resulting from all turbulence data below rated power with a probability of almost 100 %. In contrast, the power curve evaluated for the low turbulence class exceeds the power curve resulting from all turbulence data below rated power by a probability of almost 0 %. The opposite cases are present in the transition region to rated power. This result has been observed at all three machines. Thus, despite the statistical uncertainties, no doubts about the turbulence effects are present.

In Figure 5 the relative deviation of the power curves evaluated in the turbulence class 10-15 % and 0-5 % are shown for all three investigated WT's. At all three machines the turbulence effect has the same order of magnitude. The same has also been observed by comparisons of power curves from other turbulence classes. As a rule of thumb it can be concluded that the power output as evaluated from power curve measurements increases by 1-2 % per percent increase of the turbulence intensity in the wind speed range below rated power (wind speed range around maximum cp).

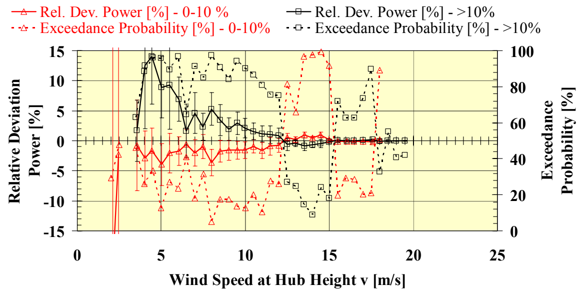

Figure 4: Relative deviation of the power curves of the Enercon E-70 E4 for the high turbulence class (I>10%) compared to the power curve from all data and of the low turbulence class (I<10%) compared to the power curve from all data. The turbulence effects have been isolated from a possible wind shear effect. In addition, the probability that the power curves exceed the power curve from all data is shown.

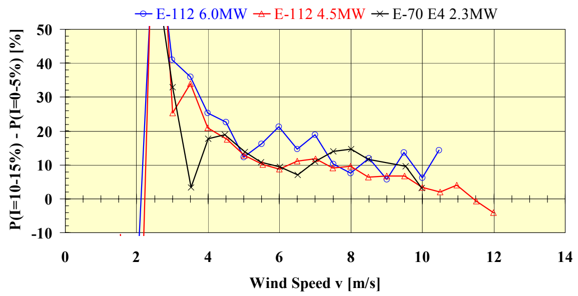

Figure 5: Relative deviations of power curves evaluated in the turbulence class 10-15 % and 0-5 %. The turbulence effect on the measured power curves has the same order of magnitude at all three investigated WT's.

5 Results of Vertical Wind Shear Analysis

Significant effects of the vertical wind shear appear at all three investigated WT's if the power curve data is not pre-filtered in accord to the turbulence intensity, i.e. if the wind shear effects are not isolated from turbulence effects. Then, a decrease of power output is observed with increasing vertical wind shear below rated power, while the opposite effect appears in the transition region to rated power. An example is given for the Enercon E-112 6 MW in Emden in Figure 6.

It is noted that at the 3 MW Aeolus II turbine the opposite effect of vertical wind shear has been observed [2]. There, an increase of power output with increasing shear below rated power has been observed. The reason for this opposite behaviour is not known. However at the Aeolus II the wind shear has been determined over the complete rotor area, while at the three investigated Enercon machines the wind shear has been measured only in the lower half of the rotor.
At the two investigated WT's of type Enercon E-112 the wind shear effect nearly vanishes, if it is isolated from the turbulence effect. This is shown for the example of the Enercon E-112 6.0 MW in Emden in Figure 7 and Figure 8. It is concluded that at the two investigated Enercon E-112 turbines no significant true wind shear effect on the power curve is present. The appearance of such an effect, without pre-filtering of the power curve data in accord to the turbulence intensity, can be understood by the fact that the vertical wind shear in tendency decreases with increasing turbulence intensity and that the appearing effect of increasing power output with decreasing wind shear below rated power is thus in reality mainly an effect of the turbulence intensity on the power curve.
However, at the investigated Enercon E-70 E4 a clear effect of the vertical wind shear on the power curve remains even after isolation from the turbulence intensity effect (Figure 9). This may be linked to the fact that at this machine significantly higher vertical wind shears are present than at the two investigated Enercon E-112 machines (Figure 1).

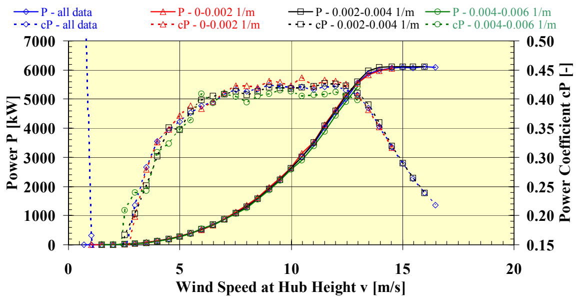

Figure 6: Effect of the turbulence intensity on the power curve measured at the E-112 6.0 MW in Emden (turbulence and wind shear effects not isolated)

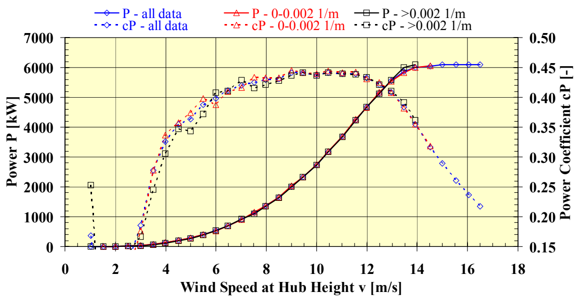

Figure 7: Effect of the vertical wind shear on the power curve measured at the E-112 6.0 MW in Emden after isolation of the wind shear effect from the turbulence effect.

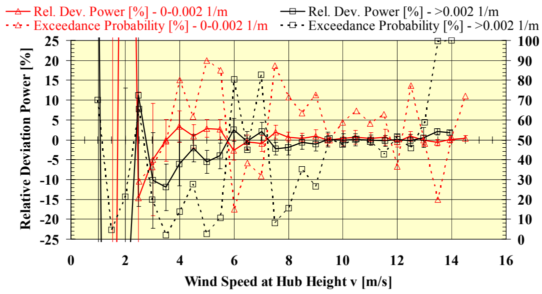

Figure 8: Relative deviation of the power curves of the Enercon E-112 6.0 MW for the high wind shear class (G>0.002 1/m) compared to the power curve from all data and of the low wind shear class (G<0.002 1/m) compared to the power curve from all data. The wind shear effects have been isolated from the effect of the turbulence intensity. In addition, the probability that the power curves exceed the power curve from all data is shown.

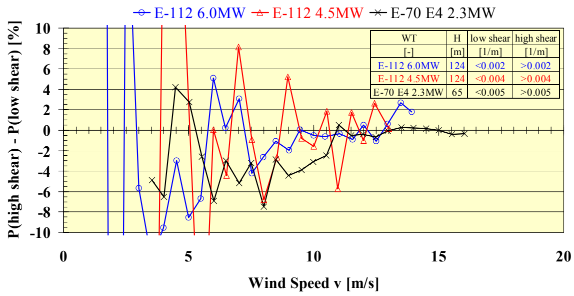

Figure 9: Relative deviations of power curves evaluated in two different classes of the vertical wind shear for all three investigated WT's. The wind shear effects have been isolated from the turbulence effects by pre-filtering the measurement data to a small band of turbulence intensities. A clear effect of the vertical wind shear is present only at the Enercon E-70 E4.

6 Normalisation of Power Curves According to the Turbulence Intensity

Due to the non-linear dependency of the power output on the wind speed the 10-minute averaging of power curve measurement data leads to a shift of measured power curves to higher power outputs where the power curve is left-curved (at lower wind speeds around maximum cp) and to lower power outputs where the power curve is right-curved (at wind speeds in the transition region to rated power). Similar power curve properties have been observed also at the three considered test WT's (see chapter 4). Hence, the question arises how much of the turbulence effects observed at the Enercon E-112 and the Enercon E-70 can be explained by the 10-minute averaging of power curve measurement data.

Taylor-Series Approach

A simple estimation of the averaging effect has first been given in reference [2] based on a Taylor-series of the power curve:

$$\overline{P(v)} = P_{I=0}(\overline{v}) + \frac{1}{2}\frac{d^2 P_{I=0}(\overline{v})}{dv^2}\sigma_v^2 \qquad (1)$$

with

$\overline{P(v)}$: power output at turbulence intensity I averaged over 10 minutes

$P_{I=0}(\bar{v})$: power output at turbulence intensity I=0 averaged over 10 minutes

σ_v: standard deviation of wind speed within 10-minute period

$\bar{v}$: average wind speed within 10-minute period

Within this work, this formula has been applied for the normalisation of the power curve raw data to a pre-defined target turbulence intensity I_{target} in the following way:

- The formula is equal to the expression:

$$\overline{P_{I_{target}}(v)} = \overline{P(v)} + \frac{1}{2}\frac{d^2 P_{I=0}(\bar{v})}{dv^2}\bar{v}^2\left(I_{target}^2 - I^2\right)$$

  Where I is the measured turbulence intensity $\sigma_v / \bar{v}$.
- All measures within this formula are known for each 10-minute period, except of the second derivative of the power curve at zero turbulence intensity.
- Thus, first a power curve without turbulence normalisation has been evaluated. The second derivative of this power curve is calculated for each wind speed bin as a first approximation of the second derivative of the power curve at zero turbulence intensity.
- With this approximation the above formula has been applied in order to normalise the measured power for each 10-minute period to zero turbulence intensity. The zero turbulence power curve has been bin-averaged.
- Then, the second derivative from the so gained zero turbulence power curve has been calculated, and the data normalisation of the uncorrected power curve data to zero turbulence has been repeated.
- The last two steps have been repeated until the zero turbulence power curve converged. For all three tested WT's a good convergence has already been gained by the first iteration step. I.e. it has been found that the second derivative of the non-zero turbulence power curve is a sufficient approximation for the second derivative of the zero turbulence power curve.
- Finally, the formula has been applied for the normalisation of raw data to a pre-defied (wind speed dependent) target turbulence intensity.

It is noted that this procedure normalises the power curve data only in respect to the effect of the data averaging over 10-minute periods. In reference [6] and [7] other applications of the Taylor-Series Approach are described, where more or less the dependency of the power curve on the wind speed standard deviation within single wind speed bins is directly fitted by second order polynomials. These applications are well suited to describe or normalise the complete effect of the turbulence intensity on measured power curves, but they do not allow distinguishing between the effect of data averaging over 10 minutes and other possible turbulence effects.

Normal Distribution Model

A new approach for the determination of the effect of the data averaging over 10-minute periods on the measured wind turbine power curves has been developed. This so-called Normal Distribution Model is based on the following assumptions:

- It is assumed that the wind speed follows a Gaussian wind speed distribution within each 10-minute period. This wind speed distribution is determined by the measured average wind speed and standard deviation of wind speeds within each 10-minute period.
- It is assumed that the wind turbine follows during each instant always the same power curve, the zero turbulence power curve. This power curve is assumed to be independent of the turbulence intensity.

These two assumptions allow calculating the effect of the 10-minute averaging on the measured power curve by integrating the zero turbulence power curve over the Gaussian wind speed distribution.

$$\overline{P(v)} = \int_{t=0s}^{t=600s} P_{I=0}(v) \cdot f(v) dv \qquad (2)$$

with

$\overline{P(v)}$: power output at turbulence intensity I averaged over 10 minutes

$P_{I=0}(v)$: zero turbulence power curve

$f(v)$: Gaussian wind speed distribution as determined by the standard deviation of wind speed σ_v and the average wind speed $\bar{v}$ within the 10-minute period

It is noted that the Normal Distribution Model does not take into account any relaxation of the power output, which may be caused by inertia effects of the wind turbine, the control algorithm of the wind turbine or the spatial averaging of turbulence over the rotor area.

the following scheme has been followed for the normalisation of power curve measurement data to a pre-defined target turbulence intensity with the Normal Distribution Model:

- An initial zero turbulence power curve has been gained from the measured power curve (at non-zero turbulence) by the following condition: The bin-averaged measured power curve should result from the zero turbulence power curve by the application of formula (2) for each wind speed bin, while the Gaussian wind speed distribution is determined by the average measured wind speed and the average measured turbulence intensity per bin. The zero turbulence power curve has been determined from this condition for each of the three investigated wind turbines by the application of a Newton solver. The resulting initial zero turbulence power curves are shown for the three considered test turbines in Figure 10. At two of the investigated turbines a clear edge at the transition from below rated power to rated power appears like expected (at the third turbine a relatively sharp corner). In addition, at all three turbines the modelled power output above rated wind speed and zero turbulence is slightly higher than the measured power output, what is also expected due to the presence of turbulence during the measurements. The initial zero turbulence power curves are not very smooth, what is a result of the complicated problem to be solved by the Newton solver. However, a smoothing of the zero turbulence power curves is reached by the next two steps.
- A new zero turbulence power curve has been determined by normalising the power curve raw data to the turbulence intensity of 0 % by the application of formula (2) with the initial zero turbulence power curve. The new zero turbulence power curve is then determined by bin averaging the so normalised raw data.
- This last evaluation step has been repeated until the zero turbulence power curve converged. For all three tested WT's a good convergence has already been gained after the first iteration step.

- Finally, formula (2) has been applied for the normalisation of the raw data to a pre-defied (wind speed dependent) target turbulence intensity.

In Figure 11 the power curve measured at the Enercon E-112 6.0 MW without turbulence filtering (average turbulence intensity about 6 %) is compared to the normalised power curves for 0 % and 10 % turbulence intensity using the Normal Distribution model and the Taylor-Series Approach (only normalisation to 10% shown). The turbulence normalisation predicts the observed turbulence effect qualitatively well (increase of power output below rated power with increasing turbulence intensity, opposite effect in the transition region to rated power). In addition, the turbulence normalisation by the application of the Normal Distribution Model agrees very well with the turbulence normalisation according to the Taylor-Series Approach if the target turbulence intensity does not deviate very much from the measured turbulence intensity. This changes, if the deviation of the measured turbulence intensity and the target turbulence intensity is large. In Figure 12 an extreme case is shown where the power curve raw data is of the Enercon E-112 6.0 MW is normalised to 20 % turbulence intensity. The Normal Distribution Model delivers plausible raw data even for such extreme turbulence normalisations. However, the Taylor-Series Approach here generates implausible data near the transition region to rated power, what is probably caused by the fact that the second order polynomial approach of the zero turbulence power curve power curve as applied at the Taylor-Series Approach is not valid in the wind speed range around rated wind speed.

The turbulence normalisation in respect to the data averaging over 10-minute periods does only explain a part of the observed turbulence effects. The true effect of the turbulence intensity on the measured power curves is larger. This is illustrated for the example of the E-112 4.5 MW in Egeln in Figure 13, where the power curve measured in the turbulence range 0-5 % is compared the power curve normalised to this turbulence range. The raw data normalisation has been done to exactly the wind speed dependent measured turbulence intensity in the range 0-5 %. It is shown that the 10-minute averaging effect is qualitatively in agreement with the observed turbulence effect, but the observed turbulence effect on the power curve is by a factor of about 2 higher. This observation is in agreement with the findings reported in reference [7].

The results gained in accord to the turbulence normalisation were the same at all three investigated WT's.

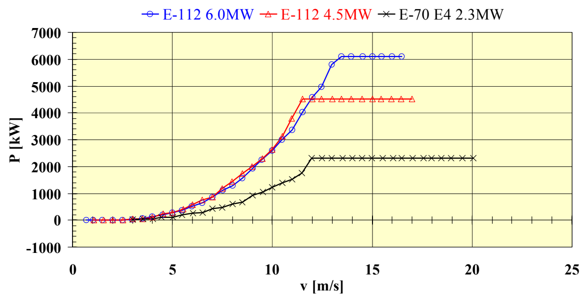

Figure 10: Initial zero turbulence power curves of the three investigated wind turbines as gained from the initialisation of the Normal Distribution Model.

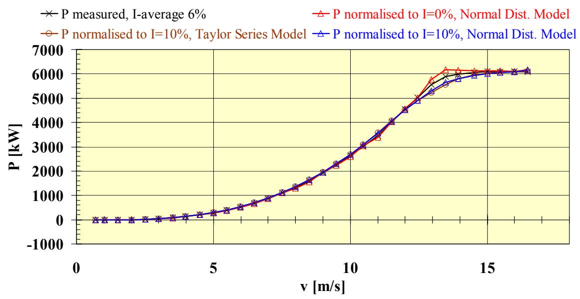

Figure 11: Turbulence normalisation of the power curve measured at the E-112 6.0 MW in Emden. Shown are the power curve measured at an average (wind speed dependent) turbulence intensity of about 6 % (black), the power curve normalised to 0 % turbulence intensity and 10 % turbulence intensity by means of the Normal Distribution Model and the power curve normalised to 10 % turbulence intensity by means of the Taylor-Series Approach.

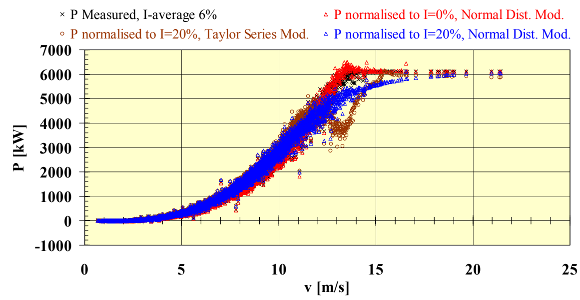

Figure 12: Turbulence normalisation of the power curve raw data measured at the E-112 6.0 MW in Emden to a high target turbulence intensity of 20 % by means of the Normal Distribution Model and the Taylor series Approach.

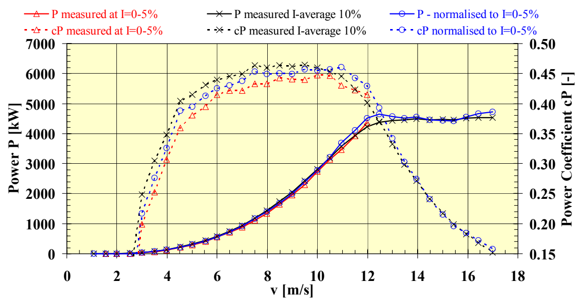

Figure 13: Comparison of the power curve of the Enercon E-112 4.5 MW in Egeln measured in the turbulence intensity range 0-5 % (red) and normalised to the turbulence intensity 0-5 % (wind speed dependent). The normalisation is based on the unfiltered power curve data, which has an average turbulence intensity of about 10 % (black curve).

7 Conclusions

The following conclusions can be drawn from the reported work:

- The measured power curves of the three investigated WT's of type Enercon E-112 6.0 MW, Enercon E-112 4.5 MW and Enercon E-70 E4 are significantly influenced by the turbulence intensity. In tendency the power output increases with increasing turbulence intensity at lower wind speeds (in the range of maximum cp-values) and decreases with increasing turbulence intensity in the transition region to rated power.

- The effect of the turbulence intensity on the measured power curves has the same order of magnitude at all three investigated machines. The increase of the power output in the wind speed around the maximum cp is about 1-2 % per percent increase of turbulence intensity.
- The effect of the turbulence intensity on the measured power curves is described qualitatively well by the effect of the 10-minute averaging on the power curve data. However, the observed effect of the turbulence intensity is significantly larger than the effect of the 10-minute averaging. Thus, other turbulence effects than the averaging over 10-minute periods must occur at the investigated WT's.
- A new model for the normalisation of measured power curves to a target turbulence intensity in accord to the effect of the 10-minute averaging has been introduced. In contrast to the older Taylor-Series Approach, this Normal Distribution Model is also capable to normalise the measured power curve data to extreme turbulence intensities.
- At all investigated turbines the power output below rated power has been found to decrease with increasing vertical wind shear. This observation is partly due to the tendency of the wind shear to increase with decreasing turbulence intensity. After isolating the wind shear and turbulence effects a significant effect of the vertical wind shear in the power output remains only at the smallest investigated turbine of type Enercon E-70 E4. At this turbine the vertical wind shear is higher than at the other two observed machines due to the much lower hub height of 65 m instead of 124 m.

8 Acknowledgement

Thanks belong to Enercon for funding the reported work and to give permission to present results from the measurements of different wind turbine prototypes.

9 References

[1] IEC 61400-12-1, Wind turbines, Part 12-1: Power performance measurements of electricity producing wind turbines, 2005

[2] A. Albers, C. Hinsch, H. Klug, D. Westermann; Einfluss verschiedener meteorologischer Parameter auf das Leistungsverhalten großer Windenergieanlagen, Tagungsband Deutsche Windenergiekonferenz 1996, Wilhelmshaven

[3] R. Hunter, T. F. Pedersen, P. Dunbabin; I. Antoniou; S. Frandsen, H. Klug, A. Albers, W. K. Lee; European Wind Turbine Testing Procedures, Task 1: Measurement Method to Verify Wind Turbine Power Performance Characteristics, Report Riso-R-1209(EN), Riso National Laboratory, Roskilde, January 2001

[4] I. Antoniou, F. Mouzakis, A. Albers, U. Follrichs, T. Curvers, H. Verhoef, P. Enevoldsen, J. Hojstrup, L. C. Christensen; Identification of Variables for Site calibration and Power Curve Assessment in Complex Terrain, proceedings of EWEC 2001, Copenhagen, p. 17-22

[5] T. F. Pedersen, S. Gjerding, P. Ingham, P. Enevoldsen, J. K. Hansen, H. K. Jorgensen; Wind Turbine Power Performance Verification in Complex Terrain and Wind Farms, Report Riso-R-1330(EN), Riso National Laboratory, Roskilde, April 2002

[6] K. Kaiser, H. Hohlen, W. Langreder; Turbulence Correction for Power Curves, proceedings of EWEC 2003, Madirid

[7] H. van Radecke; Turbulence Correction of Power Curves, DEWI-Magazin 24, February 2004, p. 56-62

[8] P. J. Ecen, F. Mouzakis, A. Cuerva; Accuwind Work Package 3 Final Report, Report ECN-C--06-047, ECN Energy Research Centre of the Netherlands, May 2006

[9] MEASNET, Cup Anemometer Calibration Procedure, 1997