Dependence of Power Performance on Atmospheric Conditions and Possible Corrections

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Abstract

The dependence of the power curve on atmospheric conditions like air density, temperature, turbulence and vertical wind shear is investigated. For this a 2.5MW ECN research turbine and a nearby meteo mast on ECN's test field are considered. It is shown that all mentioned atmospheric conditions have effect on either the power curve itself or on the standard deviation of the power.

Correction with respect to air density, as is prescribed by IEC 61400-12-1, and turbulence have been shown to be effective with respect to the standard deviation of the power for (most) interesting wind speeds. Both corrections cause the power to be lower than the uncorrected power.

Based on a power law profile, two vertical wind shear corrections are examined and they both, basically, show the same result. For most (interesting) wind speeds the standard deviation of the power is decreased, but for some wind speeds an increase of the standard deviation is seen. The power itself is increased, due to the correction.

A so-called rotor averaged wind speed, based on wind speed measurements at multiple heights, is examined to also correct for wind shear. The effect of this correction with respect to the standard deviation of the power is shown to be small for the ECN research turbine. Also in this case the power itself is increased with respect to the uncorrected power.

Keywords: Power performance, power corrections, atmospheric conditions, air density, turbulence, vertical wind shear

1. Introduction

The UpWind project (see www.upwind.eu) is a European research project, funded under the EU's Sixth Framework Programme (FP6), that focuses on the necessary up-scaling of wind energy in 2020. Among the problems that hinder the development of wind energy are measurement problems. For example: to experimentally confirm a theoretical improvement in energy production of a few percent of a new design by field experiments is very hard to almost impossible. As long as convincing field tests have not confirmed the actual improvement, industry will not invest to change turbine design. The objective of the Metrology work package (1A2) is to develop metrology tools in wind energy to significantly enhance the quality of measurement and testing techniques.

One of the subjects taken up within the Metrology work package is the power performance of wind turbines. This work focuses on the analyses of the largest sources of uncertainties in power performance testing. It is known that the power performance of a wind turbine depends on atmospheric conditions as for instance the air density. The IEC regulations for power performance [1] already include an air density correction. Besides that it is also known that other atmospheric conditions play a role as well, such as turbulence and wind shear, which was already noticed in [2] [3] [4] [5] [6]. Corrections for turbulence and wind shear have been suggested and have been shown to be effective.

We examine the power performance of a 2.5MW turbine on the ECN test field on those atmospheric conditions. This is done in section 2, where the dependence of the power performance on the air density (, temperature), stability, turbulence and vertical wind shear is examined. Corrections for these effects are studied in section 3 and the results are concluded and discussed in section 4. The work is closely related to the work in the MT12 maintenance team.

2. Dependence of Power Performance on Atmospheric Conditions

Data are taken from the test field of ECN, the ECN Wind Turbine Test station Wieringermeer (EWTW) [7] [8]. It is located in the North East of the Province 'Noord-Holland', 1 - 2km West of the lake 'IJsselmeer'. The test site and its surroundings are characterised by flat terrain.

Among others, the test field consists of 5 research turbines named T5 - T9. They have a hub height (H) of 80m, a rotor diameter (D) of 80m and a rated power of 2.5MW. A meteo mast measures wind speed and wind direction at 52m, 80m (hub height) and 108m. From now on, if not mentioned differently, the wind speed and direction always refers to the wind speed and direction at 80m. Also measured are temperature, temperature difference and pressure. Turbines T5 and T6 are suitable to perform power performance measurements [1]. Data from the turbines and the meteo mast have been gathered since 2004. These data involve 10 minute statistics as for instance mean and standard deviation.

For the analysis turbine T6 is used, which is at a distance of 2.5D from the meteo mast. For the entire period of about 6 years of data taking power curves are constructed, either by using scatter data or by using binned values according to IEC regulations [1]. They are given in Figure 2.1. For the scatter data no data selection, other than required for IEC 61400-12-1 [1], has been applied.

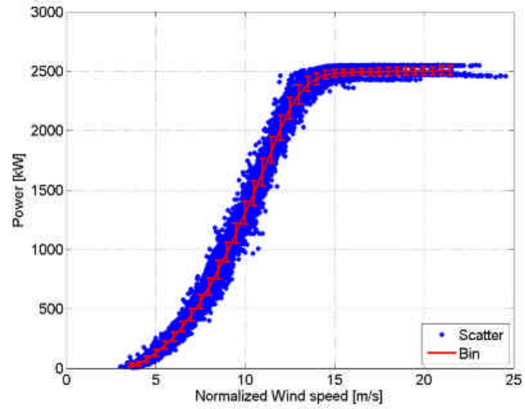

Figure 2.1 *Power curve for turbine T6.*

We note the three 'tails' in Figure 2.1 for wind speeds above 15m/s. In the remainder different (sub) data sets will be considered and the distribution of the data points for wind speeds above 15m/s over the three 'tails' may be different from one situation to another. This influences the standard deviation of the power. Therefore, when comparing standard deviations of the power, wind speeds above 15m/s are not considered in this paper.

Because of the huge database it is possible to select data based on certain atmospheric conditions to see whether the power curve depends on these conditions. The atmospheric conditions considered are air density, temperature, atmospheric stability, turbulence and vertical wind shear.

2.1 Air density

The power that a turbine can extract from a volume of wind is [9]

$$P = \frac{1}{2} \cdot c_p \cdot A \cdot \rho \cdot U^3 \quad , \qquad (1)$$

where U is the horizontal wind speed, A is the rotor swept area, ρ is the air density and c_p is the power coefficient. P is the power. Clearly, the power depends on the air density and therefore also the power curve does. The air density values encountered at the site[1] are mostly between 1.20 kg/m^3 and 1.27 kg/m^3 and the mean value is 1.237 kg/m^3.

Power curves for various values of the air density can clearly be distinguished. The maximum difference with the power curve for all densities occurs for the power curve for

[1] The air densities encountered are extracted from the same data set as used for the power performance. This will also be the case for the other atmospheric quantities.

ρ=1.205 kg/m³. This difference is at most 4% for (unnormalized) wind speeds above 5m/s.

Also for different values of temperature power curves can be distinguished. However, because the air density is calculated from temperature (and pressure) measurements, it is obvious that the two are related. This is also reflected in the power curves.

2.2 Stability

The stability of the atmosphere is determined by means of the environmental lapse rate:

- *-dT/dh < 6K/km* = stable atmospheric conditions
- *6K/km < -dT/dh < 10K/km* = conditionally unstable atmospheric conditions
- *-dT/dh > 10K/km* = unstable atmospheric conditions,

where T is the temperature and h is the height. The lapse rate is determined using the temperature difference instrument, which measures the temperature difference between a height of 37m and 10m. It is observed that unstable conditions happen the most during daytime and during summer. For stable conditions the opposite is valid. The frequency of occurrence of stable conditions is about 7 times higher than that for conditionally stable or unstable conditions.

Power curves for stable, unstable and all atmospheric conditions have been constructed and, generally, the differences between the various power curves are small. For wind speeds above, say, 6m/s the difference between the power for all atmospheric conditions and stable conditions and the between the power curve all atmospheric conditions and unstable conditions is lower than about 2%.

More interesting are the differences in the standard deviation of the power. We consider the wind speed range 4m/s - 13m/s and see that the standard deviation for unstable conditions is up to 50% larger than the standard deviation for all conditions, as can be seen in Figure 2.2. Furthermore the standard deviation for stable conditions is smaller (~10%) than the standard deviation for all conditions.

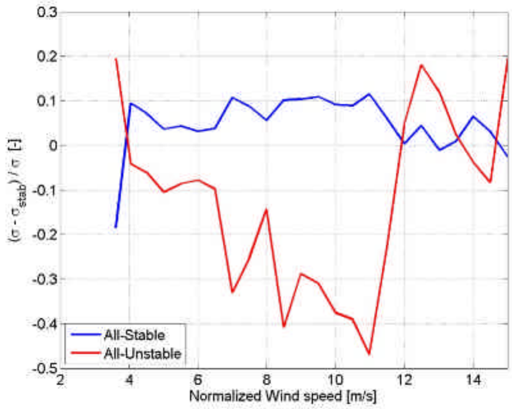

Figure 2.2 *Relative difference in standard deviation of the power for stable and unstable conditions.*

2.3 Turbulence

The turbulence intensity is defined as [2]

$$TI = \frac{\sigma_U}{U}, \qquad (2)$$

where σ_U is the standard deviation of the wind speed. It is observed that most values are between 2% and 12% and the mean is 8.1%. It is also seen that the TI is somewhat higher during daytime.

From the power curves for different turbulence intensity classes we see that for low wind speeds (4m/s - 10m/s) high TI classes yield the most power and for high wind (12m/s - 14m/s) speeds low TI classes yield the most power, as was noticed before (see for instance [10]). Also, differences in the standard deviations of the power are clearly seen (see Figure 2.3). In the wind speed range 6m/s - 13m/s we see that the standard deviation of certain turbulence intensity classes (4% - 6% and 12% - 14%) differ up to about 50% with the standard deviation for all turbulence intensities. Furthermore, it is noticed that the standard deviation of the power for high turbulence intensities is larger than the standard deviation of the power for all turbulence intensities up to wind speeds of 10m/s. For low turbulence intensities the opposite is valid.

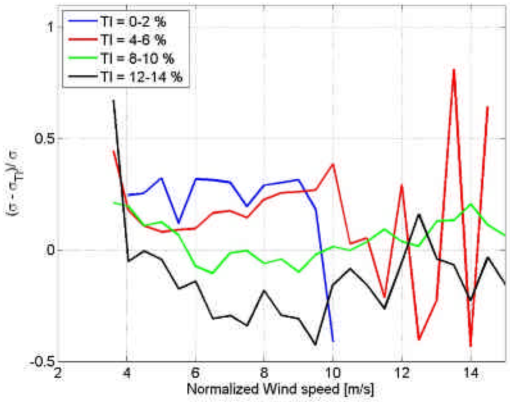

Figure 2.3 *Relative difference in standard deviation of the power for different TI classes.*

2.4 Vertical wind shear

Vertical wind shear is important because wind turbines become larger and larger. It is therefore questionable whether the hub height wind speed is still representative.

The vertical wind shear can be quantified by assuming a power law profile [9]

$$U(z) = U(z_r) \cdot \left(\frac{z}{z_r} \right)^{\alpha}, \qquad (3)$$

where U(z) is the horizontal wind speed at height *z*. The subscript r indicates the reference height and α is a dimensionless constant.

Because the horizontal wind speed is measured at three different heights, two α exponents are determined: α_1 for the heights 108m and 80m and α_2 for the heights 80m and 52m. Both α_i exponents are distributed over bins of 0.1 wide. Those cases are considered where both α_i exponents are in the same bin. In 1/3 of all possibilities the wind shear shows a profile as assumed in (3). It is noticed that most values are within α=0.1 and α=0.4. The mean value is α=0.3.

The differences between the power curves for various values of α with respect to the power curve for all α are relatively small; they are a few percent. However, differences in the standard deviation of the power are clearly seen, as can be seen from Figure 2.4. In the wind speed range, say, 5m/s - 13m/s the standard deviation of the power for different values of α differs up to about 30% with the standard deviation of the power for all values of α. It is also seen in this same wind speed range that the standard deviation for a low values of α (α=0.1) is larger than the standard deviation for all values of α and the standard deviation for a higher value of α (α=0.3, 0.5) is smaller.

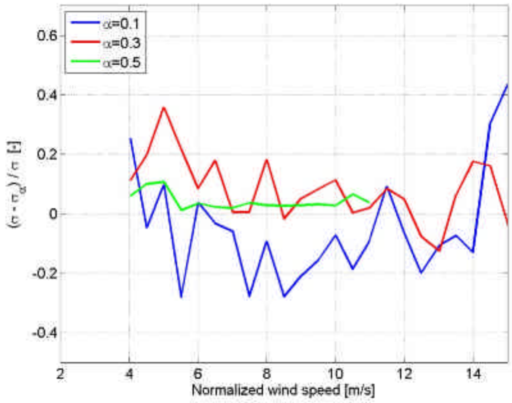

Figure 2.4 *Relative difference in standard deviation of the power for different values of α.*

2.5 Cross correlations

Although stability, turbulence and vertical wind shear are treated separately in the foregoing, it may be expected that these phenomena are correlated.

It is noticed that low values of α (say α=0.1) occur most frequent for unstable conditions and high turbulence intensity and high values of α (say α=0.3, 0.4) occur most frequent for stable conditions and low turbulence intensity. Also, in the former case the distribution of α is much sharper.

These phenomena are explained by the fact that for unstable conditions and high turbulence different layers of air mix, which increases the correlation of the horizontal wind speeds at different heights. This decreases the value of *α* and broadens the distribution. For a value of *α=0* all horizontal wind speeds at different heights are the same.

3. Corrections for Impact of Atmospheric Conditions on Power Performance

Since it is shown in section 2 that the power curve depends on atmospheric conditions it is desirable to correct for these conditions such that the power curve becomes independent of these conditions or that the dependence of the power curve on these conditions reduces. As mentioned, [1] already prescribes an air density correction. Besides that we also consider turbulence and vertical wind shear correction.

A correction with respect to stability is not considered, however, as we have seen, stability is correlated to turbulence and wind shear.

3.1 Air density

The ECN research turbines are pitch-regulated. Therefore, according to [1], the air density normalization is applied to the wind speed

$$U_{norm} = U \cdot \left(\frac{\rho}{\rho_0}\right)^{1/3}. \qquad (4)$$

Here, U_{norm} is the normalized wind speed and ρ_0 is the reference air density. As a reference the sea level air density is taken (1.225 kg/m^3).

The effect of the normalization is depicted in Figure 3.1. The upper plots show power curves for different values of the air density, where the left plots is before and the right plot is after correction. It is clear that the corrected power curves for different values of the air density are closer together. The wind speed range 9m/s - 13m/s is shown, because in this range the effect is best seen. Above 4m/s the normalized power is at most 2% less than the unnormalized power.

This point is further illustrated in the lower plot of Figure 3.1, where the relative difference in the standard deviation of the power is shown. It is observed that the standard deviation is reduced by about 8%. The wind speed range 4m/s – 13m/s is shown, because in this range the cubic dependence of the power on the wind speed (1) is most pronounced and (4) is here most effective. It is concluded that the air density correction based on (4), as prescribed by [1], is indeed effective.

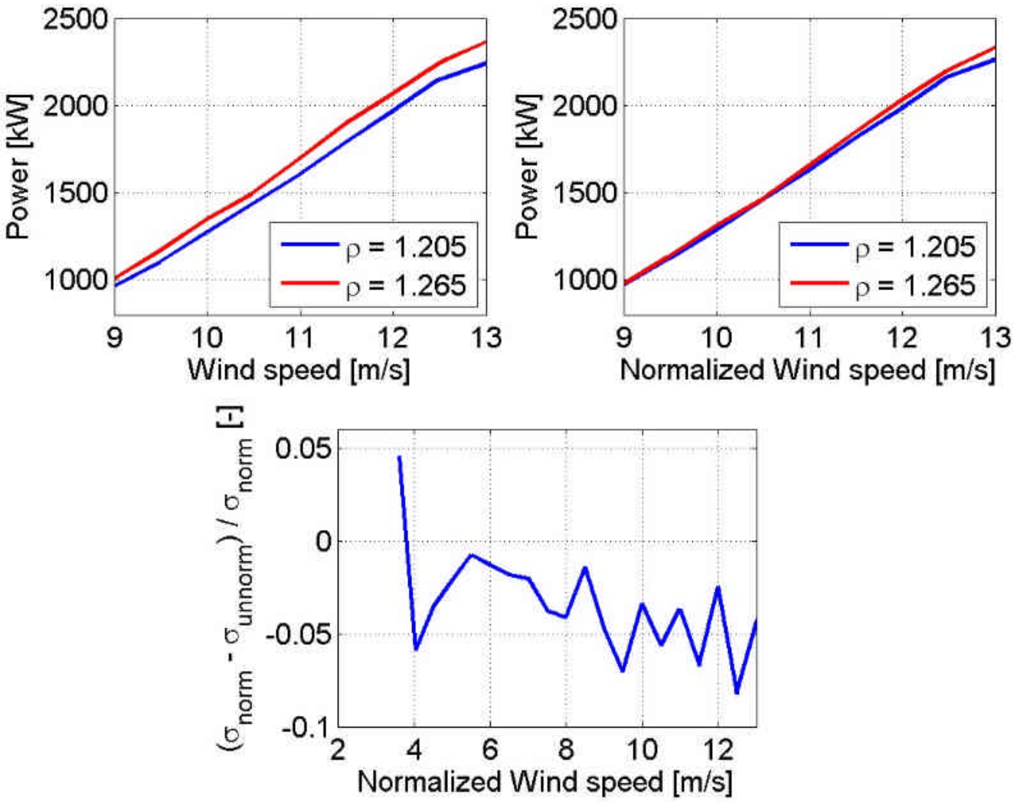

Figure 3.1 *Power curves for different values of the air density before (upper left) and after (upper right) correction. The lower plot shows the relative difference in normalized and unnormalized standard deviation of the power.*

As mentioned before temperature and air density are correlated. Therefore air density correction is implicitly also temperature correction. It is indeed observed that the air density correction is also effective for reducing the dependence of the power curve on the temperature. Nevertheless, a small influence of the temperature on the power curve remains, as is the case for the air density.

3.2 Turbulence

In (1) it is shown that the power depends cubically on the wind speed. Implicitly, the third power of the averaged wind speed was considered. However, the average of the power depends on the average of the cubed wind speed. It can be shown [5] that in this way a correction factor is added or, equivalently, a corrected wind speed is defined

$$U_{corr} = U_{norm} \cdot \left(1 + 3 \cdot \left(\frac{\sigma_U}{U}\right)^2\right)^{1/3} . \qquad (5)$$

Here, σ_U/U is the TI (2).

The turbulence corrected power is shown in Figure 3.2 for low and high values of TI. Also shown is the uncorrected power for the same values of TI for comparison. The two curves are in the corrected case somewhat closer together with respect to the uncorrected case. This is made more quantitative in the relative difference in the standard deviation of the power before and after the correction, also shown in Figure 3.2. Here, the standard deviation of the corrected power is for almost all wind speeds in the range up to 12m/s lower than the standard deviation of the uncorrected power. A reduction up to 9% is seen. The correction (5) is based on the cubical dependence of the power on the wind speed. This behaviour is most pronounced in the mentioned wind speed range. Therefore, it is concluded that the turbulence correction (5) is effective.

A difference in corrected and uncorrected power is observed up to 7%; for higher wind speeds (>6m/s) this is less than 2%. For almost all wind speeds the corrected power is lower than the uncorrected power. This is caused by the fact that the corrected wind speed is always larger that the uncorrected wind speed, due to the correction as given by (5).

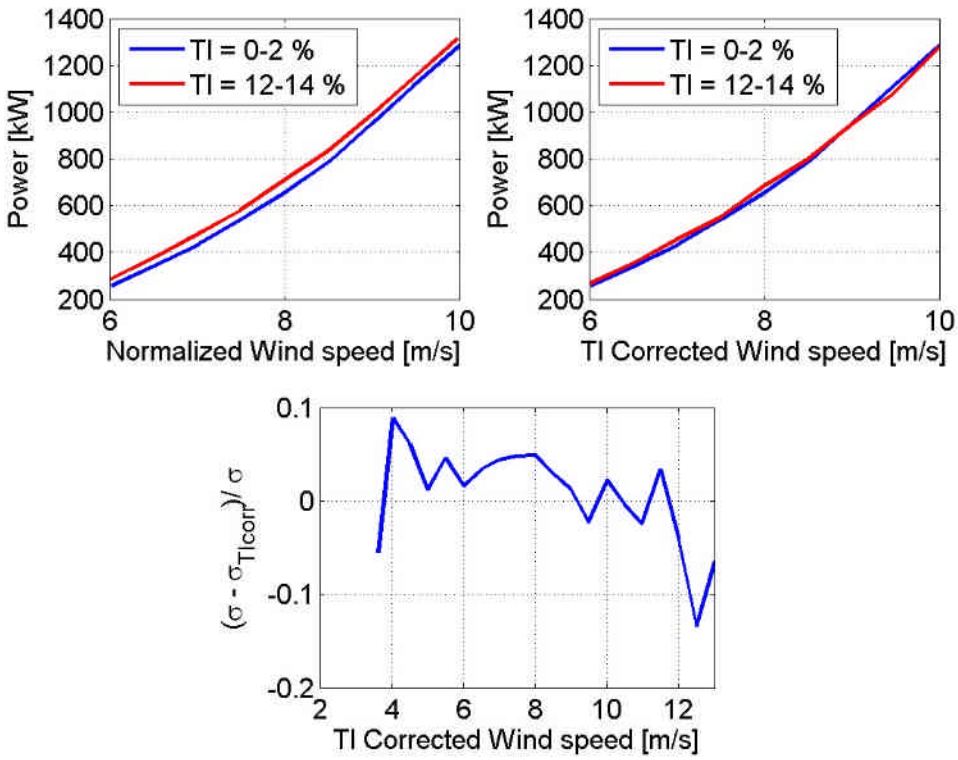

Figure 3.2 *Power curves for different TI classes before (upper left) and after (upper right) correction. The lower plot shows the relative difference in uncorrected and corrected standard deviation of the power.*

3.3 Vertical wind shear

To correct for the wind shear various approaches are considered. The first approach is to determine the power law profile (3), i.e. to determine α, based on the measurements and to correct the wind speeds according to this profile. An other approach is to directly use the measurements at multiple heights in a redefinition of the wind speed.

Wind shear corrected wind speed:
Attempts to correct for vertical wind shear are sought in the assumption of a power law pro-

file of the wind shear. Here, we first average the (horizontal) wind speed vertically

$$U_{ave,vert} = \frac{1}{2R}\int_{H-D/2}^{H+D/2} U(z)dz = U(H)\cdot\frac{1}{\alpha+1}\cdot\left(\left(\frac{3}{2}\right)^{\alpha+1} - \left(\frac{1}{2}\right)^{\alpha+1}\right), \quad (6)$$

where U(z) is defined in (1) and (3) and z_r = H. Furthermore, it has been used that H=D. From (6) it is obvious that the hub height wind speed U(H) is α corrected based on the profile it is experiencing. These corrections are in the range 0.989 - 1.0353 for the α values in the range -0.5 to 1.

A second possibility is to average the wind speed over the rotor plane [4]. Again, a power law wind profile is assumed (3)

$$U_{ave,rot} = \frac{1}{A}\int_{H-D/2}^{H+D/2} U(z)dA = U(H)\cdot\frac{2}{\pi}\cdot\int_{-1}^{1}\sqrt{1-y^2}\cdot\left(\frac{1}{2}\cdot y+1\right)^{\alpha} dy \quad ,(7)$$

where y is a dummy integration variable. Also in this case the hub height wind speed is α corrected based on the profile it is experiencing. Now, the corrections are in the range 0.9918 - 1.0259 for the same α range as before.

It is observed that both corrections have more are less the same effect.

A difference between the corrected and uncorrected power up to 12 % is seen. For wind speeds, say, above 5m/s the corrected power differs less than 3% from the uncorrected power. In all cases the corrected power is larger than the uncorrected power.

In Figure 3.3 the relative difference in the standard deviation of the corrected and uncorrected power is shown. For most wind speeds a decrease of the standard deviation of at most 10% is seen as a result of the α correction. However, for some wind speeds in the regime up to 12m/s an increase is seen.

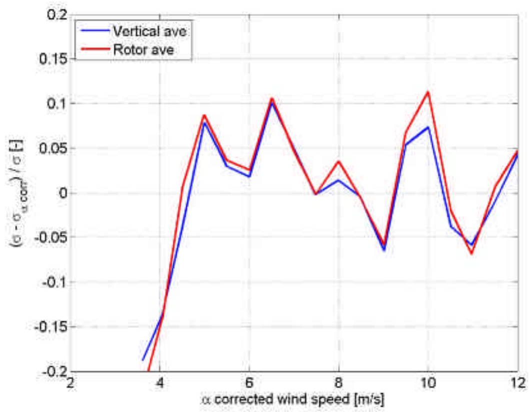

Figure 3.3 *Relative difference in uncorrected and corrected standard deviation of the power.*

Rotor averaged wind speed:

Besides assuming a power law profile of the vertical wind shear also real measurements at multiple heights can be used by redefining the wind speed. At the meteo mast the wind speed is measured at three different heights: 52m, 80m and 108m. With these measurements a so-called rotor averaged wind speed is defined, similar to for instance [5] [11]

$$U_{rotoraveraged} = \frac{1}{A}\left(A_{52}\cdot U_{52} + A_{80}\cdot U_{80} + A_{108}\cdot U_{108}\right), \quad (8)$$

Here, $U_{rotor\text{-}averaged}$ is the rotor averaged wind speed and U_{52} , U_{80} and U_{108} are the wind speed at the various height. A is the entire rotor swept area and A_{52}, A_{80} and A_{108} are different sections of this area defined by height x (see Figure 3.4).

$$A = \pi R^2$$

$$A_{80} = 2\cdot R^2\cdot\arcsin\left(\frac{x}{2R}\right) + x\cdot\sqrt{R^2 - \frac{x^2}{4}} \quad ,(9)$$

$$A_{52} = A_{108} = \frac{A - A_{80}}{2}$$

We notice that for x=80m the rotor averaged wind speed is equal to the wind speed at hub height.

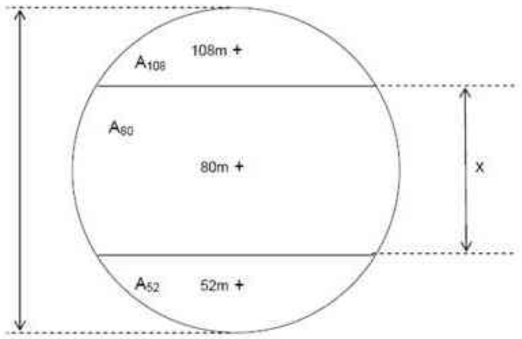

Figure 3.4 *Rotor swept area divided in three sections.*

The different corrected power curves differ up to 4% for wind speeds above 6m/s from the uncorrected power curve. In practically all cases (all x-values and wind speeds) the corrected power is larger than the uncorrected power.

Based on Figure 3.5, only for x=60m the standard deviation of the power shows for most wind speeds a decrease of about 3%. In practice, for values of x above 50m the standard deviation of the power is decreased about a few percent. Therefore, this correction is only effective for these values of x, although the effect is relatively small.

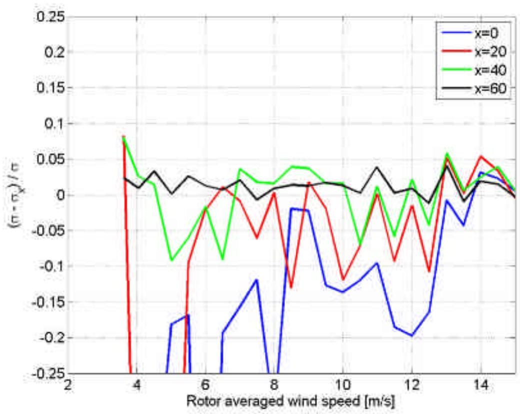

Figure 3.5 *Relative difference in standard deviation of the power for the different values of x.*

4. Conclusion and Discussion

All atmospheric conditions that have been considered, i.e. air density, temperature, turbulence and vertical wind shear, have been shown to have effect on either the power curves themselves or on the standard deviation of the power.

Corrections with respect to air density, as prescribed by [1], turbulence and vertical wind shear are examined. Corrections with respect to temperature and stability are not considered. This because temperature is correlated to air density and stability is correlated to turbulence and wind shear, as we have seen.

Correction with respect to air density (4) and turbulence (5) have been shown to be effective for (most) wind speeds in the range where the cubic dependence of the power on the wind speed is most pronounced, say 4m/s - 12m/s. In case of the air density the standard deviation is reduced up to about 8% and in case of the turbulence a reduction up to about 9% is seen. Both corrections cause the power to be lower than the uncorrected power. Above 6m/s these differences are at most 2%.

Both vertical wind shear corrections based on the α parameter basically show the same result. In the most interesting wind speed regime the standard deviations are in most cases reduced up to about 10%, but for some wind speeds a increase of the standard deviation is seen.

In case of the rotor averaged wind speed correction, only for x values above 50m an improvement in the standard deviation is seen of about 3%. The effect of the correction is considered to be small.

All considered wind shear corrections, based on a power law profile and based on measurements at multiple heights, cause the power to be higher than the uncorrected power. These differences are less than 4% above wind speeds of 6m/s.

Acknowledgements

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Power Performance and Atmospheric Conditions

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PO. 463

Introduction

The demonstration of the value of innovations in wind energy applications is difficult due to the relatively large uncertainty in measurements – the main reason is the nature of the source of energy: the turbulent wind

This work focuses on the analyses of sources of uncertainties in power performance testing. Based on an extensive set of measured data at ECN test site, the dependence of the power curve on atmospheric conditions is determined:

- Air density
- Turbulence
- Vertical wind shear

Possible correction methods are investigated to reduce the uncertainty in power performance measurements. The work is closely related to the work in the MT12 maintenance team and MEASNET.

Data and Atmospheric Conditions

Data are taken from the research wind turbines at ECN Wind Turbine Test station Wieringermeer (EWTW) [3] since 2004. The test site is located 1 – 2km West of the lake 'IJsselmeer' and the terrain and its surroundings are characterised as flat.

Turbine:

- 2.5MW rated power
- Hub height (H) 80m
- Rotor diameter (D=2R) 80m

Meteo mast:

- Wind speed 52m, 80m and 108m
- Wind direction 52m, 80m and 108m
- Temperature and temperature difference
- Pressure

Corrections

Air density correction (IEC):
IEC regulations [1] prescribe to correct the wind speed for air density for pitch regulated turbines.

$$U_{norm} = U \cdot \left(\frac{\rho}{\rho_0}\right)^{1/3}$$

Turbulence correction:
Considering the average of the cubed wind speed, it can be shown [2] that a TI-corrected wind speed is defined, where the turbulence intensity TI=σ_U/U.

$$U_{corr} = U_{norm} \cdot \left(1 + 3 \cdot \left(\frac{\sigma_U}{U}\right)^2\right)^{1/3}$$

Vertical wind shear correction: (I) Power law profile
The horizontal wind speed is corrected either by vertical averaging or by averaging over the rotor plane [3], based on a power law profile it is experiencing.

$$U(z) = U(H) \cdot \left(\frac{z}{H}\right)^{\alpha}$$

$$U_{ave,vert} = \frac{1}{2R} \int_{H-D/2}^{H+D/2} U(z)dz$$

$$U_{ave,rot} = \frac{1}{A} \int_{H-D/2}^{H+D/2} U(z)dA$$

Vertical wind shear correction: (II) Measurements at multiple heights
Wind speed measurements at multiple heights are directly used in a redefinition [2][4] of the wind speed.

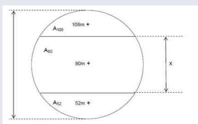
$$(a): U_{rotor-averaged} = \frac{A_{52} \cdot U_{52}}{A} + \frac{A_{80} \cdot U_{80}}{A} + \frac{A_{108} \cdot U_{108}}{A}$$

$$(b): U_{rotor-averaged,cube} = \left(\frac{A_{52} \cdot U_{52}^3}{A} + \frac{A_{80} \cdot U_{80}^3}{A} + \frac{A_{108} \cdot U_{108}^3}{A}\right)^{1/3}$$

$$A = \pi R^2$$

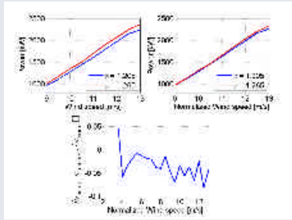
$$A_{80} = 2 \cdot R^2 \cdot \arcsin\left(\frac{x}{2R}\right) + x \cdot \sqrt{R^2 - \frac{x^2}{4}}$$

$$A_{52} = A_{108} = \frac{A - A_{80}}{2}$$



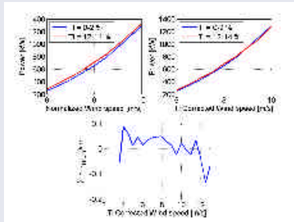
Results

Air density (IEC):



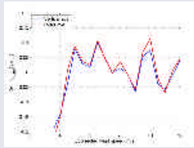
- Most effective in wind speed range 4m/s – 12m/s
- Power is decreased by at most 2% for wind speeds above 6m/s
- Standard deviation is reduced up to 8%

Turbulence:



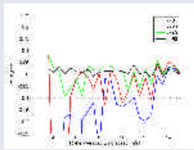
- Most effective in wind speed range 4m/s – 12m/s
- Power is decreased by at most 2% for wind speeds above 6m/s
- Standard deviation is reduced up to 9%

Vertical wind shear: (I) Power law



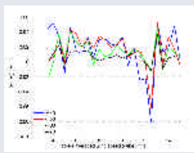
- Both power law corrections have the same effect
- Power is increased by at most 4% for wind speeds above 6m/s
- Standard deviation is reduced up to 10% for most wind speeds
- For some wind speeds an increase in standard deviation is seen

Vertical wind shear: (IIa) Measurements at multiple heights



- Only effective for x>50m
- Power is increased by at most 4% for wind speeds above 6m/s
- Standard deviation is reduced up to 3%

Vertical wind shear: (IIb) Measurements at multiple heights (ongoing research)



- Power is increased by at most 1% for wind speeds above 6m/s (x>40m)
- Standard deviation is reduced up to 5%
- Better than the linear case (IIa)

Conclusions

- The **air density** and **turbulence** corrections are most effective. s_P is reduced up to 9% - 10% for wind speeds of 4m/s - 12m/s.
- Wind shear correction:
  - The **power law** correction reduces s_P up to 10%, but shows for some wind speeds an increase.
  - The **multiple measurements (IIa)** correction reduces s_P up to 3% for x>50m.
  - The **multiple measurements (IIb)** correction reduces s_P up to 5% for x>40m.
- **Changes in power** are at most +/- 4% for wind speeds above 6m/s.

References

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3. Sumner and Masson, "Influence of atmospheric stability on wind turbine power performance curves," *Journal of Solar Energy Engineering*, vol. 128, 2006.
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