Turbulence and Shear Normalisation of Wind Turbine Power Curve

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Summary

Measured wind turbine power curves are significantly influenced by the turbulence intensity. A large part of this effect is due to the averaging of the power curve measurement data over 10-minute periods. This makes a comparison of measured power curves with guaranteed power curves difficult. In addition, the effect limits the applicability of guaranteed power curves for wind resource assessments, as the site specific turbulence intensity may differ from the reference turbulence intensity of the guaranteed power curve.

An easy to handle approach for the normalisation of wind turbine power curve data to a reference turbulence intensity has been developed and suggested to the maintenance team of the standard IEC 61400-12-1 [1] for the inclusion in the next revision of the standard [2]. The model allows also adjusting a power curve given for a reference turbulence intensity to a site specific turbulence intensity, e.g. for the purpose of wind resource assessments.

The method can further be applied for:

- check of plausibility of power curves
- evaluation of potential for optimisation of wind turbine power performance
- estimation of effect of limitation of power output, e.g. due to noise reduced operation or grid curtailment
- estimation of effect of an increase of rated power

Apart of the turbulence intensity, also the wind shear has a significant influence on wind turbine power curves. Thus, also a simple approach for normalising power curves to a reference wind shear has been developed and suggested for the improvement of the standard IEC 61400-12-1.

1 Introduction

Measured wind turbine power curves are influenced by the turbulence intensity and wind shear present during the measurement period [3]. These effects are not considered in the current standard for wind turbine power curve testing [1]. The author has developed different approaches to describe the turbulence effect on power curves since 1994 [3], [4]. A recent breakthrough was the development of an easy to handle but efficient procedure for normalising power curve measurement data to a reference turbulence intensity. The measured power output is corrected for the turbulence intensity for each 10-minute period, similar to the normalisation in respect to the air density. The procedure has been tested with measurement data from different pitch and stall controlled wind turbines [2]. Furthermore, a procedure for the normalisation of power curve data in respect to the wind shear has been developed.

2 Observed Effects of Turbulence Intensity on Measured Wind Turbine Power Curves

A clear observation is that the measured power output of wind turbines tends to increase at lower wind speeds and wind speeds around the maximum power coefficient with increasing turbulence intensity. The opposite effect has often been observed in the transition region to rated power. The effect of the turbulence intensity in terms of the annual energy production can be up to +/-5 %. As is explained in references [3], [4], [5] and [6], a significant part of this effect is due to the averaging of power curve measurement data over 10-minute periods in combination with the non-linear relationship of the wind turbine power output and the wind speed.

3 Power Curve Turbulence Normalisation Procedure

3.1 Principle of Turbulence Normalisation

The proposed power curve normalisation procedure is designed to correct the turbulence effect due to 10-minute averaging of power curve measurement data. Other effects of the turbulence intensity on the power curve are not considered. The effect of averaging over 10-minute periods according to the actual measured turbulence intensity is corrected, and afterwards the data is referenced back to a pre-defined turbulence intensity (reference turbulence intensity).

The latter step is needed in order to make the normalised power curve applicable for energy yield predictions for sites where the reference turbulence intensity is present. The reference turbulence intensity may be defined as function of the wind speed.

The turbulence normalisation procedure applies one key assumption: At each instant the wind turbine follows the same power curve. This power curve is called zero turbulence power curve. This assumption is believed to be justified as normally the wind turbine power output follows very well variations of the wind speed. This is due to the fact that the typical maximum of the spectral density of the wind speed has its maximum in the frequency range of about 1/100 Hz, while even large wind turbines can accelerate and decelerate the rotor within only a few seconds (frequency of response higher than 1/10 Hz).

If the zero turbulence power curve of the wind turbine $P_{I=0}(v)$ and the wind speed distribution within a 10-minute period f(v) are known, the power output of the wind turbine averaged over the 10-minute period can be calculated by:

$$\overline{P_{sim}(v)} = \int_{v=0}^{\infty} P_{I=0}(v) \cdot f(v) dv \qquad (1)$$

The wind speed distribution within a 10-minute period is measured at a power curve test. If the time series with the 10-minute period is not stored, f(v) can be approximated as a Gaussian wind speed distribution, which is determined by the mean wind speed and the standard deviation of the wind speed within the 10-minute period, i.e. by the mean wind speed and by the turbulence intensity (both values must at least be stored for a power curve test). Equation (1) is applied for the measured wind speed distribution and for a reference wind speed distribution with the same mean wind speed. It is proposed to apply a Gaussian wind speed distribution as reference wind speed distribution, which is determined by the measured mean wind speed and by the reference turbulence intensity.

The normalisation of the power output measured during the 10-minute period to the reference turbulence intensity is then reached by:

$$\overline{P_{I_{ref}}(v)} = \overline{P(v)} - \overline{P_{sim,I}(v)} + \overline{P_{sim,I_{ref}}(v)} \qquad (2)$$

where

$\overline{P(v)}$:	mean measured power output
$\overline{P_{sim,I}(v)}$:	power output according to equation (1) for the measured turbulence intensity (measured wind speed distribution)
$\overline{P_{sim,I_{ref}}(v)}$:	power output according to equation (1) for the reference turbulence intensity
$\overline{P_{I_{ref}}(v)}$:	normalised power output

Equation (2) is applied for each 10-minute period. As a Gaussian wind speed distribution is proposed as reference wind speed distribution, the method is called Normal Distribution Model.

3.2 Determination of Zero Turbulence Power Curve

The challenge is the determination of the zero turbulence power curve needed for the application of equation (1). A 3-step procedure for the determination of this power curve on the basis of the measured bin-averaged power curve is proposed.

In the first step, an initial zero turbulence power curve is determined from the measured power curve and basic turbine characteristics as illustrated in Figure 1. The initial zero turbulence power curve is determined by:

- the maximum measured power coefficient (gained form bin-averaged measured power curve),
- the rated power defined as maximum measured power output (gained from bin-averaged measured power curve),
- the cut-in wind speed (gained form bin-averaged measured power curve),
- the rotor diameter,
- the air density to which the measured power curve is referenced.

Details of the determination of the initial zero turbulence power curve are described in reference [2].

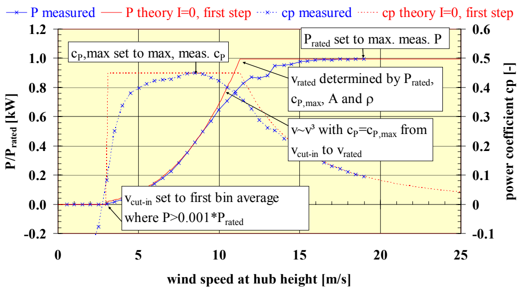

Figure 1: Illustration of setting of initial zero turbulence power curve on the basis of the measured power curve and basic turbine characteristics

In the second step, the initial zero turbulence power curve is integrated over a Gaussian wind speed distribution according to formula (1) with the average wind speed equal to the bin average of the measured power curve and with the standard deviation calculated as product of the bin-averaged wind speed and the bin averaged turbulence intensity. By this, the measured power curve is simulated for each wind speed bin, while the simulated power curve refers to exactly the same wind speed bins than the measured power curve. The rated power, the cut-in wind speed and the maximum power coefficient of the initial zero turbulence power curve are then adjusted such that these three numbers as gained for the simulated power curve fit exactly the measured cut-in wind speed, the measured maximum power coefficient and the measured maximum power output according to the measured bin-averaged power curve. Details of these adjustments are described in reference [2], and the effect of these adjustments on the zero turbulence power curve is illustrated in Figure 2. Also a consistent treatment of the air density normalisation for different types of turbine power controls is given in reference [2].

In the third step, the final zero turbulence power curve is gained by applying the normalisation procedure described in chapter 3.1 with the initial zero turbulence power curve gained from step 2 and the reference turbulence intensity of zero percent, i.e. the power curve raw data is normalised to zero turbulence. An example of the effect of step three is shown in Figure 3. Figure 1 to Figure 3 refer to the same example. It is noted that the final turbulence power curve has normally a sharp corner at rated wind speed in case of actively controlled wind turbines.

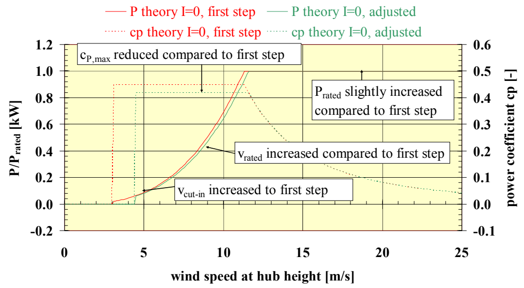

Figure 2: Illustration of effect of adjustment of the zero turbulence power curve according to step 2

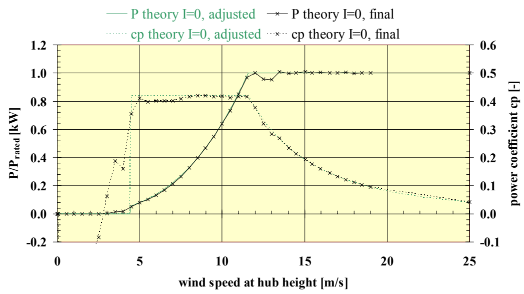

Figure 3: Illustration of effect of final determination of the zero turbulence power curve according to step 3

The procedure for the determination of the initial zero turbulence power curve has been developed on a series of measured power curves. The procedure has been designed such that it can be applied for all measured power curves in a unified way, even in case of stall controlled turbines.

4 Examples of Power Curve Turbulence Normalisations

The turbulence normalisation procedure has been tested on a series of power curve measurements. A typical example of a turbulence normalisation of a measured power curve of a wind turbine in the 2-3 MW range is shown in Figure 4 to Figure 7 (same measurement than applied for Figure 1 to Figure 3). The average turbulence intensity present during the power curve measurement is in the order of 15-20 %, depending on the wind speed.

Figure 4 and Figure 5 show the turbulence normalisation of the power curve raw data and of the bin-averaged power curve to a reference turbulence intensity of 25 %. In this case the reference turbulence intensity is relatively close to the average measured turbulence intensity. The normalised power curve agrees well with the measured power curve filtered to the turbulence range around the reference turbulence intensity (only data with 22.5%-27.5 % turbulence intensity evaluated), i.e. the turbulence normalisation procedure works well in this case. The key advantage of the power curve normalisation compared to a simple filtering is that no measurement data is lost.

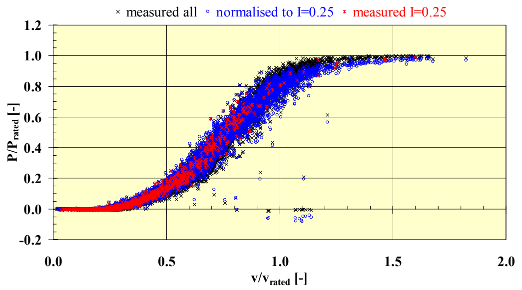

Figure 4: comparison of power curve raw data of a turbine in the 2-3 MW-range: measured (all turbulence intensities, black), normalised to 25 % turbulence intensity (blue) and filtered to the turbulence range 22.5%-27.5 % (red).

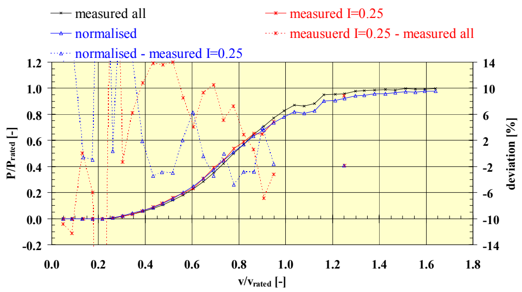

Figure 5: comparison of bin averaged power curves of a 2-3 MW turbine: measured (all turbulence intensities, black), normalised to 25 % turbulence intensity (blue) and filtered to the turbulence range 22.5%-27.5 % (red).

Figure 6 and Figure 7 show the turbulence normalisation of the power curve raw data and of the bin-averaged power curve to a reference turbulence intensity of 5 %. In this case the reference turbulence intensity is far of the average measured turbulence intensity. It is seen here that the normalisation procedure shifts the data to the right direction. However, the complete turbulence effect is not described by the normalisation procedure in this case. This result has been found to be typical in case of larger deviations of the measured averaged turbulence intensity and the reference turbulence intensity.

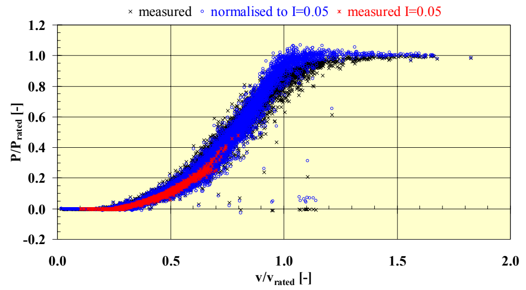

Figure 6: same as Figure 4 but normalisation to 5 % turbulence intensity (blue) and filtering to turbulence range 2.5%-7.5 % (red).

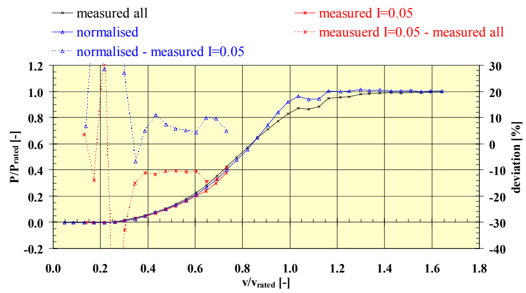

Figure 7: same as Figure 5 but normalisation to 5 % turbulence intensity (blue) and filtering to turbulence range 2.5%-7.5 % (red).

5 Other Application of the Turbulence Normalisation Procedure

5.1 Normalisation of Power Curves for Wind Resource Assessments

Power curves provided by wind turbine manufacturers are quite often valid only for a certain turbulence intensity. The site specific turbulence intensity may deviate form this turbulence intensity. Thus, for the purpose of wind resource assessments, it would make sense to normalise the power curve to the site specific (wind speed dependent) turbulence intensity. This is possibly with the method described in chapter 3 for measured power curves. However, the power curve raw data is often not available to site assessment experts. Furthermore, wind turbine manufacturers offer often theoretical power curves. If only bin-averaged or theoretical power curves are available, the normalisation procedure described in chapter 3 can be applied with the following modifications:

- the zero turbulence power curve is determined only up to step 2 of the procedure explained in chapter 3.2.
- The normalisation according to formula (2) is performed only for the bin averages (or for the wind speeds given for a theoretical power curve) instead of for the raw data.

5.2 Plausibility Check of Power Curves

The setting of the zero turbulence power curve up to step 2 of the procedure described in chapter 3.2 requires only knowledge of some basic turbine characteristics like the rotor diameter, rated power, cut-in wind speed as well as the maximum power coefficient and the reference air density. Based on this information, a power curve of the turbine can be simulated for any turbulence intensity by the application of formula (1). If the simulation is performed for the bin-averaged turbulence intensity of a measured power curve or for the reference turbulence intensity of a theoretical power curve, the simulated power curve has often been found to agree well with the measured power curve or with the referring theoretical power curve provided by the manufacturer. This is especially true for the wind speed range between maximum power coefficient and rated power, i.e. the shape of the power curve in this wind speed range is often almost fully described by the turbulence effect. This feature can be applied in order to verify measured or theoretical power curves. Power outputs much higher than the power outputs according to formula (1) must be considered as unrealistic.

An example is shown in Figure 8. Here, the bin-averaged power curve used for the examples in chapters 3 and 4 has been simulated only by application of the initial zero power curve up to step 2 and by the bin-averaged measured turbulence intensity. There is a high level of agreement of the simulated and measured power curve. The difference in terms of the annual energy production is below 1 % for annual average wind speeds from 5 m/s to 11 m/s. Only at annual average wind speeds below 5 m/s the simulated power curve results in a significantly higher annual energy production than the measured power curve. This result has been found to be typical.

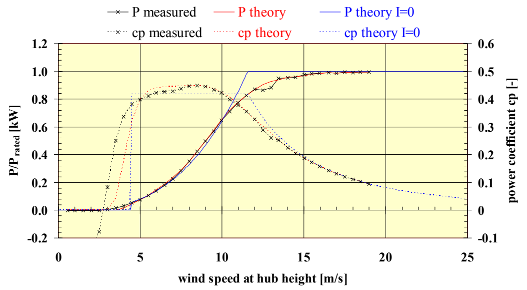

Figure 8: Comparison of measured power curve (black), the referring initial zero turbulence power curve (after step 2, blue) and the resulting simulated power curve for the average measured turbulence intensity (red)

5.3 Determination of Approximate Power Curves for Wind Resource Estimations

Based on the method described in chapter 5.2, it is possible to estimate quite realistic wind turbine power curves for any size and dimensioning of wind turbine under only a few assumptions:

- rotor diameter
- rated power
- maximum power coefficient
- cut-in wind speed
- air density (site specific)
- turbulence intensity (site specific)

Such power curves are sometimes useful for resource estimations or for the optimisation of wind farm layouts.

5.4 Estimation of Effect of Limitation or an Increase of Maximum Power Output

Quite often, wind turbine power curves for reduced rated power are needed, e.g. in case of noise reduced operation or in case of a grid curtailment. Furthermore, an often asked question is, how a power curve would change in case of an increase of the rated power.

The method outlined in chapter 5.1 can be applied in order to determine a power curve with reduced or increased rated power on the basis of a measured or theoretical power curve like follows:

- The zero turbulence power curve is determined only up to step 2 of the procedure explained in chapter 3.2 for the rated power of the measured or theoretical power curve.

- A second zero turbulence power curve is calculated for the new rated power. For this, only the rated power has to replaced in the parameterisation of the already determined zero turbulence power curve.
- The normalisation according to formula (2) is replaced by:

$$\overline{P_{P_{r,n}}(v)} = \overline{P(v)} - \overline{P_{sim,P_r}(v)} + \overline{P_{sim,P_{r,n}}(v)} \quad (3)$$

where

$\overline{P(v)}$:	mean measured or theoretical power output for normal rated power
$\overline{P_{sim,P_r}(v)}$:	power output according to equation (1) for the normal rated power and the turbulence intensity referring to the measured or theoretical power curve
$\overline{P_{sim,P_{r,n}}(v)}$:	power output according to equation (1) for the new rated power and the turbulence intensity referring to the measured or theoretical power curve
$\overline{P_{P_{r,n}}(v)}$:	power curve for new rated power

6 Wind Shear Normalisation

If the wind speed has a large variation over the rotor swept area, the wind speed averaged over the rotor swept area will deviate from the wind speed at hub height. This effect can become significant, especially if the wind shear does not follow a regular power law.

In case of measured power curves, this effect can be compensated for by averaging the wind speed or the cubic of the wind speed over the rotor swept area, so far the wind speed is measured over the entire height range of the rotor:

$$v_{area,m} = \frac{1}{A} \cdot \left(\int_{H-R}^{H+R} v_m^3 dA \right)^{\frac{1}{3}} \quad (4)$$

where

$v_{area,m}$:	rotor area weighted effective wind speed for measured wind profile
v_m:	wind speed measured at different heights
H:	hub height
R:	rotor diameter
A:	rotor swept area

A power curve evaluated by means of such an effective wind speed will be systematically shifted compared to a power curve based on hub height wind speed. As power curves are normally applied for wind resource calculations, and as wind resource calculations are at this stage based on the hub height wind speed, it is proposed to reference back power curves determined on the basis of a measured effective wind speed to a reference wind profile. This can be reached by calculating an effective wind speed also for the reference wind profile with the same hub height wind speed as follows:

$$v_{area,r} = \frac{1}{A} \cdot \left(\int_{H-R}^{H+R} v_r^3 dA \right)^{\frac{1}{3}} \quad (5)$$

where

$v_{area,r}$:	rotor area weighted effective wind speed for reference wind profile and measured wind speed at hub height
v_r:	wind speed according to measured wind speed at hub height and reference wind profile at different heights

The normalised wind speed is then gained by:

$$v_{normalised} = v_m(H) \cdot \frac{v_{area,r}}{v_{area,m}} \quad (6)$$

The wind shear normalisation should be performed on the basis of power curve raw data (10-minute averages) in case of power curve measurements. In case of wind resource assessments, a normalisation of bin-averaged power curves is also possible (like in case of turbulence normalisations). The wind shear normalisation is fully compatible to the air density normalisation as formulated in the current standard IEC 61400-12-1 and to the turbulence normalisation as proposed in chapter 3.

In case of power curve measurements, it is of course preferable to apply the wind shear normalisation on the basis of wind profiles measured over the entire rotor range. However, If wind speed measurements are available only up to hub height, it may be useful to extrapolate the measured wind profile up to the upper rotor tip height and to apply formula (4) on the basis of the extrapolated wind profile. An alternative may be to perform the shear normalisation by integrating the measured profile and the reference wind profile only up to hub height if the wind shear is not measured above hub height.
It is further proposed to increase the uncertainty of power curve measurements if the wind speed is measured only in the lower rotor half compared to the case of a measurement over the full rotor height range. In addition, it is proposed to increase the uncertainty even more if only a wind speed measurement at hub height is available, and thus no shear normalisation can be performed at all.

7 Conclusions

Procedures for normalising wind turbine power curves in according to the turbulence intensity and wind shear have been developed. Both methods are reviewed and tested by the maintenance team of the standard IEC 61400-12-1 and are considered for a possible inclusion in the next revision of the power curve measurement standard.
The turbulence normalisation method has been designed on the basis of simple assumptions in a way that it can be applied for any type of turbine. It shifts power curve raw data always in the right direction. However, the effect of turbulence intensity is not quantified correctly if the reference turbulence intensity deviates much from the measured turbulence intensity. The observed effects of the turbulence intensity on the power curves are then mostly underestimated.
The proposed turbulence and wind shear normalisation procedures are fully consistent to the existing air density normalisation of power curve data. Typically, the effect of turbulence intensity and wind shear on wind turbine power curves is of the same order of magnitude than the air density effect.
Furthermore, the proposed methods can be applied in a fully reversible way in order to shift a power curve given for reference conditions to site specific conditions in terms of turbulence intensity and wind shear. This is needed for an application of power curves for wind resource assessments or for guaranteeing site specific power curves.
The introduced turbulence normalisation procedure can also be applied for plausibility checks of wind turbine power curves or for estimating the effect of a change of rated power.

8 References

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