Practical Aspects of Power Curve Testing Uncertainty Due to Turbulence Effects

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Report No.: PP23035.A2
Report Date: 2023-12-01

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Revision History

Revision No.	Date	Status	Amendment
A0	2023-11-24	final report	---
A1	2023-11-24	final report	factor g corrected from $\sqrt{3}$ to $\frac{1}{\sqrt{3}}$ in legend of equation (2) and subsequent text
A2	2023-12-01	final report	editorial corrections and corrections of equations in Annex A

Note: The last revision replaces all previous versions of the report.

Contents

Disclaimer:

We hereby state, that the results in this report are based upon generally acknowledged and state-of-the-art methods and have been neutrally conducted to the best of our knowledge and belief. No guarantee, however, is given and no responsibility is accepted by Deutsche WindGuard Consulting GmbH for the correctness of the derived results. Any partial duplication of this report is allowed only with written permission of Deutsche WindGuard Consulting GmbH. The results of the following report refer to the investigated object only.

This report covers 19 pages.

1 Introduction

IEC 61400-12-1 [1] requires to assess the uncertainty of power curve tests due to turbulence effects by the application of the turbulence normalisation procedure as given in Annex M of the standard [1]. The calculation of the respective uncertainty component in terms of the annual energy production (AEP) according to equation (E.4) or (E.5) of the standard usually leads to unrealistically high uncertainties in terms of the AEP. This report provides guidance how this uncertainty component of the power curve can be properly converted to an uncertainty in terms of the AEP and how this uncertainty in AEP can be cumulated with other uncertainty components to a total uncertainty in AEP.

The shown principle does not only apply for the power curve uncertainty due to turbulence effects but also to certain further uncertainty components, which is also detailed in this report.

Further guidance is provided on the choice of the two turbulence intensities to which the measured power curve is normalised for the assessment of the uncertainty due to turbulence effects in case of the application of a turbulence filter on the power curve testing data.

2 Cumulating of Power Curve Uncertainty Due to Turbulence Effects to an Uncertainty in Terms of the AEP

2.1 Theory

When applying equation (E.4) or (E.5) of [1] full correlation of category B uncertainty components across the wind speed bins is assumed. This assumption is often not valid in case of the uncertainty due to turbulence effects as modelled according to Annex M.5 of [1]. According to Annex M.5, the uncertainty of the turbulence normalisation or the uncertainty due to turbulence effects in case of the absence of the turbulence normalisation is assessed per wind speed bin as multiple of the difference of two power curves, namely:

I. the difference of the turbulence normalised and the non-turbulence normalised power output divided by $\sqrt{3}$ in case the turbulence normalisation is applied,

II. in case the measured power curve is not turbulence normalised and there is no benchmark power curve to be compared to the measured power curve or no reference turbulence intensity is defined for the benchmark power curve: the difference of the power curve normalised to an extremely high turbulence intensity and normalised to an extremely low turbulence intensity times $\frac{2}{\sqrt{3}}$ with turbulence intensities of 0.05 and 0.15 as default values,

III. in case the measured power curve is not turbulence normalised and the measured power curve shall be compared to a benchmark power curve (e.g. warranted power curve) for which a reference turbulence intensity is defined: the difference of the power curve normalised to this reference turbulence intensity and the power curve normalised to the bin-averaged turbulence intensity present at the power curve test times $\frac{2}{\sqrt{3}}$.

In all three cases, very often the two compared power curves cross each other at a certain wind speed. This is due to the fact that that an increase of the turbulence intensity will lead to an increase of the power output at wind speeds where the power curve is left-curved (at low wind speeds) and to a decrease of the power output where the power curve is right-curved (at high wind speeds below rated wind speed). Hence, the effect of the turbulence intensity (or the uncertainty of the turbulence normalisation if applied) in terms of the AEP is anti-correlated in the two wind speed ranges separated by the crossing point of the two compared power curves. This means in more detail: The uncertainty of turbulence effects in terms of the AEP is fully anticorrelated across wind speed bins with a different sign of the difference of the two power curves as compared for the assessment of the uncertainty (correlation coefficient of -1). The uncertainty of turbulence effects in terms of the AEP is fully correlated across wind speed bins with the same sign of the difference of the two power curves (correlation coefficient of +1).

The uncertainty in AEP due to turbulence effects (or the uncertainty of the turbulence normalisation in terms of the AEP) can then be calculated according to equation (E.2) of [1] by considering just this one uncertainty component as:

$$u_{AEP,M,ti}^2 = N_h^2 \sum_{i=1}^{N} \sum_{j=1}^{N} f_i c_{P,i} u_{M,ti,i} f_j c_{P,j} u_{M,ti,j} \rho_{i,j} \tag{1}$$

where

f_i: relative occurrence of wind speed bin *i* (more exact: relative occurrence of wind speed from bin-averaged wind speed in bin *i-1* to bin-averaged wind speed in bin *i*)

f_j: relative occurrence of wind speed bin *j* (more exact: relative occurrence of wind speed from bin-averaged wind speed in bin *j-1* to bin-averaged wind speed in bin *j*)

$c_{P,i}$: sensitivity factor of power output in wind speed bin *i*

$c_{P,j}$: sensitivity factor of power output in wind speed bin *j*

$u_{M,ti,i}$: standard uncertainty of power curve due to turbulence effects (or standard uncertainty of turbulence normalization) in bin *i* (more exact: mean of standard uncertainties of bin *i* and bin *i-1*)

$u_{M,ti,j}$: standard uncertainty of power curve due to turbulence effects (or standard uncertainty of turbulence normalization) in bin *j* (more exact: mean of standard uncertainties of bin *j* and bin *j-1*)

$\rho_{i,j}$: correlation coefficient between uncertainty of power curve due to turbulence effects (or uncertainty of turbulence normalization) in bin *i* and the respective uncertainty in bin *j*

N: number of wind speed bins

N_h: number of hours in one year

Given the fact that $u_{M,ti,i}$ is determined by the absolute of the power curve differences explained in above bullets I to III times the factor $\sqrt{3}$ or $\frac{2}{\sqrt{3}}$ and the fact that $\rho_{i,j}$is equal to the product of the sign of the power curve differences in bins i and j and that $c_{P,i} = 1$, equation (1) simplifies to:

$$u_{AEP,M,ti}^2 = N_h^2 g^2 \sum_{i=1}^{N} \sum_{j=1}^{N} f_i d_{,i} f_j d_j \tag{2}$$

where

d_i: difference of power curves explained in above bullets I to III including sign in wind speed bin *i* (more exact: mean of power curve differences in wind speed bin *i-1* and wind speed in bin *i*)

d_j: difference of power curves explained in above bullets I to III including sign in wind speed bin *j* (more exact: mean of power curve differences in wind speed bin *j-1* and wind speed in bin *j*)

g: factor $\frac{1}{\sqrt{3}}$ or $\frac{2}{\sqrt{3}}$ as explained in above bullets I to III

As is shown in Annex A, equation (2) is equal to:

$$u_{AEP,M,ti}^2 = N_h^2 g^2 \left(\sum_{i=1}^{N} f_i d_{,i} \right)^2 \tag{3}$$

Hence, for assessing the uncertainty of a power curve due to turbulence effects in terms of the AEP (or uncertainty of turbulence normalisation) just the power curve differences explained in above bullets I to III (including sign) times the frequency of wind speeds has to be summed up across the wind speed bins.

Furthermore, equation (3) can be rewritten as:

$$u_{AEP,M,ti}^2 = N_h^2 g^2 \left(\sum_{i=1}^{N} f_i \left(P_{2,i} - P_{1,i} \right) \right)^2 \qquad (4)$$

where

P_{2i}:	power output of one of the two power curves to be compared as explained in above bullets I to III in wind speed bin *i* (more exact: mean of power outputs in wind speed bin *i-1* and wind speed in bin *i*)
P_{1i}:	power output of the other power curves to be compared as explained in above bullets I to III in wind speed bin *i* (more exact: mean of power outputs in wind speed bin *i-1* and wind speed in bin *i*)

With the AEP as defined by equation (17) of [1], equation (4) transforms to:

$$u_{AEP,M,ti} = g\left| AEP_2 - AEP_1 \right| \qquad (5)$$

This means, the standard uncertainty of a power curve due to turbulence effects in terms of the AEP is the absolute difference of AEPs of the two power curves to be compared according to above bullets I to III times the respective factor $\frac{1}{\sqrt{3}}$ or $\frac{2}{\sqrt{3}}$ (as the case may be).

2.2 Example

An example of an application of equation (3) for the assessment of the uncertainty of turbulence effects in terms of the AEP is compared in Table 1 to the respective calculation under the assumption of full correlation of the uncertainty across wind speed bins as in equation (E.4) or (E.5) of [1]. The calculations are based on the power curves shown in Figure 1 and have been carried out for a Rayleigh wind speed distribution with a mean wind speed of 7.5 m/s. The uncertainty according to equation (3) is reduced by a factor of about 3 compared to the assumption of full correlation of the uncertainty across wind speed bins in this example.

The results of the calculations for integer annual wind speeds from 4 m/s to 11 m/s are summarised in Table 2.

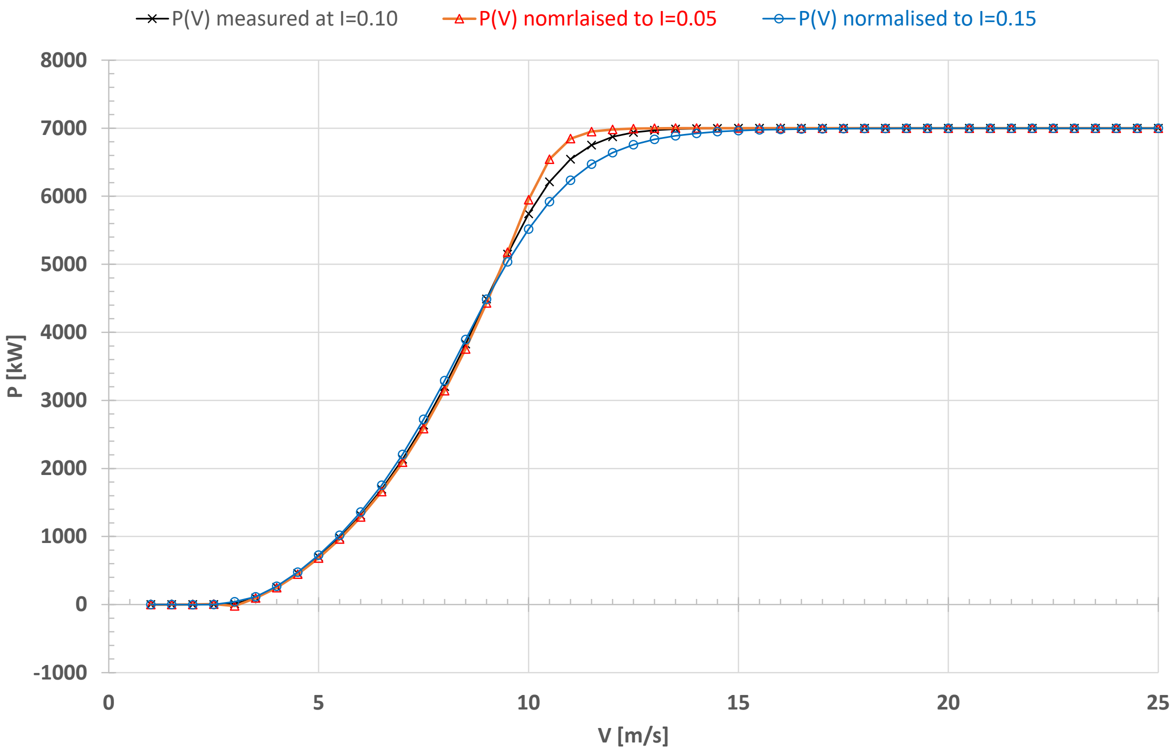

Figure 1: power curves used for exemplary calculation of uncertainty due to turbulence effects

bin	V	P measured	P I=0.05	P I=0.15	$(P_i+P_{i-1})/2$ measured	$(P_i+P_{i-1})/2$ I=0.05	$(P_i+P_{i-1})/2$ I=0.15	d_i	$u_{M,ti,i}/g$	f_i
[-]	[m/s]	[kW]	[kW]	[kW]				[kW]	[kW]	[-]
3	1.0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.01038104
4	1.5	0	0	0	0.0	0.0	0.0	0.0	0.0	0.01706197
5	2.0	0	1	-2	0.0	0.3	-0.8	-1.1	1.1	0.02339196
6	2.5	0	7	-1	0.0	4.0	-1.2	-5.2	5.2	0.02924760
7	3.0	12	-21	40	6.0	-6.9	19.8	26.6	26.6	0.03452149
8	3.5	97	95	114	54.3	37.1	77.0	39.9	39.9	0.03912543
9	4.0	255	247	269	175.9	171.4	191.4	20.0	20.0	0.04299280
10	4.5	458	446	477	356.6	346.6	373.3	26.7	26.7	0.04607994
11	5.0	699	684	726	578.7	564.9	601.6	36.7	36.7	0.04836653
12	5.5	983	962	1018	841.2	823.1	871.7	48.6	48.6	0.04985501
13	6.0	1313	1286	1358	1148.0	1124.0	1188.1	64.0	64.0	0.05056911
14	6.5	1695	1660	1753	1504.1	1473.0	1555.7	82.7	82.7	0.05055164
15	7.0	2135	2092	2206	1915.1	1875.9	1979.5	103.6	103.6	0.04986165
16	7.5	2637	2585	2721	2386.0	2338.4	2463.7	125.3	125.3	0.04857114
17	8.0	3203	3141	3292	2919.8	2863.2	3006.9	143.7	143.7	0.04676159
18	8.5	3827	3756	3894	3514.7	3448.6	3593.4	144.8	144.8	0.04452035
19	9.0	4490	4432	4488	4158.6	4094.0	4191.1	97.1	97.1	0.04193721
20	9.5	5149	5179	5037	4819.8	4805.6	4762.3	-43.3	43.3	0.03910118
21	10.0	5741	5948	5518	5445.2	5563.5	5277.6	-285.9	285.9	0.03609768
22	10.5	6212	6545	5919	5976.3	6246.3	5718.7	-527.6	527.6	0.03300615
23	11.0	6543	6846	6235	6377.2	6695.7	6077.1	-618.6	618.6	0.02989824
24	11.5	6752	6950	6471	6647.6	6898.1	6353.2	-544.9	544.9	0.02683648
25	12.0	6873	6981	6640	6812.5	6965.6	6555.6	-410.0	410.0	0.02387353
26	12.5	6937	6994	6757	6905.1	6987.5	6698.3	-289.2	289.2	0.02105186
27	13.0	6970	6999	6836	6953.8	6996.2	6796.2	-200.1	200.1	0.01840390
28	13.5	6986	7001	6889	6978.1	7000.1	6862.2	-137.8	137.8	0.01595258
29	14.0	6994	7002	6924	6989.8	7001.4	6906.5	-94.9	94.9	0.01371206
30	14.5	6997	7002	6948	6995.3	7001.6	6936.2	-65.5	65.5	0.01168879
31	15.0	6999	7001	6964	6997.9	7001.4	6956.1	-45.3	45.3	0.00988261
32	15.5	6999	7001	6975	6999.0	7001.0	6969.6	-31.4	31.4	0.00828789
33	16.0	7000	7001	6983	6999.5	7000.7	6978.8	-21.9	21.9	0.00689475
34	16.5	7000	7000	6988	6999.8	7000.5	6985.1	-15.4	15.4	0.00569018
35	17.0	7000	7000	6991	6999.9	7000.3	6989.5	-10.9	10.9	0.00465898
36	17.5	7000	7000	6994	7000.0	7000.2	6992.5	-7.7	7.7	0.00378477
37	18.0	7000	7000	6995	7000.0	7000.1	6994.6	-5.5	5.5	0.00305065
38	18.5	7000	7000	6997	7000.0	7000.1	6996.1	-4.0	4.0	0.00243989
39	19.0	7000	7000	6998	7000.0	7000.0	6997.1	-2.9	2.9	0.00193638
40	19.5	7000	7000	6998	7000.0	7000.0	6997.9	-2.1	2.1	0.00152501
41	20.0	7000	7000	6999	7000.0	7000.0	6998.4	-1.6	1.6	0.00119188
42	20.5	7000	7000	6999	7000.0	7000.0	6998.8	-1.2	1.2	0.00092445
43	21.0	7000	7000	6999	7000.0	7000.0	6999.1	-0.9	0.9	0.00071160
44	21.5	7000	7000	6999	7000.0	7000.0	6999.3	-0.7	0.7	0.00054364
45	22.0	7000	7000	7000	7000.0	7000.0	6999.5	-0.5	0.5	0.00041221
46	22.5	7000	7000	7000	7000.0	7000.0	6999.6	-0.4	0.4	0.00031021
47	23.0	7000	7000	7000	7000.0	7000.0	6999.7	-0.3	0.3	0.00023171
48	23.5	7000	7000	7000	7000.0	7000.0	6999.8	-0.2	0.2	0.00017179
49	24.0	7000	7000	7000	7000.0	7000.0	6999.8	-0.2	0.2	0.00012642
50	24.5	7000	7000	7000	7000.0	7000.0	6999.9	-0.1	0.1	0.00009235
51	25.0	7000	7000	7000	7000.0	7000.0	6999.9	-0.1	0.1	0.00006696
AEP [MWh]									25894	
AEP [%]									100	
$u_{AEP,M,ti}$ according to equation (3) [MWh]								**434**		
$u_{AEP,M;ti}$ according to equation (3) [% of AEP]								**1.7**		
$u_{AEP,M,ti}$ as in equation (E.4) or (E.5) of [1] [MWh]								1338		
$u_{AEP,M,ti}$ as in equation (E.4) or (E.5) of [1] [% of AEP]								5.2		

Table 1: Exemplary comparison of application of equation (3) and equation (E.4) or (E.5) of [1]. The factor g in equation (3) is set to $\frac{2}{\sqrt{3}}$ and the factor N_h to 8760 hours. Shown are from left to right:

- bin number, bin-averaged wind speed and bin-averaged power output of measured power curve (here measured at a turbulence intensity of 0.1
- power output normalized to a turbulence intensity of 0.05
- power output normalized to a turbulence intensity of 0.15
- measured power output averaged over two successive bins
- power output normalized to a turbulence intensity of 0.05 averaged over two successive bins
- power output normalized to a turbulence intensity of 0.15 averaged over two successive bins
- difference of power output of the two turbulence normalized power curves averaged over two successive bins as used in equation (3)
- absolute of difference of power output of the two turbulence normalized power curves averaged over two successive bins as used in equation (E.4) or (E.5) of [1]
- probability of wind speed between two successive bin averages for a Rayleigh wind speed distribution with a mean wind speed of 7.5 m/s

V-average	$u_{AEP,M,ti}$ according to equation (3)	$u_{AEP,M,ti}$ as in equation (E.4) or (E.5) of [1]
[m/s]	[% of AEP]	[% of AEP]
4.0	5.3	7.3
5.0	1.9	6.4
6.0	0.3	5.9
7.0	1.4	5.4
8.0	1.9	4.9
9.0	2.0	4.4
10.0	2.0	3.9
11.0	1.9	3.5

Table 2: results of calculation as in Table 1 for integer annual mean wind speeds from 4 m/s to 11 m/s

3 Further Guidance on Power Curve Uncertainty Due to Turbulence Effects

3.1 Setting of Default Turbulence Intensities at Offshore Sites

The two default turbulence intensities of 0.05 and 0.15 to which the measured power curve is normalised for the assessment of the uncertainty due to turbulence effects in the scenario given in chapter 2.1, bullet II are considered being appropriate for onshore sites. However, for offshore sites no representative turbulence range is represented by 0.05 and 0.15. Hence, it is proposed to adjust the default values to 0.03 and 0.09 for offshore sites.

3.2 Uncertainty Assessment in Case of Turbulence Filtering Without Turbulence Normalisation

If a filter on the turbulence intensity is applied and the measured power curve is not turbulence-normalised, as it is often required in power curve warranties for verifying the fulfilment of warranted power curves, turbulence effects on the measured power curve remain as the distribution of turbulence intensities within the filter range is dependent on the test conditions (test site and test period). However, turbulence effects on the measured power curve are then reduced compared to the case of not applying turbulence filters and not applying the turbulence normalisation.

It is proposed to treat this case for the assessment of the uncertainty of turbulence effects as described in chapter 2.1, bullet III with a reference turbulence intensity equal to the mean of the lower and upper turbulence filter limit unless a reference turbulence intensity is explicitly announced for the benchmark (warranted) power curve. Note that the two turbulence limits and hence also the so-defined reference turbulence intensity may be dependent on the wind speed (see example in Figure 2). In case a reference turbulence intensity is given for the benchmark power curve, this reference turbulence intensity should be applied for assessment detailed in chapter 2.1, bullet III.

In both cases the uncertainty is assessed based on the difference of the measured power curve normalised to the mean turbulence intensity per wind speed bin and the measured power curve normalised to the reference turbulence intensity, where the uncertainty in AEP is calculated according to equation (3) under application of a factor g of $\frac{2}{\sqrt{3}}$.

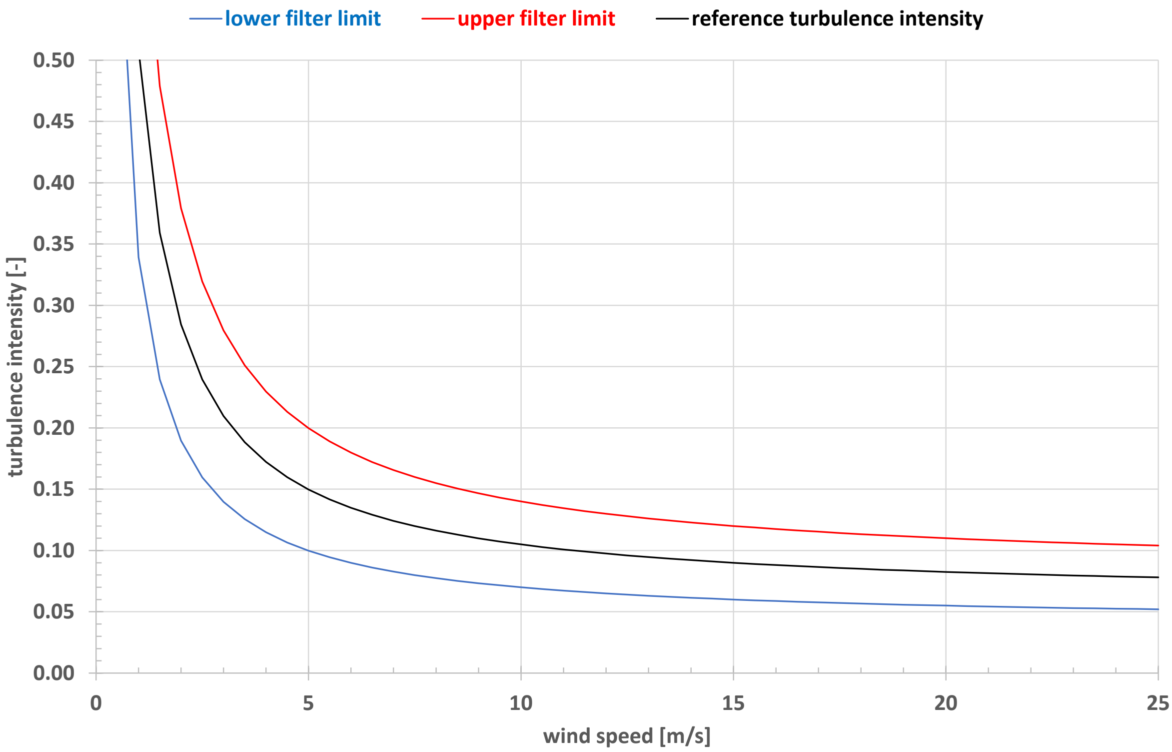

Figure 2: example of the proposed reference turbulence intensity in case of turbulence filtering

4 Other Similar Uncertainty Components

There are further systematic (so-called category B) uncertainty components of power curve tests where the assumption of full correlation of the uncertainty across wind speed bins as assumed in equation (E.4) or (E.5) of [1] is not correct. These uncertainties can be assessed in terms of the AEP similar to chapter 2.1. The different uncertainty components are described in the sub chapters below.

4.1 Anemometer Calibration Residuals

Measurements of cup or sonic anemometers are often applied with a two-parametric linear correction (slope and offset from linear regression) derived at the wind tunnel calibration of the instrument. It is pointed out that this uncertainty is not part of the calibration uncertainty as assessed according to [1], and it is also not included in the uncertainty assessment of power curve tests as described in [1]. The latter is considered as a gap of [1], which should be removed in a future revision of [1].

In the wind speed range where the corrected anemometer measurement is higher than the reference measurement at the wind tunnel calibration, the measured power curve is shifted to the right compared to the real power curve of the test turbine, which leads to an underestimation of the AEP in the wind speed range where the slope of the power curve is positive. Contrary, in the wind speed range where the corrected anemometer measurement is lower than the reference, the measured power curve is shifted to the left compared to the real power curve of the test turbine, which is linked to an overestimation of the AEP in the wind speed range where the slope of the power curve is positive. Hence, the uncertainty due to anemometer residuals is anti-correlated in terms of the AEP across wind speed bins with opposite sign of the calibration residuals (correlation coefficient of -1) and fully correlated across wind speed bins with the same sign of the calibration residuals (correlation coefficient of +1). Therefore, the theory explained in chapter 2.1 applies for this uncertainty component. It is to be noted that the sensitivity of the power curve on the wind speed needs to be overtaken for the derivation of the analogue of equation (3) and that the sign of this sensitivity is not always positive. The respective uncertainty in AEP then turns out as:

$$u_{AEP,VS,precal\_res}^2 = N_h^2 \left(\sum_{i=1}^{N} f_i c_{V,i} r_{,i} \right)^2 \tag{6}$$

where

$u_{AEP,VS,precal\_res}$:	uncertainty due to calibration residuals in terms of AEP
r_i:	calibration residual including sign in wind speed bin *i* (more exact: mean of calibration residuals in wind speed bin *i-1* and wind speed in bin *i*)
$c_{V,i}$:	sensitivity of the power curve on the wind speed including sign in bin i (more exact: slope of power curve calculated based on bin averages of wind speed and power output of bin *i* and bin *i-1*)

A similar uncertainty applies to anemometers used at site calibrations: $u_{AEP,VT,precal\_res}$.

4.2 Lidar Calibration Residuals

The uncertainty of calibration residuals of wind speed measurements of ground-based lidars is integrated in the respective calibration uncertainty according to IEC 61400-50-2 [2]. Therefore, the sign of the calibration residuals cannot be taken care of in the uncertainty of the AEP if the full calibration uncertainty as specified in [2] is applied. Consequently, it is proposed to separate the uncertainty of the calibration residuals from the other calibration uncertainties in a future revision of [2]. For the meantime, it is recommended to reduce the calibration uncertainty of calibrations of ground-based lidars by the calibration residuals as outlined in calibration certificates and to treat the remaining calibration uncertainties as fully correlated across wind speed bins and additionally the uncertainty due to calibration residuals according to equation (6) for the assessment of power curve testing uncertainties in terms of the AEP.

It is pointed out that this separation of calibration uncertainties and the uncertainty due to calibration residuals is already given in IEC 61400-50-3 [3] for nacelle-based lidars (chapter 9.2.1 of [3]). The respective uncertainty due to calibration residuals of nacelle-based lidars in terms of the AEP should also be assessed according to equation (6).

4.3 Uncertainty of Air Density Correction

The uncertainty of the air density correction of power curve testing data is determined for wind turbines with active power control by half of the difference of the air density corrected wind speed and the measured wind speed and for stall-regulated wind turbines by half of the difference of the air density corrected power output and the measured power output according to [1].

The air density correction can be assumed to lead to either a too low absolute air density correction over the entire wind speed range or to a too high air density correction over the entire wind speed range compared to the real impact of the air density on the power curve data. Therefore, the uncertainty of the air density correction in terms of the AEP is fully anti-correlated across wind speed bins with the opposite sign of the difference of the air density corrected wind speed and the measured wind speed (correlation coefficient of -1) and fully correlated across wind speed bins with the same sign of the difference of the air density corrected wind speed and the measured wind speed (correlation coefficient of +1) for wind turbines with active power control. The same principle holds for stall-regulated wind turbines under consideration of the sign of the air density corrected power output and the measured power output. Consequently, the uncertainty of the air density correction in terms of the AEP should be calculated for wind turbines with active power control according to equation (6) by replacing r_i by the difference of the air density corrected wind speed and the measured wind speed including sign of that difference time the factor 0.5. For stall-regulated wind turbines equation (3) should be applied by replacing d_i by the difference of the air density corrected power output and the measured power output including sign and by replacing the factor g by 0.5.

5 Calculation of Total Uncertainty in AEP

Under the assumption that the single uncertainty components of a power curve test are independent from each other equation (E.2) of [1] simplifies to:

$$u_{AEP}^2 = N_h^2 \sum_{k=1}^{M} \left(\sum_{i=1}^{N} \sum_{j=1}^{N} f_i c_{k,i} u_{k,i} f_j c_{k,j} u_{k,j} \rho_{k,i,j} \right)^2 \tag{7}$$

where

f_i: relative occurrence of wind speed bin *i* (more exact: relative occurrence of wind speed from bin-averaged wind speed in bin *i-1* to bin-averaged wind speed in bin *i*)

f_j: relative occurrence of wind speed bin *j* (more exact: relative occurrence of wind speed from bin-averaged wind speed in bin *j-1* to bin-averaged wind speed in bin *j*)

$c_{k,i}$: sensitivity factor of component k in wind speed bin *i*

$c_{k,j}$: sensitivity factor of component k in wind speed bin *j*

$u_{k,i}$: standard uncertainty of power curve due to uncertainty component k in bin *i* (more exact: mean of standard uncertainties of bin *i* and bin *i-1*)

u_{kj}: standard uncertainty of power curve due to uncertainty component k in bin *j* (more exact: mean of standard uncertainties of bin *j* and bin *j-1*)

$\rho_{k,i,j}$: correlation coefficient of uncertainty of power curve due to uncertainty component k in bin *i* and bin *j*

N: number of wind speed bins

M: number of uncertainty components

N_h: number of hours in one year

Note that equation (E.4) of [1] is only a special case of equation (7) with $\rho_{k,i,j} = 0$ for the statistical uncertainty (category A uncertainty) and $\rho_{k,i,j} = 1$ for the systematic uncertainty components (category B uncertainties) of the power curve.

Equation (7) is equal to:

$$u_{AEP}^2 = \sum_{k=1}^{M} {u_{AEP,k}}^2 \tag{8}$$

where

$u_{AEP,k}$: uncertainty component k in terms of the AEP

It is proposed to calculate each uncertainty component separately in terms of the AEP and then to apply equation (8) for determining the total uncertainty in AEP. Equation (8) is a simplification and generalisation of equation (E.4) of [1] and allows other assumptions for the correlation of $u_{k,i}$ across wind speed bins than full correlation and zero correlation.

For category A uncertainty components (statistical uncertainties) the correlation of $u_{k,i}$ across wind speed bins is 0, and $u_{AEP,k}$ is:

$$u_{AEP,k}^2 = N_h^2 \sum_{i=1}^{N} \left(f_i c_{k,i} u_{k,i}\right)^2 \tag{9}$$

For those category B uncertainty components (systematic uncertainties) fully correlated across wind speed bins (correlation coefficient of 1) $u_{AEP,k}$ is:

$$u_{AEP,k}^2 = N_h^2 \left(\sum_{i=1}^{N} f_i c_{k,i} u_{k,i}\right)^2 \tag{10}$$

For the category B components treated is chapters 2 and 3 $u_{AEP,k}$ follows from equation (3) and equation (6), respectively.

It is pointed out that pre-cumulating of uncertainty components to component groups of measurands as stimulated by equations (E.6), (E.7), (E.8), (E.13), (E.25), (E.26). (E.27), (E.28), (E.29), (E.30), (E.45), (E.47), (E.48), (E.49), (E.50), (E.51), (E.52), (E.53), (E.54). (E.55), (E.56) and (E.57) of [1] in combination with equations (E.4) or (E.5) (or (E.58) and (E.59)) of [1] leads to an overestimation of the total uncertainty in AEP and should therefore not be done. Actually, as none of these equations is really needed they should be replaced by the above set of equations (7), (8), (9), (10), (3) and (6) in a future revision of [1].

It is pointed out that especially the application of equation (E.5) of [1] leads to an overestimation of the uncertainty in AEP compared to the more exact equation (E.4) of [1], which increases significantly with the number of uncertainty components considered in (E.4). The above set of equations (7), (8), (9), (10), (3) and (6) further reduces the uncertainty in AEP compared to equation (E.4) of [1]. At an example of a power curve test with 39 uncertainty components as available to the author, the application of equation E.5 of [1] has led to a 39 % higher uncertainty in AEP than the use of the equations (7), (8), (9), (10), (3) and (6).

Furthermore, the application of above equation (7) provides the advantage over equation E.5 of [1] that each single uncertainty component can be reported in terms of the AEP, which provides a better understanding of the relevance of each source of uncertainty.

6 Literature

[1] IEC 61400-12-1, Edition 3.0, Wind energy generation systems - Part 12-1: Power performance measurements of electricity producing wind turbines, 2022-09

[2] IEC 61400-50-2, Edition 1, Wind energy generation systems - Part 50-2: Wind measurement – Application of ground-mounted remote sensing technology, 2022-08

[3] IEC 61400-50-3, Edition 1, Wind energy generation systems - Part 50-3: Use of nacelle-mounted lidars for wind measurement, 2022-01

7 Annex A: Proof of Identity of Equations (2) and (3)

The identity of equations (2) and (3) can be proven by induction as follows.

For N=2:

$$\sum_{i=1}^{2}\sum_{j=1}^{2} f_i d_{,i} f_j d_j = f_1^2 d_1^2 + f_2^2 d_2^2 + 2 f_1 d_1 f_2 d_2 = (f_1 d_1 + f_2 d_2)^2 = \left(\sum_{i=1}^{2} f_i d_{,i}\right)^2$$

The identity is proven for N=2.

If the identity of equations (2) and (3) is true for N bins, then the right side of equation (2) converts to:

$$\sum_{i=1}^{N+1}\sum_{j=1}^{N+1} f_i d_{,i} f_j d_j = \sum_{i=1}^{N}\sum_{j=1}^{N} f_i d_{,i} f_j d_j + (f_{N+1} d_{N+1})^2 + 2 f_{N+1} d_{N+1} \sum_{j=1}^{N} f_i d_{,i}$$

$$\Leftrightarrow \sum_{i=1}^{N+1}\sum_{j=1}^{N+1} f_i d_{,i} f_j d_j = \left(\sum_{i=1}^{N} f_i d_{,i}\right)^2 + (f_{N+1} d_{N+1})^2 + 2 f_{N+1} d_{N+1} \sum_{j=1}^{N} f_i d_{,i}$$

If the identity of equations (2) and (3) is true for N bins, then the right side of equation (3) converts to:

$$\left(\sum_{i=1}^{N+1} f_i d_{,i}\right)^2 = \left(\sum_{i=1}^{N} f_i d_{,i}\right)^2 + (f_{N+1} d_{N+1})^2 + 2 f_{N+1} d_{N+1} \sum_{j=1}^{N} f_i d_{,i}$$

which is equal the right side of (2) as shown above.

As the identity of equations (2) and (3) is proven for N+1 bins when it is fulfilled for N bins and as the identity is proven for N=2, it is also fulfilled for all N>2.

end of report