Assessment of Wind Profile Effects for a Set of Site Calibration Measurements following IEC 61400-12-1

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1. Introduction

The current standard for power curve testing IEC 61400-12-1 [1] describes power performance measurements based on wind speeds measured on a mast at turbine hub height 2 to 4 times rotor diameters away from the turbine location. This approach implicates that the wind conditions at the top of the mast are representative for the complete rotor area. As it is known that this is not necessarily the case e.g. for measurements in complex terrain or for large multi-MW turbines, the community is discussing further site specific effects within the next upcoming IEC standard, which may influence the turbine behaviour or the measurements like vertical wind profile or turbulence intensity.

The present work focuses on effects of the vertical wind profile shape on site calibration measurements which have to be performed at sites in complex terrain before the power performance testing phase.

2. Site Calibration Measurements

Eight site calibration measurements (sc) according to IEC 61400-12-1 [1] were compiled. They were performed in the course of commercial power curve verifications. Additionally to the measurement at hub height, wind speed measurements at the lower blade tip height were performed at both masts, i.e. at the reference mast (ref-mast) and at the mast located at the future turbine location (WTGS-mast). For the wind measurements at the upper position, top anemometers in free flow were used, whereas the lower position was optimised for low disturbance by booms and the mast. The hub height of the future turbines is between 65 m and 80 m. For two site calibrations cup anemometers of type Risø P2546A and for the others those of type Thies 1st Class were used. The resolution of the site calibration bins was 5 respectively 10 degrees.

For all eight sites power performance measurements have not yet been performed.

The measurements were done in five different sites in complex terrain. The maximum terrain slopes range from about 2 to 16 degrees in the expected measurement sectors for the later power performance measurements, considering a radial distance of 4D (D: rotor diameter of measured turbine) seen from the ref-mast. Outside the measurement sectors also higher terrain slopes are observed.

	sc 1	sc 2	sc 3	sc 4	sc 5	sc 6	sc 7	sc 8
ref-mast	0.04	0.04	0.14	0.18	0.19	0.21	0.23	0.13
WTGS-mast	0.07	0.01	0.13	0.11	0.14	0.18	0.17	0.14

Tab. 1: Average wind shear exponent *p* for the eight site calibrations within the expected later measurement sector, wind speed range:]4 m/s ; 16 m/s], temperature > 2°C.

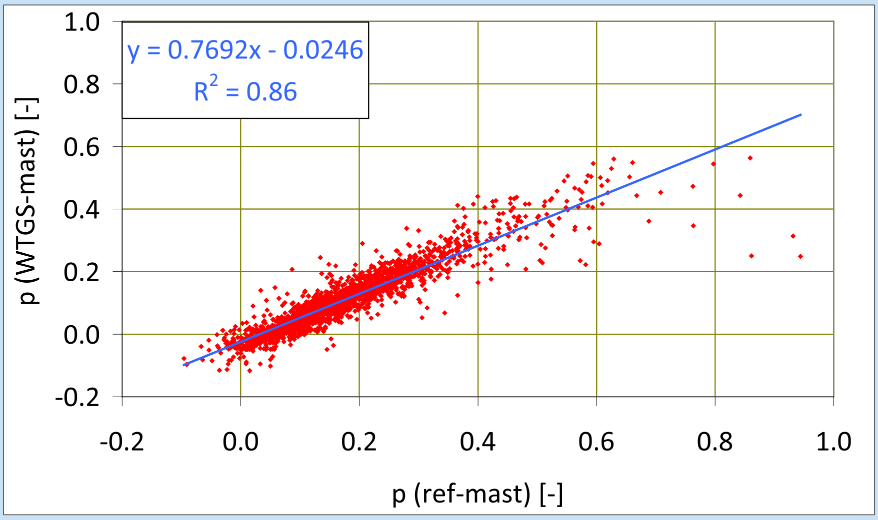

Fig. 1: Wind shear exponent *p* at WTGS-mast versus *p* at ref-mast (sc 4) for expected later measurement sector, wind speed range:]4 m/s ; 16 m/s], temperature > 2°C.

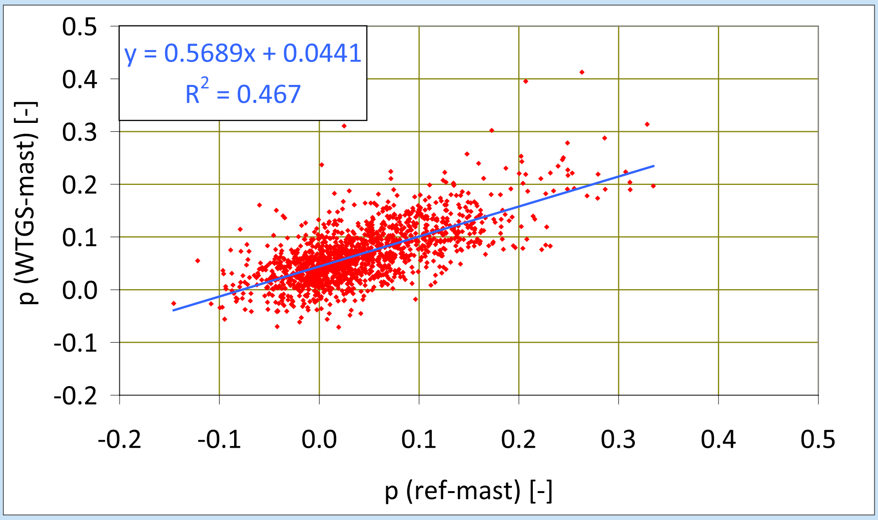

Fig. 2: Wind shear exponent *p* at WTGS-mast versus *p* at ref-mast (sc 1) for expected later measurement sector, wind speed range:]4 m/s ; 16 m/s], temperature > 2°C.

3. Vertical Wind Profile

The vertical wind profile was estimated by the power law profile [2]:

$$v_{Top} = v_{LowBlade} \cdot \left(\frac{h_{Top}}{h_{LowBlade}} \right)^p \qquad \text{(Equation 1)}$$

where

- p : Wind shear exponent
- v_{Top}: Wind speed measured at the top of the mast (hub height)
- $v_{LowBlade}$: Wind speed measured at the lower blade tip height
- h_{Top}: Height of measuring v_{Top}
- $h_{LowBlade}$: Height of measuring $v_{LowBlade}$

In case of a positive exponent the wind speed is increasing with the height, in case *p* is negative the wind speed is decreasing with the height. For ideal flat terrain the wind shear exponent is 0.14 [3], assuming a roughness length of 0.03 m.

The wind shear exponent *p* was determined as 10 minutes average for the eight different measurements for both locations i.e. the ref-mast and the WTGS-mast. These data have been limited to the expected measurement sector for the later power performance measurements so that no obstacles or already erected turbines influenced the data.

Tab. 1 gives an overview about the wind shear exponents for each site averaged over the expected measurement sector.

In addition a wind direction bin analysis of the wind shear exponent was performed using the bin resolution of the site calibration evaluation.

The relation between *p* at the WTGS-mast and at the ref-mast is exemplary shown for two site calibrations in Fig. 1 and Fig. 2.

For the example given in Fig. 1 there is a good correlation visible between *p* at the WTGS-mast and *p* at the ref-mast. Furthermore it can be seen that the wind profile at the ref-mast is increasing stronger than at the WTGS-mast which is demonstrated by the larger wind shear exponent at the ref-mast.

This relation was observed for sites where the ref-mast is located upstream of the WTGS-mast on a lower level. The height differences were between about 10 and 23 m at these sites.

But also the opposite was found, i.e. the wind profile at the WTGS-mast is increasing stronger than at the ref-mast (see Fig. 2). This was observed at a site where the slope upstream of the ref-mast is more than 15 degrees within 4D, which is much higher compared to the other sites and the WTGS-mast location. Height differences between ref-mast and WTGS-mast location seem to have no significant effects at this site.

Furthermore the scatter of the data is much higher in comparison to the first example given in Fig. 1, which was expected due to the more complex structure of this site.

According to IEC the site calibration correction factor is determined by considering only the wind speed measurements at hub height. But both cases demonstrate that the wind profile can be clearly different between the ref-mast and the turbine location. Thus in such a case it is advisable to consider the vertical wind profile in addition while evaluating a site calibration.

The present study aims to suggest a method to consider only typical wind profiles for the respective sites. To exclude those data with extreme wind profiles only data fulfilling the following conditions were therefore used for a second data evaluation (p-Filter):

$$p_{ref,\mu,j} \pm p_{ref,\sigma,j} \quad \text{(Equation 2)}$$

where

$p_{ref,\mu,j}$: Average wind shear exponent at ref-mast for wind direction bin j

$p_{ref,\sigma,j}$: Standard deviation of wind shear exponent at ref-mast for wind direction bin j

Only the data of the ref-mast can be used for the filtering, as this is the information available during the power curve measurement. Generally the presented diagram also allows to correlate the *p*-exponents as a function of the direction, provided that a sufficient data base is available.

An example for applying the wind profile filter to the site calibration data base is given in Fig. 3.

4. Site Calibration with Wind Profile Filter

The results of the site calibration evaluation by applying the wind profile filter to the main data base in addition ($sc_{p\text{-Filter}}$) were compared with the site calibration evaluation according to IEC (sc_{IEC}). Differences in the range of –0.7 % and

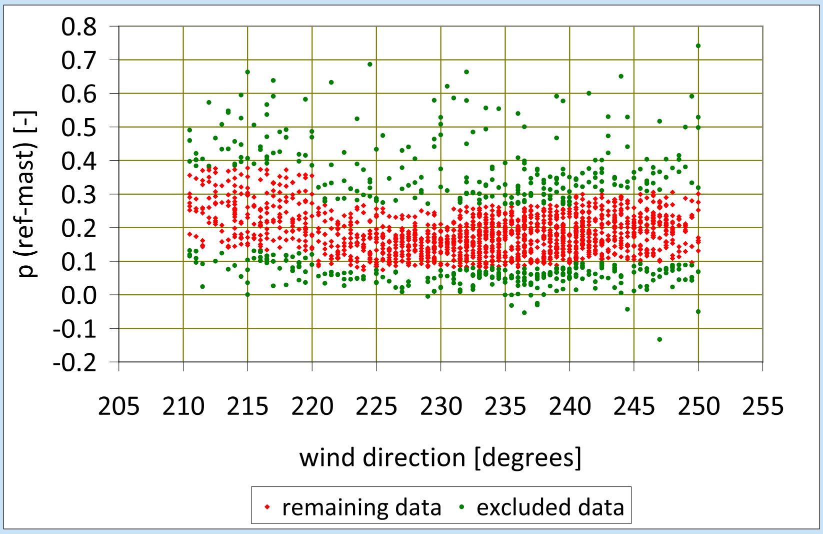

Fig. 3: Wind shear exponent *p* at ref-mast for main data base and filtered data set after applying the wind profile filter (sc 5) for expected later measurement sector, wind speed range:
]4 m/s ; 16 m/s], temperature > 2°C.

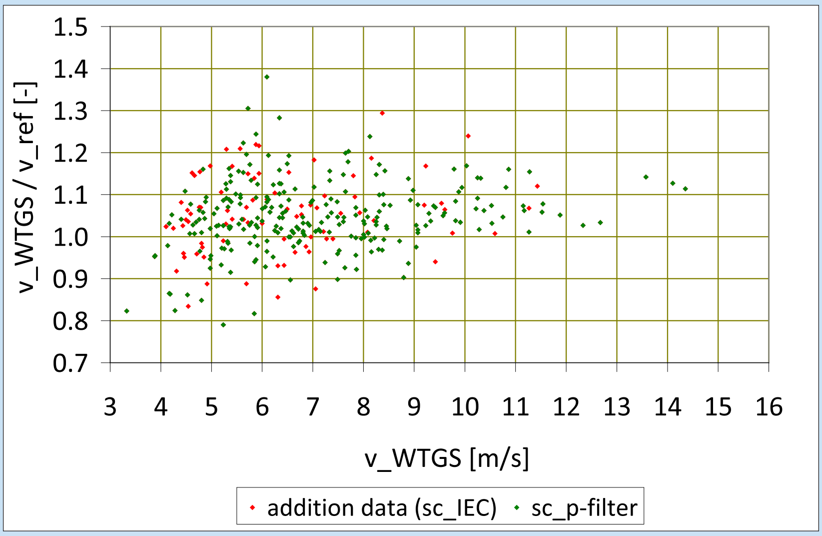

Fig. 4: Site calibration correction factor versus wind speed measured at WTGS-mast for the different data bases (sc 1), wind speed range:
]4 m/s ; 16 m/s], temperature > 2°C, one 5 degrees sector with maximum slope of 14.6 degrees within 4D from ref-mast.

+1.1 % for the individual site calibration factors were observed.

The maximum correction within the expected measurement sector was partly higher, partly less after applying the wind profile filter, differences between –0.4 % and +0.6 % were observed. This demonstrates that by applying the suggested wind profile filter the untypical wind profiles for the respective site will be filtered, but this does not automatically mean an approximation to ideal flat terrain.

Fig. 4 gives an example for the site calibration correction factors of the different data sets after applying the wind profile filter to the main data base.

For the eight site calibrations it was observed that for nearly all wind direction bins within the expected measurement sector the standard deviation of the site calibration correction factors was reduced after applying the wind profile filter in comparison to the results of the IEC compliant evaluation.

Nevertheless the statistical uncertainty that is used within the calculation of the site calibration uncertainty according to IEC 61400-12-1 increased for most of the respective wind direction bins because the number of data sets was reduced, too. As average for the eight sites the number of used data sets was 135 data sets less per wind direction bin within the expected measurement sector. This is a significant reduction, as 144 10-minute data sets are required to complete a wind direction bin according to IEC 61400-12-1.

However the remaining measurement sector is still large enough for a power curve measurement according to IEC. For four site calibrations the expected measurement sector gained from the IEC compliant site calibration was not even reduced.

5. Influence of Site Specific Parameters

The influence of different site specific parameters on the differences between the two site calibration correction factors $sc_{p\text{-Filter}}$ and sc_{IEC} were investigated.

There is a trend visible that in case of an increased slope within 4D the site calibration factor with additional wind profile filter gets relatively more pronounced compared to the one calculated according to IEC.

Average turbulence intensities between 9.0 % and 16.6 % were observed for the top mounted anemometer on the ref-mast at the eight sites. However, there seems to be no direct correlation to differences between the site calibration correction factors.

Further parameters like density conditions at the site or distance between ref-mast and WTGS-mast do not show significant correlation either.

Possible seasonable influences could not be investigated because the measuring period at most of the sites lasted for about two months only. For two site calibrations the measuring periods lasted longer, but the number of data sets was too low in the different seasonal periods.

6. Conclusions and Outlook

1. The present study shows a method to quantify the terrain induced effects on a site calibration measurement. The approach allows for filtering and correlation of vertical profiles and should be discussed in the evaluation of the measurement standards.
2. A method for data filtering has been proposed to exclude data with extreme vertical wind profiles from the site calibration data base.
3. Possible influences of the proposed wind profile filter on the power curve respectively the energy yield of the measured turbine will be checked during the power performance measuring campaign for the considered turbines.
4. Further investigations on possible influences of the vertical wind profile for different conditions like possible seasonal effects should be performed in a research frame for at least one year measuring time.
5. To estimate the vertical wind profile versus the complete rotor area, wind speed measurements at the higher blade tip height should also be performed. Remote sensing methods offer a convenient approach for this data base.

References

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

[2] IEC 61400-1 Ed. 3: Wind turbines – Part 1: Design requirements, 2005

[3] Gasch, R., Twele, J.: Windkraftanlagen, 4. Auflage, B. G. Teubner Verlag, 2005