भारतीय मानक IS/IEC 61400-12-6 : 2022

Indian Standard

पवन ऊर्जा उत्पादन प्रणाली

भाग 12-6 पवन टर्बाइनों का उत्पादन करने वाली बिजली का मापन आधारित नैकेल ट्रांसफर फ़ंक्शन

Wind Energy Generation Systems

Part 12-6 Measurement Based Nacelle Transfer Function of Electricity Producing Wind Turbines

ICS 27.180

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NATIONAL FOREWORD

This India Standard (Part 12/Sec 6) which is identical with IEC 61400-12-6 : 2022 óWind energy generation systems — Part 12-6: Measurement based nacelle transfer function of electricity producing wind turbinesô issued by the International Electrotechnical Commission (IEC) was adopted by the Bureau of Indian Standards on the recommendation of the Wind Turbines Sectional Committee Sectional Committee and approval of the Electrotechnical Division Council.

The text of the IEC standard has been approved as suitable for publication as an Indian Standard without deviations. Certain conventions are, however, not identical to those used in Indian Standards. Attention is particularly drawn to the following:

a) Wherever the words óInternational Standardô appears referring to this standard, they should be read as ‘Indian Standard’; and

b) Comma (,) has been used as a decimal marker, while in Indian Standards the current practice is to use a point (.) as the decimal marker.

In this adopted standard, reference appears to International Standards for which Indian Standards also exists. The corresponding Indian Standards, which are to be substituted, are listed below along with their degree of equivalence for the editions indicated:

International Standard	*Corresponding Indian Standard*	*Degree of Equivalence*
IEC 60688 Electrical measuring transducers for converting AC and DC electrical quantities to analogue or digital signals	IS 14570 : 2021 Electrical measuring transducers for converting ac and DC electrical quantities to analogue or digital signals	Identical with IEC 60688 : 2012
IEC 61400-12-1 Wind energy generation systems — Part 12-1: Power performance measurements of electricity producing wind turbines	IS/IEC 61400-12-1 : 2017 Wind energy generation systems: Part 12 Electricity producing wind turbines, Section 1 Power performance measurement	Identical

The technical committee has reviewed the provisions of the following international standards referred in this adopted standard and decided that they are acceptable for use in conjunction with this standard.

International Standard	*Title*
IEC 61400-12-2	Wind energy generation systems ð Part 12-2: Power performance of electricity producing wind turbines based on nacelle anemometry
IEC 61400-12-3	Wind energy generation systems ð Part 12-3: Power performance ð Measurement based site calibration
IEC 61400-12-5	Wind energy generation systems ð Part 12-5: Power performance ð Assessment of obstacles and terrain

(*Continued on third cover*)

CONTENTS

INTRODUCTION

The IEC 61400-12 series consists of the following parts, under the general title Wind energy generation systems:

IEC 61400-12:	*Power performance measurements of electricity producing wind turbines – Overview*
IEC 61400-12-1:	*Power performance measurement of electricity producing wind turbines*
IEC 61400-12-2:	*Power performance of electricity producing wind turbines based on nacelle anemometry*
IEC 61400-12-3:	*Power performance – Measurement based site calibration*
IEC 61400-12-4:	*Numerical site calibration*
IEC 61400-12-5:	*Power performance – Assessment of obstacles and terrain*
IEC 61400-12-6:	*Measurement based nacelle transfer function of electricity producing wind turbines*

The purpose of this document is to provide a uniform methodology of measurement, analysis, and reporting for the determination of a nacelle transfer function of electricity producing wind turbines utilising nacelle-anemometry methods. This document is intended to be applied only to horizontal axis wind turbines of sufficient size that the nacelle-mounted anemometer does not significantly affect the flow through the turbine's rotor and around the nacelle and hence does not affect the wind turbine's performance. The intent of this document is that the methods presented herein be utilised when applying the methodology described in IEC 61400-12-2 to determine the power performance of individual wind turbines. This will ensure that the results are as consistent, accurate, and reproducible as possible within the current state of the art for instrumentation and measurement techniques.

This procedure describes how to characterise a wind turbine's nacelle transfer function in terms of wind speeds measured on a meteorological mast as well as a wind speed measured on the hub or nacelle of a wind turbine. The anemometer that is placed on the turbine is measuring a wind speed that is strongly affected by the test turbine's rotor. This procedure includes methods for determining and applying appropriate corrections for this interference. Such a correction is termed a nacelle transfer function which relates the wind speed measured on the turbine to a free-stream wind speed as measured on a meteorological mast. The procedure also provides guidance on determination of measurement uncertainty including assessment of uncertainty sources and recommendations for combining them into uncertainties.

Even when anemometers are carefully calibrated in a quality wind tunnel, fluctuations in magnitude and direction of the wind vector can cause different anemometers to perform differently in the field. Further, the flow conditions close to a turbine nacelle are complex and variable. Therefore, special care should be taken in the selection and installation of the anemometer. These issues are addressed in this document.

This document will benefit those parties interested in power performance testing of wind turbines using IEC 61400-12-2 as well as parties involved in the installation, planning and execution of such tests. When and where appropriate, the technically accurate measurement and analysis techniques recommended in this document should be applied by all parties to ensure that continuing development and operation of wind turbines is carried out in an atmosphere of consistent and accurate communication relative to environmental concerns. This document presents measurement and reporting procedures expected to provide accurate results that can be replicated by others.

Meanwhile, a user of this document should be aware of differences that arise from large variations in wind shear and turbulence intensity, and from the chosen criteria for data selection. Therefore, a user should consider the influence of these differences and the data selection criteria in relation to the purpose of the test before engaging in nacelle transfer function measurements.

Indian Standard

WIND ENERGY GENERATION SYSTEMS
PART 12-6 MEASUREMENT BASED NACELLE TRANSFER FUNCTION OF ELECTRICITY PRODUCING WIND TURBINES

1 Scope

This part of IEC 61400-12 specifies a procedure for measuring the nacelle transfer function of a single electricity-producing, horizontal axis wind turbine, which is not considered to be a small wind turbine in accordance with IEC 61400-2. It is expected that this document be used when a valid nacelle transfer function is needed to execute a power performance measurement according to IEC 61400-12-2.

A wind speed measured on the nacelle or hub of a wind turbine is affected by the turbine rotor (i.e. speeded up or slowed down wind speed). In IEC 61400-12-1, an anemometer is located on a meteorological tower that is located between two and four rotor diameters upwind of the test turbine. This location allows direct measurement of the "free" wind with minimum interference from the test turbine's rotor. In the procedure of this document, the anemometer is located on or near the test turbine's nacelle. In this location, the anemometer is measuring a wind speed that is strongly affected by the test turbine's rotor and the nacelle. The procedure in this document includes methods for determining and applying appropriate corrections for this interference. However, note that these corrections inherently increase the measurement uncertainty compared to a properly configured test conducted in accordance with IEC 61400-12-1.

This document specifies how to characterise a wind turbine's nacelle transfer function. The nacelle transfer function is determined by collecting simultaneous measurements of nacelle-measured wind speed and free stream wind speed (as measured on a meteorological mast) for a period that is long enough to establish a statistically significant database over a range of wind speeds and under varying wind and atmospheric conditions. The procedure also provides guidance on determination of measurement uncertainty including assessment of uncertainty sources and recommendations for combining them.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60688, *Electrical measuring transducers for converting AC and DC electrical quantities to analogue or digital signals*

IEC 61400-12-1, *Wind energy generation systems – Part 12-1: Power performance measurement of electricity producing wind turbines*

IEC 61400-12-2:2022, *Wind energy generation systems – Part 12-2: Power performance of electricity producing wind turbines based on nacelle anemometry*

IEC 61400-12-3, *Wind energy generation systems – Part 12-3: Power performance – Measurement based site calibration*

IEC 61400-12-5:2022, *Wind energy generation systems – Part 12-5: Power performance – Assessment of obstacles and terrain*

IEC 61400-50-1, *Wind energy generation systems – Part 50-1: Wind measurement – Application of meteorological mast, nacelle and spinner mounted instruments*

ISO/IEC GUIDE 98-3:2008, *Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
accuracy
closeness of the agreement between the result of a measurement and a true value of the measurand

3.2
complex terrain
terrain surrounding the test site that features significant variations in topography and terrain obstacles that may cause flow distortion

3.3
data set
collection of data sampled over a contiguous period

3.4
documentation
any information regarding the test which is kept in files or data, or both, but which is not necessarily presented in the final report

3.5
flow distortion
change in air flow caused by obstacles, topographical variations, turbine's rotor, turbine's nacelle or other wind turbines that results in a significant deviation of the measured wind speed from the free stream wind speed

3.6
free stream wind speed
horizontal wind speed measured upstream of the rotor of the wind turbine generator that is unaffected by rotor aerodynamics

3.7
turbulence intensity
ratio of the wind speed standard deviation to the mean wind speed, determined from the same set of measured data samples of horizontal wind speed, and taken over a specific period of time

3.8
hub height
<wind turbine> height of the centre of the swept area of the wind turbine rotor above the ground level at the tower base

3.9

measurement period

period during which a statistically significant database has been collected for the power performance test

3.10

measurement sector

sector of wind directions from which data are selected for the measured power curve or during the determination of the nacelle transfer function

3.11

measurement uncertainty

parameter, associated with the result of a measurement, which characterises the dispersion of the values that could reasonably be attributed to the measurand

3.12

method of bins

data reduction procedure that groups test data for a certain parameter into intervals (bins)

Note 1 to entry: The method of bins is normally used for wind speed bins but is also applicable to other parameters.

Note 2 to entry: For each bin, the number of data sets or samples and their sum are recorded, and the average parameter value within each bin is calculated.

3.13

nacelle

housing which contains the drive train and other elements on top of a horizontal axis wind turbine generator

3.14

NPC

nacelle power curve

measured power performance of a wind turbine expressed as net active electric power output from the wind turbine as a function of free stream wind speed

Note 1 to entry: For the NPC, the free stream wind speed is not directly measured, but rather the nacelle wind speed is measured and a nacelle transfer function is applied to arrive at the free stream wind speed.

3.15

nacelle wind speed

horizontal wind speed measured on top of or in front of the nacelle of a wind turbine

3.16

obstacle

object that blocks the wind and distorts the flow, such as a building or tree

3.17

pitch angle

angle between the chord line at a defined blade radial location (usually 100 % of the blade radius) and the rotor plane of rotation

3.18

report

any information regarding the test which is stated in the final report

3.19

roughness length

extrapolated height at which the mean wind speed becomes zero if the vertical wind profile is assumed to have a logarithmic variation with height

3.20

ruggedness index

RIX$_{xx}$

measure of terrain, the ruggedness index of which is calculated as the percentage of altitude differences within a given direction sector that exceed an altitude difference of xx × (D + H)

3.21

site calibration

procedure that quantifies and potentially reduces the effects of terrain and obstacles by measuring the correlation over wind direction between the wind speed measured at a reference meteorological mast and the wind speed measured at the wind turbine position

3.22

standard uncertainty

uncertainty of the result of a measurement expressed as a standard deviation

3.23

swept area

for a horizontal-axis turbine, the projected area of the moving rotor upon a plane normal to axis of rotation

Note 1 to entry: For teetering rotors, it should be assumed that the rotor remains normal to the low-speed shaft.

3.24

test site

location of the wind turbine under test and its surroundings

3.25

turbine online

status of the wind turbine, during normal operation excluding cut-in or cut-out, but including any operation at rotor speed in normal operating range where the turbine briefly disconnects from the grid, e.g. switching between generators, generator stages, star/delta or similar

3.26

wind shear

variation of wind speed across a plane perpendicular to the wind direction

4 Symbols, units and abbreviated terms

Symbol or abbreviated term	Description	Unit
A	swept area of the wind turbine rotor	[m^2]
AEP	annual energy production	
ASL	above sea level	[m]
B	barometric pressure	[Pa]
$B_{10\text{min}}$	measured air pressure averaged over 10 minutes	[Pa]
c	sensitivity factor on a parameter (the partial differential)	
$c_{B,i}$	sensitivity factor of air pressure in bin i	[W/Pa]
$c_{d,i}$	sensitivity factor of data acquisition system in bin i	
$c_{k,i}$	sensitivity factor of component k in bin i	
$c_{l,j}$	sensitivity factor of component l in bin j	
$c_{m,i}$	sensitivity factor of air density correction in bin i	[W/m^{3}kg]

Symbol or abbreviated term	Description	Unit
$c_{m,k,i}$	sensitivity factor of component k in bin i on turbine m	
$c_{T,i}$	sensitivity factor of air temperature in bin i	[W/K]]
$c_{V,i}$	sensitivity factor of wind speed in bin i	[W / ms^{-1}]
D	rotor diameter	[m]
D_e	equivalent rotor diameter	[m]
D_n	rotor diameter of neighbouring and operating wind turbine	[m]
D_r	blade rotor diameter	[m]
Elevation	elevation above sea level	[m]
$F(V)$	the Rayleigh cumulative probability distribution function for wind speed	
fi	relative occurrence of wind speed between V_i − 1 and V_i ($F(V_i) – F(V_i$ − 1)) within bin i	
H	hub height of wind turbine	[m]
K	von Karman constant, 0,4	
NT	number of turbines	
L	distance between turbine and met mast (2,5D) in terms of rotor diameters	
Lx	contribution factor related to source x	
M	number of uncertainty components in each bin	
M_A	number of category A uncertainty components	
M_B	number of category B uncertainty components	
N	number of bins	
N_h	number of hours in one year ≈ 8 760	
N_i	number of 10-min data sets in wind speed bin i	
N_j	number of 10-min data sets in wind direction bin j	
N_k	is the number of 10-min data sets in bin k	
N_m	number of bins on turbine m	
N_n	number of bins on turbine n	
n_Test	number of turbines tested	
N	velocity profile exponent (n = 0,14)	
NPC	nacelle power curve	
NTF	nacelle transfer function	
P_i	normalised and averaged power output in bin i	[W]
P_n	normalised power output	[W]
$P_{n,i,j}$	normalised power output of data set j in bin i	[W]
P_10min	measured power averaged over 10 min	[W]
P_w	water vapour pressure	[Pa]
R_0	gas constant (= 287,05)	[J/(kg × K)]
R_w	gas constant of water vapour (= 461,5)	[J/(kg × K)]
RIX$_{20}$	percentage of calculated slopes within a given direction sector that exceed 20 %	
$s_{sc,i}$	standard deviation of the wind speed ratios in bin i	
S	uncertainty component of category A	[W]

Symbol or abbreviated term	Description	Unit
$s_{k,i}$	category A standard uncertainty of component k in bin i	[W]
s_i	combined category A uncertainties in bin i	[W]
$s_{P,i}$	category A standard uncertainty of power in bin i	[W]
$s_{\mathrm{NTF},i}$	statistical uncertainty in captured dataset	
$s_{\alpha,j}$	category A standard uncertainty of wind speed ratios in bin j	[W]
Slope_i	slope between adjacent elevation points	[°]
T	absolute temperature	[K]
TI	turbulence intensity	
T_{10min}	measured absolute air temperature averaged over 10 min	[K]
T	time	[s]
U	uncertainty component of category B	
U_i	Combined category B uncertainties in bin i	
u_{AEP}	combined standard uncertainty in the estimated annual energy production	[Wh]
$u_{\mathrm{AEP,AVG}}$	uncertainty in the average AEP	[Wh]
$u_{\mathrm{AEP},k}$	uncertainty in AEP from category B component k	[Wh]
$u_{\mathrm{AEP},m,k}$	uncertainty in AEP from category B component k on turbine m	[Wh]
u_{AEPRATIO}	ratio of the uncertainty in the AEP	[Wh]
$u_{\mathrm{ano\_class}}$	uncertainty related to anemometer class	[W]
$u_{B,i}$	category B standard uncertainty of air pressure in bin i	[W]
$u_{c,i}$	combined standard uncertainty of the power in bin i	[W]
$u_{c,m,i}$	combined uncertainty in power in bin i on turbine m	[W]
$u_{\mathrm{dFS},i}$	uncertainty component for data acquisition system	
$u_{\mathrm{dP},i}$	uncertainty component for data acquisition of power in bin i	
$u_{\mathrm{dT},i}$	uncertainty component for data acquisition of temperature in bin i	
$u_{\mathrm{d}V,i}$	uncertainty component for data acquisition of wind speed in bin i	
$u_{\mathrm{dWD},i}$	uncertainty component for data acquisition of wind direction in bin i	
u_{FS}	uncertainty component for free stream wind speed	[W]
U_i	combined category B uncertainties in bin i	
$u_{k,i}$	category B standard uncertainty of component k in bin i	[W]
$u_{m,k,i}$	standard uncertainty of component k in bin i on turbine m	[W][kg/m^3]
$u_{l,j}$	standard uncertainty of component l in bin j	[W]
$u_{m,i}$	category B standard uncertainty of air density correction in bin i	[kg/m^3]
u_N	uncertainty component for nacelle wind speed	
$u_{P,i}$	category B standard uncertainty of power in bin i	[W]
u_{sc}	category B standard uncertainty of power in bin i	[W]
$u_{\mathrm{sc},i,j}$	uncertainty component for site calibration in wind speed bin i and wind direction bin j	[W]
$u_{T,i}$	category B standard uncertainty of air temperature in bin i	[K]
$u_{V,i}$	category B standard uncertainty of wind speed in bin i	[W]

Symbol or abbreviated term	Description	Unit
$u_{V,k,i}$	standard uncertainty of wind speed component k in bin i	
u_{WD}	wind direction uncertainty	[°]
$u_{\text{WD,SENSOR}}$	wind direction uncertainty, nacelle measured	[°]
u_{YAW}	wind direction uncertainty, yaw component	[°]
$u_{\text{wind farm\_AEP}}$	total uncertainty in wind farm AEP	[Wh]
$u_{\alpha,i,j}$	combined standard uncertainty of site calibration in wind speed bin i and wind direction bin j	[m/s]
$u_{c,m,i}$	combined uncertainty in power in bin i on turbine m	[W]
V	wind speed	[m/s]
V_{ave}	annual average wind speed at hub height	[m/s]
V_{free}	measured nacelle wind speed, corrected with the nacelle transfer function	[m/s]
V_i	normalised and averaged wind speed in bin i	[m/s]
$V_{\text{met},i}$	bin averages of the met-mast wind speed in bin i wind speed determined with the nacelle anemometer	[m/s]
V_n	normalised wind speed	[m/s]
$V_{n,i,j}$	normalised wind speed of data set j in bin i	[m/s]
$V_{n,k,j}$	normalised wind speed of data set j in bin k	
V_{nacelle}	measured value of the nacelle anemometer for which we want to estimate the free stream wind speed	[m/s]
$V_{\text{nacelle},i}$	bin average value of the nacelle anemometer for bin i	[m/s]
V_{10min}	measured wind speed averaged over 10 min	[m/s]
v_P	wind speed evaluated from the power output	[m/s]
X	distance downstream obstacle to met mast or wind turbine	[m]
Z	height above ground	[m]
z_0	roughness length	[m]
A_j	ratio of wind speeds in wind direction bin j (wind turbine position to meteorological mast position)	
ΔU_z	influence of an obstacle in wind speed difference	[m/s]
Δz_i	Vertical distance between adjacent elevation points	[m]
P	correlation coefficient	
$\rho_{k,l,i,j}$	correlation coefficient between uncertainty component k in bin i and uncertainty component l in bin j	
$\rho_{k,m,n}$	correlation coefficient between turbine m and turbine n for component k	
$P_{k,m,i,l,j,n}$	correlation coefficient between uncertainty component k in bin i on turbine m and uncertainty component l in bin j on turbine n	
ρ_0	reference air density	[kg/m^3]
ρ_{10min}	derived air density averaged over 10 min	[kg/m^3]
$\rho_{ubi,m,n}$	correlation coefficient for pressure	
$\rho_{umi,m,n}$	correlation coefficient for method	
$\rho_{upi,m,n}$	correlation coefficient for electric power	
$\rho_{sp,m,n}$	statistical correlation coefficient	

Symbol or abbreviated term	Description	Unit
$\rho_{uti,m,n}$	correlation coefficient for temperature	
$\rho_{uvi,m,n}$	correlation coefficient for wind speed	
$\sigma_{P,i}$	standard deviation of the normalised power data in bin i	[W]
Σ_{10min}	standard deviation of parameter averaged over 10 min	
$\sigma_u/\sigma_v/\sigma_w$	standard deviations of longitudinal/transversal/vertical wind speeds	[m/s]
Φ	relative humidity (range 0 to 1)	
Ω	angular speed	[s^{-1}]

5 Overview of test method

This test method is based on a basic power performance measurement as per IEC 61400-12-1 with some added signals from the nacelle of the wind turbine, consisting of wind speed and wind direction.

Such a set of signals allows for a correlation to be established between the free stream wind speed signal and the nacelle-based wind speed signal.

The free stream wind speed is derived from a wind speed measurement performed on a meteorological mast. In complex terrain the wind speed from the meteorological mast shall be corrected for flow distortion due to terrain using the IEC 61400-12-3 site calibration procedure.

As this method is closely related to both IEC 61400-12-1 and IEC 61400-12-2, both standards are referred to frequently in this document.

The nacelle wind speed transfer function measurement procedure is designed to assess the effect of the wind turbine rotor on the nacelle wind speed and to quantify the relationship of free stream wind speed to nacelle wind speed. The nacelle wind speed transfer function shall be established by a measurement that is almost identical to an IEC 61400-12-1 measurement. All requirements of IEC 61400-12-1 shall be adhered to, unless this document explicitly deviates from IEC 61400-12-1.

The key result of the nacelle wind speed transfer function measurement is a table or a fitted function of flow correction factors for all measured wind speeds. Another result is an estimate of the uncertainty of these correction factors. This test may also provide information that justifies a change to the allowable measurement sector. An informative flowchart overview of the NTF method is provided in Annex G.

6 Preparation for measurement of nacelle transfer function

6.1 General

The specific test conditions related to the nacelle transfer function measurement of the wind turbine shall be well documented and reported, as detailed in Clause 10.

6.2 Wind turbine

As detailed in Clause 10, the wind turbine shall be assessed, described, and reported to uniquely identify the specific machine configuration that is tested. Note that the validity of the nacelle transfer function depends in part on this description.

The turbine configuration has a significant influence on the measured nacelle power curve of the wind turbine. In particular, nacelle and rotor-based flow distortion effects will cause the wind speed as measured at the turbine nacelle to be different from, though correlated to, the free stream wind speed.

All checks as per Annex A of IEC 61400-12-2:2022 shall be done as part of the wind turbine assessment.

The turbine configuration shall be reported as detailed in Clause 10.

6.3 Test site

6.3.1 General

Conditions at the test site may significantly influence the uncertainty and validity of the measured nacelle transfer function. Although the proximity of the nacelle anemometer to the desired measurement position (the rotor centre) reduces the distortion that exists between an anemometer that is mounted on a meteorological tower and the turbine rotor, topography and obstructions may still influence test results.

The test site shall be assessed for sources of wind flow distortion in order to:

a) define a suitable measurement sector taking the location of obstacles and the terrain classification into consideration;
b) define the site conditions that will help determine the validity of the nacelle transfer function for use in establishing a nacelle power curve;
c) evaluate the uncertainty in the power curve due to wind flow distortion.

The following factors shall be considered, in particular:

1) topographical variations and reference roughness length (as defined in IEC 61400-12-1);
2) other wind turbines;
3) turbulence as function of wind speed and wind direction;
4) obstacles (buildings, trees, etc.).

Two factors are particularly important:

- First, other turbines or significant obstacles upwind of the test turbine produce wakes that influence both the test turbine's power production and the nacelle anemometer's measurements. There are currently no techniques available to minimise this interference with the measurement campaign. Therefore, wakes shall be avoided.
- Second, topographical variations may change the vertical angle of the wind vector at the turbine. Depending on the position of the anemometer on the nacelle, the nacelle transfer function may be altered significantly by changes in the vertical angle of wind. Therefore, the relationship of local wind speed at the nacelle anemometer to vertical wind angle should be assessed. Based on this relationship and test site topology, certain wind directions may be excluded.

The measurement sector shall be determined using the procedure described in IEC 61400-12-2:2022 and IEC 61400-12-5:2022. It is strongly recommended that care be taken such that the average slopes of the 10° direction sectors making up the whole measurement sector have the same sign – i.e. the terrain in the measurement sector is either sloping down towards the turbine or sloping up towards the turbine. A measurement sector that has both uphill and downhill slopes becomes difficult as the NTF is sensitive to this. Therefore, the measurement sector shall be restricted to slopes of the same sign and only an NTF derived for a slope of the same sign and satisfying the other terrain classification validity requirements (6.3.2) shall be used.

If a site calibration is required in accordance with IEC 61400-12-1 it shall be performed as described in IEC 61400-12-3 and applied to the reference met mast wind speed. The following changes to the IEC 61400-12-3 site calibration procedure are allowed:

- The site calibration data may be evaluated in such a way so as to capture variation of the site calibration results with wind speed in addition to the variation with wind direction. This would lead to flow correction values as a function of binned wind speed as well as wind direction. To ensure a reasonable chance of obtaining sufficient data in each bin, a 10° wide wind direction bin and 4 m/s wide wind speed bin shall be used. The wind speed bins shall be centred around 2 m/s plus integer multiples of 4 m/s.
- A linear regression of wind speed from the reference met mast versus wind speed from the temporary met mast for each wind direction bin may be made to determine the variation with wind speed and to allow a better characterisation if offsets are present. If offsets are present, the flow correction factors are the resulting regression formula per wind direction bin.
- An additional analysis that may be implemented is a wind direction site calibration in order to establish the difference in wind direction between the permanent mast and the temporary mast as a function of wind speed and wind direction at the temporary mast. The consideration behind such an evaluation is that the turbine rotor influences the wind direction on the nacelle as well as the wind speed on the nacelle. A more accurate result may be possible by applying an NTF on both wind speed and wind direction. An NTF on wind direction can be established from the same data as an NTF on wind speed. But in order to establish an NTF on wind direction, the influence of the terrain needs to be separated from the influence of the rotor as much as is possible. A site calibration on direction will focus on offsets instead of ratios. Disregarding the influence of terrain and/or rotor on wind direction will increase the uncertainty of the absolute wind direction and therefore decrease the measurement sector when establishing an NPC.

The exact procedure used to establish a site calibration for wind speed and possibly wind direction shall be reported in such detail that it can be reviewed and, if necessary, repeated. An uncertainty assessment for all results from the site calibration shall be performed and reported.

The test site and the measurement sector shall be reported as detailed in Clause 10.

6.3.2 Terrain classification

The terrain around the turbine under test shall be classified as per IEC 61400-12-5.

As the validity of the nacelle transfer function depends (among other aspects) on the terrain classification, it shall be clearly documented in which of the five defined terrain classes in IEC 61400-12-5 the nacelle transfer function has been measured.

6.4 Test plan

A test plan shall be prepared prior to the test that addresses the information covered in Clause 10 of this document to the extent that it can be determined prior to the tests. The guidelines in Annex F should also be considered regarding the organisation of the test, safety and communication.

7 Test equipment

7.1 General

The signals that shall be measured in accordance with the requirements in IEC 61400-12-1 are:

a) wind speed on the meteorological mast;
b) wind direction on the meteorological mast;
c) wind turbine power;

d) electric power;
e) turbine generator grid connection status signal.

Additional to the requirements of IEC 61400-12-1, the following signals shall be measured in accordance with the requirements in IEC 61400-12-2:

1) nacelle wind speed;
2) nacelle wind direction;
3) nacelle yaw position;
4) air temperature;
5) air pressure.

The following signals may be captured in accordance with requirements in IEC 61400-12-2:

- rotor speed;
- pitch angle(s);
- relative humidity.

Instead of measuring the rotor speed and pitch angles, the software version, relevant parameters and their values may be documented for future validity check.

The nacelle wind direction signal shall be verified in-situ to determine correct operation and establish a specific relation to the nacelle's longitudinal axis. The nacelle yaw position shall be verified to determine correct operation and establish true north.

Note that some of these signals are required not to establish the nacelle transfer function but to perform the self-consistency check as mentioned in IEC 61400-12-2.

7.2 Data acquisition

The data acquisition system may be external to the turbine, it may be the turbine controller data system, or it may be a combination of both. A data acquisition system having a sampling rate per channel of at least 1 Hz shall be used to collect measurements and store pre-processed data.

The turbine controller data system (i.e. SCADA system) may be used for data acquisition as long as it fulfils the requirements and gives sufficient insight into the traceability of the signals and signal processing.

The calibration and accuracy of the data system chain (transmission, signal conditioning and data recording) shall be verified by injecting known signals at the transducer ends and comparing these inputs against the recorded readings. This shall be done using instrumentation that is calibrated traceable to national standards. As a guideline, the uncertainty of the data acquisition system should be negligible compared with the uncertainty of the sensors.

Any influence or operation performed by the data acquisition system on the data shall be reported. The following checks shall be done:

a) any averaging or filtering of the data by the data acquisition system shall be reported in such detail that its effect on the data and the uncertainty of the data can be established;
b) any internal calibrations, applied offsets or corrections applied to the data shall be reported in such detail that the calibrations, applied offsets or corrections can be undone during data processing;
c) the uncertainty of the whole signal chain shall be calculated for each signal;
d) a correct treatment of the wind direction north jump (360° to 0° transition or vice versa) averaging shall be verified.

If the conditions in this Subclause 7.2 cannot be fulfilled due to the fact that a turbine controller data system is used, a separate, independent data system that is capable of fulfilling these requirements shall be installed and used instead.

8 Measurement procedure

8.1 General

The objective of the measurement procedure is to collect data that meet a set of clearly defined criteria to ensure that the data are of sufficient quantity and quality to determine the nacelle transfer function of the wind turbine accurately. The measurement procedure shall be documented, as detailed in Clause 10 so that every procedural step and test condition can be reviewed and, if necessary, repeated.

Accuracy of the measurements shall be expressed in terms of standard uncertainty, as described in Annex B, Annex C and Annex D. During the measurement period, data should be periodically validated to ensure high quality. Test logs shall be maintained to document all important events during the power performance test.

The nacelle wind speed transfer function should be measured on a turbine in similar terrain to that of the turbine to which the NTF will be applied to determine the NPC. If this is not possible then the NTF should be measured in flat terrain.

The nacelle wind speed transfer function measurement procedure is designed to assess the effect of the wind turbine rotor on the nacelle wind speed and to quantify the relationship of free stream wind speed to nacelle wind speed. The nacelle wind speed transfer function shall be established by a measurement that is almost identical to an IEC 61400-12-1 measurement. All requirements of IEC 61400-12-1 shall be adhered to, unless this document explicitly deviates from IEC 61400-12-1.

The key result of the nacelle wind speed transfer function measurement is a table or a fitted function of flow correction factors for all measured wind speeds. Another result is an estimate of the uncertainty of these correction factors. This test may also provide information that justifies a change to the allowable measurement sector.

In line with 6.3, appropriate nacelle wind speed transfer functions shall be established for the valid sector according to terrain classification. If not already done, a wind turbine assessment (6.2), site assessment and terrain classification (6.3) shall be done. Similar to 6.4, a test plan shall be written which includes the test set-up, selection of sensors and measurement equipment and other relevant information. For the data acquisition system, 7.2 applies.

8.2 Data system(s) synchronisation

If, during one test, the signals are measured with more than one data acquisition system, the synchronisation of all systems shall be ensured throughout the measurement period. The maximum synchronisation difference between any two data acquisition systems shall be less than 1 % of the averaging time. Any violation of this synchronisation requirement shall be reported.

It is recommended to avoid synchronisation problems by measuring with one single measurement system. The recommended time convention is coordinated universal time (UTC) or a reference to the UTC time base. The time correction applied for each update shall be logged. The selected time reference shall be reported.

8.3 Data collection

Data shall be collected continuously at a sampling rate of 1 Hz or faster. The data acquisition system should as a minimum store statistics of data sets of all signals as follows:

a) 10-min mean value;
b) 10-min standard deviation;
c) 10-min maximum value;
d) 10-min minimum value.

If the data collection system present in the turbine cannot do this for all signals, then 10-min minimum, 10-min maximum, 10-min standard deviation and 10-min mean shall be stored for all wind speed and power signals. For the other signals, storing a 10-min mean signal will suffice.

Selected data sets shall be based on 10-min periods derived from contiguous measured data. Data shall be collected until the requirements defined in 8.7 are satisfied.

The standard analysis will be based on the 10-min statistics of the measured data. This has been chosen to keep the results closely linked to those of IEC 61400-12-1.

It is important to note that the choice to use 10-min statistics in itself influences the result of the power performance test, for instance through the effect of turbulence. Originally, the 10-min period was selected, among other reasons, to allow for the time the wind needs to flow from mast to turbine and to ensure reasonable correlation between wind speed and power. In the case of nacelle anemometry, this is no longer needed and there are arguments to reduce the averaging time to a period less than 10 min.

In order to keep the link with IEC 61400-12-1 and at the same time not prevent more accurate reporting, the choice has been made to always report the standard result based on 10-min statistics, but to allow analysis based on shorter averaging periods to be reported as well. The validity of the applied transfer function shall be checked when using shorter averaging periods.

8.4 Data quality check

8.4.1 General

To ensure the data included in the final valid database of results are accurate, quality control steps shall be performed on the data during, or prior to, the data reduction and analysis process. Subclauses 8.4.2 to 8.4.5 list examples of quality control methods, but do not include all methods that may be required. Data points that fail to meet the quality control criteria defined by the user shall be removed from the valid database. All data filtering methodology shall be reported thoroughly as required by Clause 10. These steps are in addition to the check/calibration of the measurement system as described in 6.2.

8.4.2 Measured signals are in range and available

Ensure that each data set in which a required signal is outside the signal range is excluded from the valid database. Similarly, exclude data sets in which one or more of the required signals are unavailable or not operating for one or more samples. These exclusions shall be reported and described as per the requirements listed in Clause 10.

8.4.3 Sensors are operating properly

The individual data set average, maximum, minimum and standard deviation statistics of the measured signals shall be checked periodically to ensure the values are consistent with the expected values (e.g. no significant signal noise; or no significant data when the sensors are influenced by their mounting structure or other sensors). Manually interrogating time-series and/or scatter plots of a subset of the measured data (database sampling) is suggested, in addition to automated techniques, in order to ensure all irregularities are identified. Additionally, compare like signals with one another (e.g. primary and control wind speed on meteorological tower; turbine-measured power and independent power signal; turbine yaw position to meteorological tower, or nearby wind direction measurement) to ensure the deviations are consistent with the expected values. Suspect data should be excluded from the valid database. These exclusions shall be reported and described as per the requirements listed in Clause 10.

8.4.4 Ensure data acquisition system(s) is(are) operating properly

Steps should be taken to verify that the data acquisition system operates properly throughout the measurement period. These steps include, but are not limited to:

a) ensuring data records are not repeated;

b) investigating the cause for any significant data gaps in measured signals;

c) investigating any discontinuities in measured signals that do not correspond to data gaps.

If any issues are found, these findings shall be documented and reported. The checks themselves shall also be reported.

8.4.5 Sector self-consistency check

Once a (draft) NPC is available the sector self-consistency check in 9.3.3 shall be carried out.

8.5 Data rejection

Certain data sets shall be excluded from the database to ensure:

a) analysis and results are commensurate with normal operating conditions of the turbine;

b) corrupted and inaccurate data are excluded.

Data sets shall be excluded from the database under the following circumstances:

1) external conditions other than wind speed are out of the operating range of the wind turbine;
2) external conditions are out of the operating range of the test instruments;
3) turbine is not online (except for turbines that temporarily go offline as part of normal operation, e.g. generator switching. These effects shall be captured in the power curve and the precise filter applied shall be reported);
4) turbine is output-limited by external factors such as the power grid; this shall be documented in situ, for instance with a logbook or status-signal from the turbine;
5) failure or degradation (e.g. due to icing) of test equipment;
6) 10-min average wind direction outside the measurement sector is as defined in IEC 61400-12-5;
7) blade icing events and snow cover on the nacelle;
8) turbine cannot operate because of a turbine fault condition;
9) turbine is manually shut down or in a test or maintenance operating mode.

Any other rejection criteria shall be clearly reported. All data rejected for these reasons shall be clearly documented and reported.

8.6 Data correction

For the selected data sets the following data corrections shall be made to the following measurements:

a) air pressure correction to rotor centre altitude ASL (if required by 7.2);

b) the absolute wind direction shall be calculated from the nacelle yaw position and the nacelle vane signal;

c) signal modifications applied by the wind turbine controller shall be taken into account to ensure correct final values;

d) data may be corrected for any calibrations, applied offsets or corrections performed by the data acquisition system in order to ensure the highest data quality, as applicable and as long as clearly reported;

e) nacelle wind speed shall be corrected to free stream wind speed using the valid nacelle transfer function;

f) any other corrections made to the data shall be reported clearly and in detail.

The data correction details shall be reported as detailed in Clause 10.

8.7 Database

After data normalisation (see 9.1) the selected data sets shall be sorted using the "method of bins" procedure (see 9.2). The selected data sets shall at least cover a wind speed range extending from cut-in to 1,5 times the wind speed at 85 % of the rated power of the wind turbine. Alternatively, the wind speed range shall extend from cut-in to a wind speed at which "AEP-measured" is greater than or equal to 95 % of "AEP-extrapolated" (see 9.3). The report shall state which of the two definitions has been used to determine the range of the measured power curve. The wind speed range shall be divided into 0,5 m/s contiguous bins centred on multiples of 0,5 m/s.

The database shall be considered complete when it has met the following criteria:

a) each bin includes a minimum of 30 min of sampled data;

b) the database includes a minimum of 180 h of sampled data.

Should a single incomplete bin be preventing completion of the test, then that bin value can be estimated by linear interpolation from the two adjacent complete bins.

In order to complete the power curve at high wind speeds the following procedure can be used. For wind speeds above 1,6 times the wind speed at 85 % of rated power the measurement sector can be opened.

The following condition shall be fulfilled when using the above two extended procedures: AEP-measured from extended procedures deviates less than 1 % from AEP-extrapolated up to the highest complete wind speed bin for the extended procedures (for the Rayleigh distribution in 9.3). Note that the power curve referred to in this Subclause 8.7 is the NPC measured during the NTF measurement.

The database shall be presented in the test report as detailed in Clause 10.

9 Derived results

9.1 Overview of derived results

The derived results are:

a) A nacelle transfer function (NTF) for wind speed describing V_{free} as a binned result or a mathematical function of bin averaged V_{nacelle}.

b) A site calibration for wind speed (if required by IEC 61400-12-1), expressed as:
   1) flow correction factors per wind direction bin, or
   2) flow correction factors per wind direction and wind speed bin, or
   3) linear regression parameters per wind direction bin.

c) Optionally, a nacelle transfer function (NTF) for wind direction, expressed as an offset per wind speed bin or as a mathematical function of nacelle wind speed.

d) Optionally, a site calibration for wind direction, expressed as:
   4) offsets per wind direction bin, or
   5) offsets per wind direction and wind speed bin, or
   6) linear regression parameters per wind direction bin.

e) Results of the self-consistency check, in accordance with 9.3.3.

f) Uncertainty analysis on all of the derived results, in accordance with Clause 10.

g) Report on the nacelle transfer function, in accordance with Clause 10.

9.2 Determination of measured nacelle transfer function

The nacelle transfer function is determined by applying the "method of bins" for the normalised data sets, using 0,5 m/s bins and by calculation of the mean values of the normalised wind speed and normalised nacelle wind speed for each wind speed bin according to Equation (1) and Equation (2):

$$V_i = \frac{1}{N_i} \sum_{j=1}^{N_i} V_{n,i,j} \tag{1}$$

$$V_k = \frac{1}{N_k} \sum_{j=1}^{N_k} V_{n,k,j} \tag{2}$$

where

V_i is the normalised and averaged wind speed in bin i;

$V_{n,i,j}$ is the normalised wind speed of data set j in bin i;

V_k is the normalised and averaged nacelle wind speed in bin k;

$V_{n,k,j}$ is the normalised nacelle wind speed of data set j in bin k;

N_i is the number of 10-min data sets in bin i;

N_k is the number of 10-min data sets in bin k.

The nacelle wind speed shall be binned against the free stream wind speed according to the method of bins described in the IEC 61400-12-1, with the free stream wind speed on the x-axis. Then a linear interpolation can be made to interpolate between bins. Using the data in the database, V_{free} shall be calculated using Equation (3):

$$V_{\text{free}} = \frac{V_{\text{free},i+1} - V_{\text{free},i}}{V_{\text{nacelle},i+1} - V_{\text{nacelle},i}} \cdot \left(V_{\text{nacelle}} - V_{\text{nacelle},i}\right) + V_{\text{free},i} \tag{3}$$

where

$V_{\text{nacelle},i}$ and $V_{\text{nacelle},i+1}$ are bin averages of the nacelle wind speed in bin i and i + 1;

$V_{\text{free},i}$ and $V_{\text{free},i+1}$ are bin averages of the met-mast wind speed in bin i and i + 1, flow correction factors shall be applied from the site calibration measurement, if appropriate;

V_{nacelle} is the measured value of the nacelle anemometer for which the free stream wind speed is estimated;

V_{free} is the free stream wind speed estimated using the measured nacelle and met mast wind speed, corrected for flow distortion due to terrain (V_{nacelle} and V_{free}, respectively).

The nacelle transfer function (NTF) is defined as V_{free} as a function of V_{nacelle} per bin. The NTF is only valid from the lowest wind speed bin to the highest wind speed bin and extrapolation of the NTF is never allowed.

Alternatively, the function of V_{free} on y-axis and V_{nacelle} on x-axis (binned on V_{nacelle}) may be fitted with a mathematical function. A weighted fit may be considered, for instance to adequately account for outliers. It shall be reported how the fit has been made and what weighting function has been used, as well as what the uncertainty contribution of the fitted result is.

A similar procedure can be followed to establish the NTF for wind direction; that procedure would focus on offsets rather than ratios.

The measured power curve shall be presented as detailed in Clause 10.

9.3 Data quality check

9.3.1 General

A data quality check shall be performed as described in 8.4.

Additionally, create and review scatter plots of relevant signals to verify that the provided met mast instrumentation and test site layout description are correct. For example:

- Plot the 10-min average primary and control anemometer ratio (as defined in IEC 61400-12-1) versus wind direction.
- Compare the location (degrees with respect to true north or other reference) of the mounting structure (single hub-height anemometer mounting option) or the location of the primary/control anemometer wakes (double hub-height anemometer mounting option) inferred by these plots to the documented instrumentation arrangement.

These plots can also be used to verify the documented turbine to meteorological tower bearing by comparing the inferred turbine wake centre with the expected value.

Discrepancies found shall be investigated and corrected for in the analysis, if possible. Unresolved discrepancies shall be reported in the measurement report.

9.3.2 Directional stability check

A measured transfer function may show larger variation in certain wind directions. This can be caused by the local terrain but also because the wind direction may fluctuate a lot if the wind is not from the predominant wind direction. It is recommended to analyse the variance of the transfer function with wind direction in the following way.

The data set that the transfer function is based on shall be binned into 10° wind direction bins, centred on integer multiples of 10°. Where a site calibration has been previously performed, it is recommended to use the same direction bins in order to reflect the directional effect of the site calibration on the transfer function. $V_{\text{free}}/V_{\text{nacelle}}$ shall be averaged for each bin, and the standard deviation of $V_{\text{free}}/V_{\text{nacelle}}$ shall be calculated for each direction. The wind speed range for which this is done shall be selected such that it excludes significant pitch activity with adequate margin to allow for the 10-min averaging. It is also recommended to compare residuals as part of the stability check.

The average and standard deviation shall be plotted against the wind direction average of each bin. This plot will show if the transfer function is sensitive to wind direction. If a clear effect of wind direction can be seen, the measurement sector may be reduced to include only those directions that show a consistent result.

In those cases where a sector has been reduced, the self-consistency check described in 9.3.3 shall show evidence of the improvement of the new NTF.

9.3.3 Self-consistency check for NTF, using the NPC

The nacelle wind speed shall be corrected with the established transfer function, and a power curve and AEP shall be calculated using the corrected wind speed. Optionally, the nacelle wind direction may be corrected with the established transfer function for wind direction. Note that the NPC referred to in this Subclause 9.3.3 is the NPC during the NTF measurement.

A power curve and AEP shall also be made based on the IEC 61400-12-1 measurement and method, with the difference that the filtering shall be done with the turbine online signal. The same database of valid measured data shall be used for both analyses limiting the wind speed range, as necessary, to ensure both analyses cover the same wind speed range.

Both results shall be compared as binned power curves as well as AEP. The maximum difference in power per bin shall be 1 % of bin power or 0,5 % of rated power whichever is largest. The maximum difference in AEP shall be 1 % for hub height annual average wind speed 4 m/s to 11 m/s as per 9.3.

If the self-consistency check does not meet the criteria listed above, the root cause shall be investigated and corrected or another NTF method should be considered for use. If the root cause for the discrepancy cannot be determined and as long as the differences on binned power and AEP are less than 3 % or 1,5 % of rated power whichever is largest, additional uncertainty shall be estimated, documented and reported. If the differences are larger than 3 % of bin power or 1,5 % of rated power (whichever is largest) a new test shall be done.

9.4 Uncertainty analysis

The uncertainty of the nacelle transfer function(s) shall be calculated according to Annex B, Annex C and Annex D of this document.

10 Reporting format

The test shall be reported in such detail that every significant procedural step and test condition can be reviewed, and, if necessary, repeated. This document differentiates between documentation and reporting. The measurement party shall maintain all documentation for future reference, even in the event that the documentation is not reported. The documents should be retained for a prescribed period of time, typically ten years per ISO 17025. An example of such documentation would be turbine maintenance records. The following are the minimum nacelle power performance test reporting requirements.

The test report shall contain, at a minimum, the following information:

a) A description of the test site (see 6.3), including:
    1) photographs of all measurement sectors preferably taken from the wind turbine at hub height;
    2) a test site map with such scale as to detail the surrounding area covering a radial distance of at least 20 times the wind turbine rotor diameter and indicating the topography, location of the wind turbine under test, meteorological masts (if applicable), significant obstacles, other wind turbines, vegetation type and height, and measurement sector;

   3) results of site assessment, as reported according to the terrain classification process in accordance with 6.3;
   4) if a site calibration is undertaken to establish the nacelle transfer function, the limits of the final measurement sector(s) shall also be reported;
   5) terrain description including estimates of the slope angle for various directions;
   6) nominal site-specific air density.

b) A description of the test equipment, inclusive of the site calibration, nacelle transfer function, nacelle power curve tests (see Clause 7):
   1) identification of the sensors and data acquisition system(s) for each measurement parameter, including documentation of calibrations for the sensors, transmission lines, and data acquisition system;
   2) description of the arrangement of anemometers on the mounting structure on the nacelle, following the requirements and descriptions in Annex A;
   3) sketch of the arrangement of the mounting structure showing principal dimensions of the structure and instrument mounting fixtures;
   4) description of in-situ calibration method (if applicable) and documentation of results that show that the calibration is maintained;
   5) results of the end-to-end calibration for power, wind speed, wind direction, temperature and pressure.

c) A description of the measurement procedure:
   1) reporting of the procedural steps, test conditions, sampling rate, averaging time, measurement period;
   2) documentation of the data filtering, including exact filter criteria limit values, filtering order and the total number of data points removed;
   3) documentation of all corrections applied to the data;
   4) a summary of the test log book that records all important events during the power performance test, including a listing of all maintenance activities that occurred during the test and a listing of any special actions (such as blade washing) that were completed to ensure good performance;
   5) identification of any data rejection criteria beyond those listed in 8.5;
   6) if more than one measurement system was used, a statement regarding the synchronisation of all systems shall be included. The maximum time difference registered between these systems shall be documented and a graph or table showing the time corrections made during the measurement campaign on each measurement system shall be shown.

d) Presentation of measured nacelle transfer function:
   1) the measured nacelle transfer function shall be presented in a graph similar to Figure 1 and a table similar to Table 1;
   2) both the graph and the table shall state the reference air density, used for the normalisation.

e) Uncertainty of measurement:

   Uncertainty assumptions on all uncertainty components shall be provided as well as assumptions regarding contribution of uncertainties and correlated/uncorrelated uncertainties, as described in Annex B, Annex C and Annex D.

f) Deviations from the procedure:

   Any deviations from the requirements of this document shall be clearly reported in a separate clause. Each deviation shall be supported with the technical rationale and an estimate given of its effect on the test results.

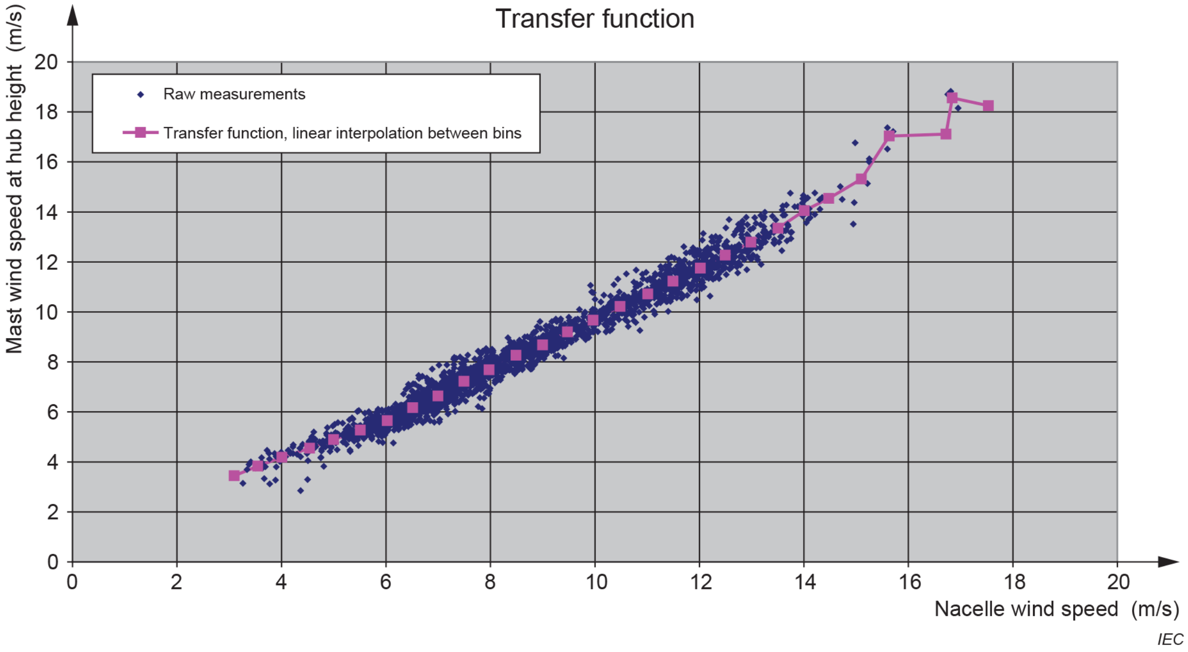


Figure 1 – Presentation of example data: measured transfer function

Table 1 – Example of presentation of a measured power curve based on data from the meteorological mast, for consistency check

Wind turbine + meteorological mast							
Reference air density: 1,225 kg/m^3					Category A	Category B	Combined uncertainty
Bin no.	$V_{\text{free stream}}$ wind speed m/s	Power output kW	C_p	No. of data sets #	Standard uncertainty s_i kW	Standard uncertainty u_i kW	Standard uncertainty u_{ci} kW
7	3,71	−9,3	−0,053	3	2,35	20,43	20,56
8	4,00	17,2	0,077	24	5,21	23,37	23,94
9	4,52	64,2	0,201	27	5,57	23,89	24,53
10	5,03	119,9	0,272	77	3,49	25,89	26,12
11	5,53	204,6	0,349	124	3,32	33,49	33,65
12	6,02	293,4	0,386	200	3,26	36,25	36,40
13	6,51	389,0	0,406	231	3,41	40,48	40,62
14	7,00	498,8	0,418	240	4,46	46,40	46,62
15	7,48	616,7	0,424	203	5,42	53,19	53,47
16	7,99	768,8	0,433	165	7,23	65,46	65,86
17	8,49	946,0	0,445	163	7,86	81,83	82,21
18	8,97	1 098,1	0,438	118	10,89	75,82	76,60
19	9,50	1 282,5	0,431	90	12,11	87,63	88,47
20	10,03	1 526,5	0,435	86	12,84	117,68	118,38
21	10,50	1 707,7	0,424	84	12,41	105,27	105,99
22	11,03	1 950,9	0,419	111	10,61	129,94	130,37
23	11,48	2 119,7	0,403	112	12,68	109,25	109,98
24	11,98	2 296,7	0,385	113	8,87	110,43	110,78
25	12,5	2 393,5	0,352	80	5,49	64,97	65,20
26	12,97	2 440,6	0,322	49	5,34	45,24	45,55
27	13,50	2 462,5	0,288	29	2,56	35,00	35,10
28	13,99	2 469,1	0,260	17	1,01	32,57	32,58
29	14,45	2 469,1	0,235	5	1,32	32,24	32,27
30	15,07	2 472,3	0,208	3	0,46	32,32	32,33
31	15,72	2 472,0	0,183	3	0,56	32,27	32,27

Annex A
(informative)

Nacelle instrument mounting

A.1 General

Appropriate arrangement of instruments on the nacelle is important for accurate wind turbine testing. In particular, the anemometer should be mounted to minimise flow distortions, especially from boom influences. The anemometer on the nacelle should be positioned to make it insensitive to turbine settings and the flow distortion caused by the complexity of the surrounding terrain. Other instruments and objects on the nacelle should be mounted in such a way that avoids interference with the anemometer.

A.2 Preferred method of anemometer's mounting

The preferred method for mounting the anemometer is vertically on top of a tube with no other instruments or equipment nearby. Satisfying all provisions of this Clause A.2 achieves negligible distortion of the wind measurements induced by the mounting. The anemometer should be mounted on a round vertical tube, with the same outer diameter as used during calibration, which carries the cable to the anemometer inside. The angle deviation from vertical should be less than 2°, and it is recommended to use an inclinometer to verify the verticality of the anemometer during installation. The tube should be no larger in diameter than the body of the anemometer. The bracket connecting the anemometer to the vertical tube should be compact, smooth, and symmetrical.

A.3 Preferred position of anemometer

The anemometer should be located in the symmetry plane of the nacelle. It should be located somewhere along the nacelle where the movements and vibrations are small. A candidate location, if possible, is to mount the anemometer on the extension of the tower centre.

A wind sensor mounted on the nacelle should be mounted above the boundary layer caused by the nacelle, indicated by the 10° line in Figure A.1, and it should also be mounted outside the influence of root vortexes caused by the change from cylindrical blade root to profiled blade, indicated by the upper line of the grey area. Additionally, the sensor should be mounted at least one and a half blade root diameters ($1{,}5D$) behind the blade root centre, and it should not be mounted on the downwind side of railings or in wake of other sensors or warning lights. The sensor should not be mounted within 1 m of the downwind end of the nacelle.

A wind sensor mounted on the spinner may be mounted, centred on the shaft axis, on a rod extending from the spinner at a practical distance based on engineering experience. Alternatively, it may be mounted on the spinner surface in the case that the measurement principle of the sensor is based on the flow over the spinner. Either way, it shall be mounted at least $0{,}6D$ in front of the blade root centre.

Figure A.1 shows the recommended locations for the anemometer. In Figure A.1, D_r is used for the blade root diameter.

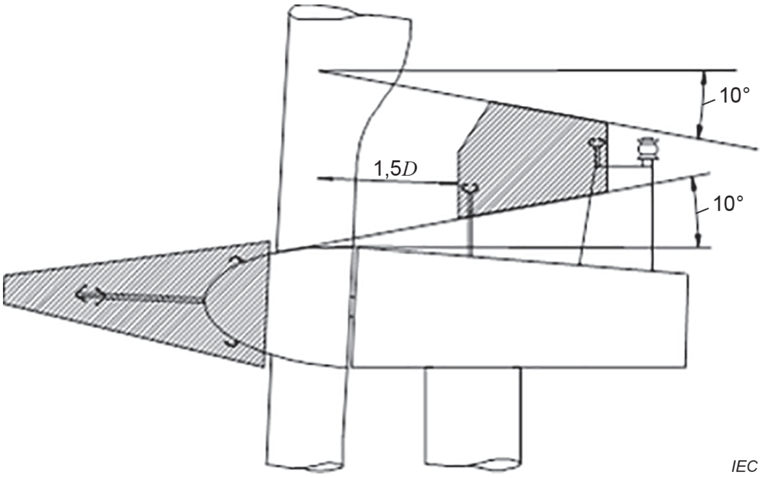


Figure A.1 – Mounting of anemometer on top of nacelle

The anemometer should be mounted inside the hatched areas.

Annex B
(normative)

Evaluation of uncertainty in measurement

B.1 General

This annex addresses the requirements for the determination of uncertainty in measurement. The theoretical basis for determining the uncertainty using the method of bins can be found in Annex C and an example of estimating uncertainties, in Annex D.

The measured NTF and NPC shall each be supplemented with an estimate of the uncertainty of the results due to uncertainty in the measurement as well as other factors such as terrain. The estimate shall be based on the provisions of ISO/IEC GUIDE 98-3.

Following ISO/IEC GUIDE 98-3, there are two types of uncertainties: category A, the magnitude of which can be deduced from measurements, and category B, which are estimated by other means. In both categories, uncertainties are expressed as standard deviations and are denoted standard uncertainties.

B.2 The measurands

The measurands are the power curve, determined by the measured and normalised bin values of electric power and wind speed (see 9.1 and 9.2), and the estimated annual energy production (see 9.3). Uncertainties in the measurements are converted to uncertainty in the measurand by means of sensitivity factors.

B.3 Uncertainty components

Table B.1 and Table B.2 provide minimum uncertainty parameters that shall be included in the uncertainty analysis of the NTF and NPC, respectively.

Table B.1 – Uncertainty components in nacelle transfer function evaluation

Measured parameter	Uncertainty component	Uncertainty category
Site calibration (if carried out)	Reference position	
	Anemometer calibration	B
	Operational characteristics	B
	Mounting effects	B
	Data acquisition system	B
	Turbine position	
	Anemometer calibration	B
	Operational characteristics	B
	Mounting effects	B
	Data acquisition system	B
	Statistical variation	A
Free stream wind speed	Anemometer calibration	B
	Operational characteristics	B
	Mounting effects	B
	Site calibration (if carried out)	B
	Data acquisition system	B
Nacelle wind speed	Anemometer calibration due to wind speed (sonics)	B
	Anemometer calibration due to wind direction (sonics)	B
	Operational characteristics	B
	Mounting effects	B
	Data acquisition system	B
Transfer function	Type A uncertainty in transfer function regression or bin average as appropriate.	A
Method	Seasonal variation of site calibration results	B
	Seasonal variation (changing climatic conditions) on NTF	B

The components mentioned in Table B.1 constitute a minimum list of uncertainty components. Components can be added as needed.

NOTE The implicit assumption of the method of this document is that the 10-min mean power yield from a wind turbine is fully explained by the simultaneous 10-min mean wind speed measured by the nacelle anemometer (related to the free stream wind speed by a turbine-type specific measured NTF) and the air density. This is not the case. Other flow variables affect both the power yield and the NTF. Thus identical wind turbines will yield different power and different nacelle wind speeds at different sites even if the free stream hub height wind speed and air density are the same. These other variables include turbulent fluctuations of wind speed (in three directions), the inclination of the flow vector relative to horizontal scale of turbulence, and shear of mean wind speed over the rotor. Currently, analytical tools offer little help in identification of the impact of these variables and experimental methods encounter equally serious difficulties.

The result is that the power curve will vary from one site to the next, but since the other influential variables are not measured and taken into account, the variation in the power curve will appear as uncertainty.

This apparent uncertainty stems from differences in observed power yield under different topographical and climatic conditions, i.e. when comparing an AEP measured in homogeneous terrain with an AEP measured at a non-homogeneous wind farm site.

Quantification of this apparent uncertainty is difficult. Depending on site conditions and climate, the uncertainty in the nacelle power curve can be around 10 % or more. In general terms, the uncertainty can be expected to increase as the complexity of the site conditions under which the NTF was measured and the complexity of the site conditions under which the NPC was measured diverge, with increasing complexity of topography and with increasing frequency of non-neutral atmospheric conditions. This document addresses this issue by adding uncertainty components such as seasonal variation and inflow to rotor.

B.4 Wind direction uncertainty

The uncertainty of the wind direction does not directly influence the uncertainty of the power curve or the uncertainty of the annual energy production but it does influence the calculation of the measurement sector, as required in Annex B. Therefore, some estimates of the contributing uncertainty components are given in this Clause B.4.

The uncertainty in the wind direction measurement consists of three components: the uncertainty in the yaw position, the uncertainty in the nacelle wind vane and the uncertainty in the data acquisition system. Furthermore, the uncertainty in the yaw position consists of the uncertainty in the alignment (or sensor mounting) and of the signal resolution (or sensor uncertainty). The uncertainty in the nacelle measured wind direction consists of the calibration uncertainty (sonic sensors only), the in-situ calibration uncertainty and the effects the rotor and terrain have on the measurement (the latter includes up-flow effects for the specific site). Table B.2 lists the uncertainty components associated with the nacelle based absolute wind direction.

Table B.2 – Uncertainty components in nacelle based absolute wind direction

Measured parameter	Uncertainty component	Uncertainty category
Yaw position	Field calibration	B
	Signal resolution	B
Nacelle measured wind direction	Calibration – sensor mounting position uncertainty (sonic sensors only)	B
	Calibration – bin averaged wind direction difference due to wind direction (sonic sensors only)	B
	Calibration – bin averaged wind direction difference due to non-vertical flow (sonic sensors only)	B
	Sensor alignment	B
	Rotor effect on average measured wind direction	B
	Terrain effects on average measured wind direction	B
Data acquisition system	Signal transmission	B
	System accuracy	B
	Signal conditioning	B

Annex C
(normative)

Theoretical basis for determining the uncertainty of measurement using the method of bins

C.1 General

The corrected wind speed derived from application of a nacelle transfer function (NTF) has uncertainty associated with measurement of the NTF and also with transferral of the NTF to the same or other turbines (of the same type) experiencing in-flow conditions different to those prevailing during measurement of the NTF relationship.

In evaluating the uncertainty, $u_{c,i}$, in the wind speed output from bin i of a measured NTF or in the power in bin i of a nacelle power curve, the combined standard uncertainty can be expressed in its most general form by:

$$u_{c,i}^2 = \sum_{k=1}^{M}\sum_{l=1}^{M} c_{k,i}u_{k,i}c_{l,i}u_{l,i}\rho_{k,l,i,j} \tag{C.1}$$

where

$c_{k,i}$ is the sensitivity factor of component k in bin i;

$u_{k,i}$ is the standard uncertainty of component k in bin i;

$c_{l,j}$ is the sensitivity factor of component l in bin j;

$u_{l,j}$ is the standard uncertainty of component l in bin j;

M is the number of uncertainty components in each bin;

$\rho_{k,l,i,j}$ is the correlation coefficient between uncertainty component k in bin i and uncertainty component l in bin j (in Equation (C.1) only the diagonal elements, $j = i$, are used).

The uncertainty component is the individual input quantity to the uncertainty of each measured parameter. The combined standard uncertainty in the estimated annual energy production, u_{AEP}, can in its most general form be expressed by:

$$u_{\text{AEP}}^2 = N_{\text{h}}^2 \sum_{i=1}^{N}\sum_{j=1}^{N}\sum_{k=1}^{M}\sum_{l=1}^{M} f_i c_{k,i}u_{k,i}f_j c_{l,j}u_{l,j}\rho_{k,l,i,j} \tag{C.2}$$

where

f_i is the relative occurrence of wind speed between V_{i-1} and V_i ($F(V_i) - F(V_{i-1})$) within bin i;

$F(V)$ is the Rayleigh cumulative probability distribution function for wind speed;

N is the number of bins;

N_{h} is the number of hours in one year ≈ 8 760.

It is seldom possible to deduce explicitly all the values of the correlation coefficients $\rho_{k,l,i,j}$ and normally significant simplifications are necessary. To allow the above expressions of combined uncertainties to be simplified to a practical level, the following assumptions may be made:

- uncertainty components are either fully correlated ($\rho = 1$, implying linear summation to obtain the combined standard uncertainty) or independent ($\rho = 0$, implying quadratic summation, i.e., the combined standard uncertainty is the square root of summed squares of the uncertainty components);
- all category A uncertainty components are mutually independent and category A and B uncertainty components are independent (irrespective of whether they are from the same bin or from different bins), while category B uncertainty components are fully correlated with category B uncertainties from the same origin in a different bin (e.g. uncertainty in power transducer in different bins).

Note that where the NPC is derived across multiple wind turbines simultaneously the NTF measurement uncertainty is fully correlated across turbines and those components of the NTF uncertainty associated with site and in-flow conditions may also be considered fully correlated as long as the same NTF is used on all turbines.

Using these assumptions, the combined uncertainty of the power within a bin, $u_{c,i}$, can be expressed by:

$$u_{c,i}^2 = \sum_{k=1}^{M_A} c_{k,i}^2 s_{k,i}^2 + \sum_{k=1}^{M_B} c_{k,i}^2 u_{k,i}^2 = s_i^2 + u_i^2 \tag{C.3}$$

where

M_A is the number of category A uncertainty components;

M_B is the number of category B uncertainty components;

$s_{k,i}$ is the category A standard uncertainty of component k in bin i;

s_i are the combined category A uncertainties in bin i;

u_i are the combined category B uncertainties in bin i.

It should be noted that $u_{c,i}{}^2$ is not independent of bin size due to the dependency of s_i on the number of data sets in the bin (see Equation (C.3) and Equation (C.9)).

The assumptions imply that the combined standard uncertainty in energy production, u_{AEP}, is:

$$u_{AEP}^2 = N_h^2 \sum_{i=1}^{N} f_i^2 \sum_{k=1}^{M_A} c_{k,i}^2 s_{k,i}^2 + N_h^2 \sum_{k=1}^{M_B} (\sum_{i=1}^{N} f_i c_{k,i} u_{k,i})^2 \tag{C.4}$$

The significance of the second term in Equation (C.4) is that each individual category B uncertainty component progresses through to the corresponding AEP uncertainty, applying the assumption of full correlation across bins for the individual components. Finally, the cross-bin combined uncertainty components are added quadratically into a resulting AEP uncertainty.

C.2 Propagation of uncertainty through the stages of NTF/NPC measurement

The uncertainty evaluation shall recognise that certain uncertainties carry through to different stages of the NTF/NPC measurement and therefore are at risk of being overestimated, if the above assumptions concerning the independence between category B uncertainties are fully applied. This can be avoided by considering a degree of cancellation between uncertainties.

The examples in Table C.1 illustrate some of the situations where a degree of cancellation may be assumed to apply.

Table C.1 – Example cancellation sources

Uncertainty source	Cancels with uncertainty source	Conditional upon
Operational characteristics of reference anemometer on the reference mast during site calibration of the NTF test turbine site	Operational characteristics of reference anemometer on reference mast during NTF measurement on test turbine	The same model of anemometer (and preferably the same anemometer) is used on the reference mast during the site calibration measurement and during the NTF measurement and similar incoming flow conditions prevail.
Mounting effects of the reference anemometer on the reference mast during site calibration of the NTF test turbine site	Mounting effects of the reference anemometer on the reference mast during the NTF measurement	Precisely the same mounting configuration is used for the reference anemometer during the site calibration and NTF measurements.
Operational characteristics of nacelle anemometer on test turbine during determination of NTF	Operational characteristics of nacelle anemometer on the test turbine during determination of NPC	The same model of nacelle anemometer is used on the NTF and NPC test turbines and similar incoming flow conditions prevail.
Mounting effects for the nacelle anemometer on the test turbine during determination of the NTF	Mounting effects for the nacelle anemometer on the test turbine during determination of the NPC	The same mounting configuration is used on the NTF and NPC test turbines and similar flow conditions prevail.
Terrain effect on NTF during NTF measurement	Terrain effect on NTF during derivation of NPC	The terrain characteristics at the NTF measurement turbine and the terrain characteristics at the NPC test turbine are identical (i.e. the same turbine in both cases) or are very similar (i.e. neighbouring turbines on a ridge).

In all the cases given in Table C.1, the degree of cancellation will decrease as the differences between the atmospheric conditions and/or site conditions prevailing during each stage of the measurement increase. These differences may arise as a result of carrying out different stages of the measurement on different sites (e.g. measuring the NTF on a simple site and using the NTF during the measurement of the NPC on a complex site) or during different seasons (e.g. measuring the NTF during the summer and measuring the NPC on the same or a different site during the winter).

This cancellation is already implicit in the IEC 61400-12-1 uncertainty analysis, but is made explicit here. An example of implicit cancellation in IEC 61400-12-1 can be found in Annex E of IEC 61400-12-1 where the uncertainties for the site calibration are calculated. The operational characteristics of the anemometer are in principle a contributing factor to the site calibration uncertainty. As both anemometers are required to be of the same type, this uncertainty contribution is assumed to cancel and therefore is not included in the calculation.

The examples in Annex D go through an estimate of the category A and B uncertainties for each bin of a measured power curve. The examples follow ISO/IEC GUIDE 98-3 and the assumptions made above.

Using the combination of the category B uncertainty components according to Equation (C.3) and taking the cancellation factors into account, all uncertainty components within each bin can be combined first to express the combined category B uncertainty of each measured parameter, as for example for the wind speed:

$$u_{V,i}^2 = \sum_{k}^{M} l_{V,k}^2 u_{V,k,i}^2 \tag{C.5}$$

where

$u_{V,i}$ is the total uncertainty of the wind speed in bin i;

$u_{V,k,i}$ is the standard uncertainty of wind speed component k in bin i (see Table C.2);

$l_{V,k}$ is the cancellation factor for uncertainty component k;

M is the number of wind speed uncertainty components.

Note cancellation factors are included in Equation (C.6). For $l = 1$ there is no cancellation and the equation reverts to its most general form (Equation (C.1)). For $l < 1$ there is a degree of cancellation, and for $l = 0$ there is full cancellation. The following rules apply to cancellation:

- because of the complex cause of the uncertainties it is difficult to accurately determine the cancellation. To yield a reasonable, but conservative estimate of the overall uncertainty the cancellation factor shall not be applied to the first appearance of an uncertainty term, only to subsequent appearances. If for instance the same anemometer is used in the site calibration as during the NTF measurement, then the calibration uncertainty of the anemometer on the permanent met-mast is fully taken into account ($l = 1$) in the uncertainty of the site calibration factors, but will cancel fully or partially in the NTF-uncertainty. A full cancellation ($l = 0$) is appropriate if the two measurements are done in a short enough time span such that no drift in the calibration factors should be expected; otherwise a partial cancellation should be used ($1 > l > 0$).
- statistical uncertainties never cancel and so they do not have a cancellation term;
- there is no full cancellation apart from the example as given in the preceding dashed list item, but in some cases there may be partial cancellation;
- the estimates given in Annex D shall be taken as lower boundaries for cancellation, lower values can only be used when backed up by evidence.

Then the standard uncertainties of the measurands can be combined to get the total uncertainty in bin i using Equation (C.6). Equation (C.7) can be used to calculate the standard uncertainty of the AEP.

$$u_{c,i}^2 = s_{P,i}^2 + u_{P,i}^2 + c_{V,i}^2 u_{V,i}^2 + c_{T,i}^2 u_{T,i}^2 + c_{B,i}^2 u_{B,i}^2 + c_{m,i}^2 u_{m,i}^2 \tag{C.6}$$

In Equation (C.6) the subscripts are as in IEC 61400-12-1 and IEC 61400-12-2. Note the uncertainties due to the data acquisition system are part of the uncertainty of each measurement parameter and flow distortion due to terrain is included in the uncertainty of wind speed.

To calculate the uncertainty in AEP the uncertainty of each category B component shall be combined over bins before adding the different components together, to accurately account for the correlations between bins.

$$u_{\mathrm{AEP}}^2 = N_{\mathrm{h}}^2 \sum_{i=1}^{N} f_i^2 \sum_{k=1}^{M_{\mathrm{A}}} c_{k,i}^2 s_{k,i}^2 + N_{\mathrm{h}}^2 \sum_{k=1}^{M_{\mathrm{B}}} \left(\sum_{i=1}^{N} f_i c_{k,i} l_k u_{k,i}\right)^2 \tag{C.7}$$

Equation (C.7) is identical to Equation (C.4) except that the cancellation factor l is included in Equation (C.7).

C.3 Category A uncertainties

C.3.1 General

The category A uncertainty that shall be considered is the uncertainty of the measured and normalized electric power data in each bin, the variance in the site calibration (when performed) and the variance in the NTF. Table C.2 lists the category A uncertainty components specifically relevant to the NTF.

C.3.2 Category A uncertainty in electric power

The standard deviation of the distribution of normalized power data in each bin is calculated by Equation (C.8):

$$\sigma_{P,i} = \sqrt{\frac{1}{N_i - 1}\sum_{j=1}^{Ni}\left(P_i - P_{n,i,j}\right)^2} \qquad \text{(C.8)}$$

where

$\sigma_{P,i}$ is the standard deviation of the normalized power data in bin i;

N_i is the number of 10-min data sets in bin i;

P_i is the normalized and averaged power output in bin i;

$P_{n,i,j}$ is the normalized power output of data set j in bin i.

The standard uncertainty of the normalized and averaged power in the bin is estimated by the Equation (C.9):

$$\sigma_{P,i} = \sqrt{\frac{1}{N_i - 1}\sum_{j=1}^{Ni}\left(P_i - P_{n,i,j}\right)^2} \qquad \text{(C.9)}$$

where

$s_{P,i}$ is the category A standard uncertainty of power in bin i;

$\sigma_{P,i}$ is the standard deviation of the normalized power data in bin i;

N_i is the number of 10-min data sets in bin i.

Table C.2 – List of category A and B uncertainties for NTF

Category B: Instruments	Note	Standard	Uncertainty
Flow distortion due to terrain (site calibration)			$u_{SC,i}$
Reference anemometer calibration *	a	IEC 61400-12-1	$u_{SC1,i}$
Reference anemometer operational characteristics *	a	IEC 61400-12-1	$u_{SC2,i}$
Reference anemometer mounting effects *	a	IEC 61400-12-1	$u_{SC3,i}$
Data acquisition system (transmission, accuracy and conditioning) *	a	IEC 61400-12-1	$u_{dSC1,i}$
Turbine position anemometer calibration *	a	IEC 61400-12-1	$u_{SC4,i}$
Turbine position operational characteristics *	a	IEC 61400-12-1	$u_{SC5,i}$
Turbine position anemometer mounting effects *	a	IEC 61400-12-1	$u_{SC6,i}$
Data acquisition system (transmission, accuracy and conditioning) *	a	IEC 61400-12-1	$u_{dSC2,i}$
Free stream wind speed			$u_{FS,i}$
Reference anemometer calibration *	a	IEC 61400-12-1	$u_{FS1,i}$
Reference anemometer operational characteristics *	a	IEC 61400-12-1	$u_{FS2,i}$
Reference anemometer mounting effects *	a	IEC 61400-12-1	$u_{FS3,i}$
Site calibration uncertainty *	bc		$u_{FS4,i}$
Data acquisition system (transmission, accuracy and conditioning) *	bcd		$u_{dFS,i}$
Nacelle wind speed			$u_{N,i}$
Nacelle anemometer calibration uncertainty due to wind speed *	a	IEC 61400-50-1 IEC 61400-12-1	$u_{N1,i}$
Nacelle anemometer calibration uncertainty due to wind direction (if sonic or propeller anemometer) *	ba	IEC 61400-12-1	$u_{N2,i}$
Nacelle anemometer operational characteristics *	a	IEC 61400-12-1	$u_{N3,i}$
Nacelle anemometer mounting *	a	IEC 61400-12-1	$u_{N4,i}$
Data acquisition system (transmission, accuracy and conditioning) *			$u_{dN,i}$
Category B: method			
Method			$U_{M,i}$
Seasonal variation (changing climatic conditions) on site calibration results *	d		$u_{M1,i}$
Seasonal variation (changing climatic conditions) on NTF	d		$u_{M2,i}$
Category A: statistical			
Statistical uncertainty in captured data set			
Variance for NTF *	e		$s_{NTF,i}$
Variance for site calibration *	e		$s_{SC,i,j}$
* parameter required for the uncertainty analysis			
Note identification of uncertainties: a = reference to standard b = calibration c = other "objective method" d = guesstimate e = statistics			

C.4 Category B uncertainties

C.4.1 General

The category B uncertainties are assumed to be related to the instruments, the data acquisition system, and the terrain surrounding the power performance test site. If the uncertainties are expressed as uncertainty limits, or have implicit, non-unity coverage factors, the standard uncertainty shall be estimated or they shall be properly converted into standard uncertainties. Table C.2 lists the category B uncertainty components specifically relevant to the NTF.

NOTE Consider an uncertainty expressed as an uncertainty limit $\pm U$. If a rectangular probability distribution is assumed, the standard uncertainty is:

$$\sigma = \frac{U}{\sqrt{3}} \tag{C.10}$$

If a triangular probability distribution is assumed, the standard uncertainty is:

$$\sigma = \frac{U}{\sqrt{6}} \tag{C.11}$$

C.4.2 Category B uncertainties in climatic variations

The power performance test may have been carried out under special atmospheric conditions that affect the test result systematically, such as very stable (large vertical shear and low turbulence) or unstable (little shear and high turbulence) atmospheric stratification or frequent and/or large changes in wind direction. This climatic uncertainty can be seen in the site calibration, the nacelle transfer function and the nacelle power curve. It is by nature a statistical uncertainty that can normally not be determined from the data because the data record is not sufficiently long. It is therefore captured by a category B uncertainty linked to the method used.

C.5 Expanded uncertainty

The combined standard uncertainties of the power curve and the AEP may additionally be expressed by expanded uncertainties. Referring to ISO/IEC GUIDE 98-3 and assuming normal distributions, intervals having levels of confidence shown in Table C.3 can be found by multiplying these combined standard uncertainties by a coverage factor also shown in Table C.3.

Table C.3 – Expanded uncertainties

Level of confidence %	**Coverage factor**
68,27	1
90	1,645
95	1,960
95,45	2
99	2,576
99,73	3

Annex D
(normative)

NTF uncertainty estimates and calculation

D.1 Methods and assumptions

D.1.1 General

In this Annex D an estimate is given of the magnitude of each uncertainty component and contribution factor as well as two examples where the calculation is further clarified. The general principles introduced in Annex B and Annex C are employed to derive the combined uncertainty in AEP.

This annex is normative in that the methods and assumptions regarding uncertainties and correlations shall be followed unless evidence is provided upon which to base another choice. Unless commented in the description of each uncertainty component, the uncertainty components are assumed to have a normally distributed uncertainty distribution.

D.1.2 Site calibration

The wind speed measurements are made on an upstream met mast with measured site calibration corrections applied to represent free stream conditions at the turbine position. The evaluation and interpretation of the power curve uncertainty shall recognise the uncertainty effects of the site calibration.

Table D.1 – Estimates for uncertainty components from site calibration

	Source	Uncertainty component	Estimate of magnitude	Method
Reference anemometer	Calibration	$u_{\mathrm{SC1},i}$	0,1 m/s	The anemometer is calibrated according to IEC 61400-12-1 procedures and the uncertainty estimate is based on the calibration.
	Operational characteristics	$u_{\mathrm{SC2},i}$	Class 1,2A	The sensor is classified per IEC 61400-50-1. This includes upflow and turbulence effects. This component has a rectangular uncertainty distribution.
	Mounting effects	$u_{\mathrm{SC3},i}$	1,0%	Mounting effects are estimated per IEC 61400-50-1. The mast used for this example is designed according to best practice from IEC 61400-50-1 so distortion is minimal.
	Data acquisition system	$u_{\mathrm{dSC1},i}$	0,03 m/s	Considering for example a 0,1 % uncertainty of the full range of 30 m/s of the measurement channel. This includes transmission, accuracy and conditioning.
Turbine position anemometer	Calibration	$u_{\mathrm{SC4},i}$	0,1 m/s	The anemometer is calibrated according to IEC 61400-12-1 procedures and the uncertainty estimate is based on the calibration.
	Operational Characteristics	$u_{\mathrm{SC5},i}$	Class 1,2A	The sensor is classified per IEC 61400-50-1. A class 1,2A for class A terrain has been used for the estimated value. This includes upflow and turbulence effects. This component has a rectangular uncertainty distribution.
	Mounting effects	$u_{\mathrm{SC6},i}$	1,0%	Mounting effects are estimated per IEC 61400-50-1. The mast used for this example is designed according to best practice from IEC 61400-50-1 so distortion is minimal
	Data acquisition system	$u_{\mathrm{dSC2},i}$	0,03 m/s	Considering 0,1 % uncertainty of the full range of 30 m/s of the measurement channel. This includes transmission, accuracy and conditioning.
Method	Seasonal variation	$u_{\mathrm{M1},i}$	2,0 %	A site calibration measured at different times of the year using same equipment will give different results. This is a guesstimate of the magnitude of this effect but the actual uncertainty will depend on the site and the complexity of the wind. The longer the data set the lower this uncertainty will be.
Statistical	Variance in wind direction bins	$s_{\mathrm{SC},j}$	$\frac{s_{\mathrm{SC},j}}{\sqrt{N_j}}$	Wind speed dependent uncertainties from the site calibration regression have been derived. s is the standard deviation of the wind speed ratios in bin i, N is the number of data points in bin i. If a linear regression is done, the standard deviation of the residuals can be used, or an uncertainty analysis of the slope and offset parameters with related correlation coefficients.

The assumptions in Table D.1 regarding uncertainties and correlations shall be followed unless evidence is provided upon which to base another choice.

The uncertainty components for $u_{\mathrm{SC},i,j}$ can be found in Table D.1. $u_{\mathrm{SC},i,j}$ is calculated similar to IEC 61400-12-1 as:

$$u_{\alpha,i,j} = \sqrt{\begin{array}{l} \frac{l_{\mathrm{SC1}}^2 u_{\mathrm{SC1},i}^2}{V_i^2} + \frac{l_{\mathrm{SC2}}^2 u_{\mathrm{SC2},i}^2}{V_i^2} + \frac{l_{\mathrm{SC3}}^2 u_{SC3,i}^2}{V_i^2} + \frac{l_{\mathrm{SC4}}^2 u_{\mathrm{SC4},i}^2}{V_i^2} + \frac{l_{\mathrm{SC5}}^2 u_{\mathrm{SC5},i}^2}{V_i^2} + \\ \frac{l_{\mathrm{SC6}}^2 u_{\mathrm{SC6},i}^2}{V_i^2} + \frac{l_{\mathrm{dSC1}}^2 u_{\mathrm{dSC1},i}^2}{V_i^2} + \frac{l_{\mathrm{dSC2}}^2 u_{\mathrm{dSC2},i}^2}{V_i^2} + \frac{l_{\mathrm{M1}}^2 u_{\mathrm{M1},i}^2}{V_i^2} + s_{\mathrm{SC},j}^2 \end{array}} \tag{D.1}$$

and

$$u_{\mathrm{SC},i,j} = u_{\alpha,i,j} V_i$$

$$= \sqrt{\begin{array}{l} l_{\mathrm{SC1}}^2 u_{\mathrm{SC1},i}^2 + l_{\mathrm{SC2}}^2 u_{\mathrm{SC2},i}^2 + l_{\mathrm{SC3}}^2 u_{\mathrm{SC3},i}^2 + l_{\mathrm{SC4}}^2 u_{\mathrm{SC4},i}^2 + l_{\mathrm{SC5}}^2 u_{\mathrm{SC5},i}^2 + \\ l_{\mathrm{SC6}}^2 u_{\mathrm{SC6},i}^2 + l_{\mathrm{dSC1}}^2 u_{\mathrm{dSC1},i}^2 + l_{\mathrm{dSC2}}^2 u_{\mathrm{dSC2},i}^2 + l_{\mathrm{M1}}^2 u_{\mathrm{M1},i}^2 + s_{\mathrm{SC},j}^2 V_i^2 \end{array}} \qquad \text{(D.2)}$$

where

$u_{\mathrm{SC},i,j}$ is the uncertainty of site calibration in wind speed bin i and wind direction bin j;

l is the contribution factor;

N_j is the number of wind speed ratios in wind direction bin j;

V_i is the wind speed in bin i.

The uncertainty related to anemometer class is defined as follows (also for NTF and NPC):

$$u_{\mathrm{ano\_class}} = (0{,}05\ \mathrm{m/s} + 0{,}005 \times U_i) \times k / \sqrt{3} \qquad \text{(D.3)}$$

where U_i and k are defined in accordance with IEC 61400-12-1.

D.1.3 Nacelle transfer function uncertainty component estimates

The measurement of the NTF is carried out using the same reference mast and data logging system as used in the site calibration. However, since the NTF was measured in a different season from the site calibration measurement, additional uncertainty is introduced. This is due to the influence of possibly varying atmospheric stability and its unknown effect on the validity of the site calibration relationship (essentially relating the wind speed at two points in space) and the NTF (which is in some way influenced by the disk averaging effect of the wind turbine rotor reduced to that point in space where the nacelle anemometer is located). The uncertainty components for $u_{V6,i}$ are as shown in Table D.2.

Table D.2 – Estimates for uncertainty components from NTF measurement

	Source	Uncertainty component	Estimate of magnitude	Method
Free stream wind speed	Anemometer calibration	$u_{\mathrm{FS1},i}$	0,1 m/s	Calibrated using best practice according to IEC 61400-50-1 procedures. Calibration is assumed valid for one year in the field and this needs to be proven with post-calibration or in-situ calibration.
	Operational characteristics	$u_{\mathrm{FS2},i}$	Class 1,2A	The sensor is classified per IEC 61400-50-1 as a class 1,2. This includes upflow and turbulence effects. This component has a rectangular uncertainty distribution.
	Mounting effects	$u_{\mathrm{FS3},i}$	1,0 %	The mast is designed according to best practice from IEC 61400-50-1 so distortion is minimal.
	Flow distortion due to terrain, site calibration undertaken	$u_{\mathrm{FS4},i}$	$u_{\mathrm{FS4},i} = \dfrac{\sum_{j} u_{\mathrm{SC},i,j} N_{i,j}}{\sum_{j} N_{i,j}}$ where $N_{i,j}$ is the number of data sets in the NTF data set in wind speed bin i and wind direction bin j.	
	Flow distortion due to terrain, no site calibration undertaken	$u_{\mathrm{FS4},i}$	2 % ($L <= 3D$) 3 % ($L > 3D$)	If no site calibration is undertaken, the uncertainty estimate is based on the distance from the meteorological mast to the turbine
	Data acquisition system	$u_{\mathrm{dFS},i}$	0,03 m/s	Considering 0,1 % uncertainty of the full range of 30 m/s of the measurement channel. This includes transmission, accuracy and conditioning.
Nacelle wind speed	Anemometer calibration uncertainty due to wind speed	$u_{\mathrm{N1},i}$	0,15 m/s	Calibrated using best practice according to IEC 61400-50-1. Calibration is assumed valid for one year in the field and this shall be proven with post-calibration or in-situ calibration.
	Anemometer calibration uncertainty due to wind direction	$u_{\mathrm{N2},i}$	1,0 %	Typical for sonic and propeller anemometers is that the wind speed uncertainty is directionally dependent.
	Operational characteristics	$u_{\mathrm{N3},i}$	Class 4A	Most standard nacelle sensors are not (yet) classified as per IEC 61400-50-1 and if that is the case a conservative estimate shall be used. This component has a rectangular uncertainty distribution.
	Mounting effects	$u_{\mathrm{N4},i}$	2,0 %	The support structure and other objects on the nacelle as well as the location of the anemometer can have a significant effect on the measurement.
	Data acquisition system	$u_{\mathrm{dN},i}$	0,03 m/s	Considering 0,1 % uncertainty of the full range of 30 m/s of the measurement channel. This includes transmission, accuracy and conditioning.
Method	Seasonal variation	$u_{\mathrm{M2},i}$	2,0 %	An NTF measured at different times of the year using same equipment will give different results. This is a guesstimate of the magnitude of this effect but the actual uncertainty will depend on the site and the complexity of the wind. The longer the data set the lower this uncertainty will be.
Statistical	Statistical uncertainty in captured dataset	$s_{\mathrm{NTF},i}$	$\dfrac{s_{\mathrm{NTF},i}}{\sqrt{N_j}}$	Wind speed-dependent uncertainties from the site calibration regression have been derived. s is the standard deviation of the wind speed ratios in bin j, N is the number of data points in bin j.

The assumptions in Table D.2 regarding uncertainties and correlations shall be followed unless evidence is provided upon which to base another choice.

$u_{V6,i}$ is calculated as follows:

$$u_{\text{FS},i} = \sqrt{l_{\text{FS1}}^2 u_{\text{FS1},i}^2 + l_{\text{FS2}}^2 u_{\text{FS2},i}^2 + l_{\text{FS3}}^2 u_{\text{FS3},i}^2 + l_{\text{FS4}}^2 u_{\text{FS4},i}^2 + l_{\text{dFS}}^2 u_{\text{dFS},i}^2} \tag{D.4}$$

$$u_{N,i} = \sqrt{l_{N1}^2 u_{N1,i}^2 + l_{N2}^2 u_{N2,i}^2 + l_{N3}^2 u_{N3,i}^2 + l_{N4}^2 u_{N4,i}^2 + l_{dN}^2 u_{dN,i}^2} \tag{D.5}$$

$$u_{\text{M\_NTF},i} = \sqrt{l_{\text{M2}}^2 u_{\text{M2},i}^2} \tag{D.6}$$

$$u_{V6,i} = \sqrt{u_{\text{FS},i}^2 + u_{N,i}^2 + u_{\text{M\_NTF},i}^2 + s_{\text{NTF},i}^2} \tag{D.7}$$

D.1.4 Nacelle power curve uncertainty component estimates

Given the good agreement between the IEC 61400-12-1 power curves on the test turbine and the NPC power curves on the test turbine, it is assumed that site effects add a relatively small amount to the wind speed uncertainty for simple sites. However, when transferred to a more complex site, the wider range of in-flow conditions experienced by the turbines and nacelle anemometer mean that certain components of uncertainty should be increased.

D.1.5 Wind direction uncertainty

The uncertainty of the wind direction does not directly influence the uncertainty of the power curve or the uncertainty of the annual energy production but it does influence the calculation of the measurement sector. Therefore, some estimates of the contributing uncertainty components are given here.

The uncertainty components for u_{WD} are as follows in Table D.3.

Table D.3 – Estimates for uncertainty components for wind direction

	Source	Uncertainty component	Estimate of magnitude	Method
Yaw position	In-situ calibration	u_{WD1}	3°	This can be estimated from comparing the variation between multiple yaw positions and related known reference points
	Signal resolution	u_{WD2}	0,5°	50 % of the yaw position signal resolution
	Data acquisition	u_{dWD1}	0,1°	Assumed uncertainty of 0,1°
Nacelle measured wind direction	Calibration sensor mounting (sonic sensor only)	u_{WD3}	1°	Estimated from calibration setup as described in Annex E
	Calibration maximum bin averaged wind direction difference due to wind direction (sonic sensor only)	u_{WD4}	2°	Estimated from calibration data as described in Annex E
	Calibration maximum bin averaged wind direction difference due to non-vertical flow (sonic sensor only)	u_{WD5}	2°	Estimated from calibration data as described in Annex E
	Sensor alignment	u_{WD6}	2°	Estimated from sensor mounting on turbine
	Rotor effects on average measured wind direction	u_{WD7}	5°	This estimate assumes a transfer function for nacelle wind direction has not been developed and takes the complete rotor effect into account.
	Data acquisition	u_{dWD2}	0,1°	Assumed uncertainty of 0,1°

The assumptions in Table D.3 regarding uncertainties and correlations shall be followed unless evidence is provided upon which to base another choice.

u_{WD} is calculated as follows:

$$u_{\mathrm{WD,YAW}} = \sqrt{u_{\mathrm{WD1}}^2 + u_{\mathrm{WD2}}^2 + u_{\mathrm{dWD1}}^2} \tag{D.8}$$

$$u_{\mathrm{WD,SENSOR}} = \sqrt{u_{\mathrm{WD3}}^2 + u_{\mathrm{WD4}}^2 + u_{\mathrm{WD5}}^2 + u_{\mathrm{WD6}}^2 + u_{\mathrm{WD7}}^2 + u_{\mathrm{dWD2}}^2} \tag{D.9}$$

$$u_{\mathrm{WD}} = \sqrt{u_{\mathrm{WD,YAW}}^2 + u_{\mathrm{WD,SENSOR}}^2} \tag{D.10}$$

D.1.6 Contribution factors

Terrain effects can be seen both in the NTF and the NPC. But similar terrain will have similar effects so a degree of contribution can also be assumed. Table D.4 gives the recommended contribution between various classes of terrain. The reference mast and anemometer are common to both the site calibration measurements, the NTF measurement and the IEC 61400-12-1 power performance measurements; therefore, it is certainly the case that some aspects of the uncertainty associated with this particular measurement will contribute to multiple stages. The values indicate minimum values that shall be used. To what extent they contribute is highly subjective.

Table D.4 – Estimates for contribution factors for site calibration

	Source	Contribution factor	Estimate of magnitude	Notes
Reference anemometer	Calibration	I_{SC1}	1	First appearance of an uncertainty term always contributes fully.
	Operational characteristics	I_{SC2}	1	First appearance of an uncertainty term always contributes fully.
	Mounting effects	I_{SC3}	1	First appearance of an uncertainty term always contributes fully.
	Data acquisition system	I_{dSC1}	1	First appearance of an uncertainty term always contributes fully.
Turbine position anemometer	Calibration	I_{SC4}	1	Calibration uncertainty always contributes fully, it is inherent to the sensor.
	Operational Characteristics	I_{SC5}	0,5	Operational uncertainty contributes in part, as the anemometers on both mounting structures are identical but it is possible that the anemometers will not see exactly the same turbulence and upflow.
	Mounting effects	I_{SC6}	0,5	Even with the mounting structure being the same, mounting effects are often a function of wind direction and therefore contribute.
	Data acquisition system	I_{dSC2}	1	First appearance of an uncertainty term always contributes fully.
Method	Seasonal variation	I_{M1}	1	First appearance of an uncertainty term always contributes fully.
Statistical	Variance in wind direction bins	n.a.	n.a.	Statistical variation always contributes fully.
Data acquisition	Data acquisition system	I_{dSC}	1	First appearance of an uncertainty term always contributes fully.

The assumptions in Table D.4 regarding uncertainties and correlations shall be followed unless evidence is provided upon which to base another choice.

Table D.5 – Estimates for contribution factors for NTF

	Source	Uncertainty component	Estimate of magnitude with site calibration	Estimate of magnitude without site calibration	Notes
Free stream wind speed	Anemometer calibration	l_{FS1}	1	1	Calibration uncertainty always contributes fully, it is inherent to the sensor.
	Operational characteristics	l_{FS2}	0,5	1	With site calibration: This contributes to a lesser degree as it is the same sensor as used on the mast for the site calibration.
	Mounting effects	l_{FS3}	0,25	1	With site calibration: This contributes to a lesser degree as it is the same sensor as used on the mast for the site calibration.
	Site calibration uncertainty	l_{FS4}	1	1	First appearance of an uncertainty term always contributes fully.
	Data acquisition system	l_{dFS}	1	1	It contributes fully as data is acquired in different environmental circumstances.
Nacelle wind speed	Anemometer calibration uncertainty due to wind speed	l_{N1}	1	1	Calibration uncertainty always contributes fully, it is inherent to the sensor.
	Anemometer calibration uncertainty due to wind direction	l_{N2}	1	1	Calibration uncertainty always contributes fully, it is inherent to the sensor.
	Operational characteristics	l_{N3}	1	1	It contributes fully as this is most likely a different kind of sensor behind the rotor so in a different environment.
	Mounting effects	l_{N4}	1	1	It contributes fully as this is most likely a different kind of sensor on a completely different kind of structure.
	Data acquisition system	l_{dN}	1	1	It contributes fully as data is acquired in different environmental circumstances.
Method	Seasonal variation	l_{M2}	1	1	First appearance of an uncertainty term always contributes fully.
Statistical	Nacelle anemometer operational characteristics	n.a.	n.a.	n.a.	Statistical variation always contributes fully.

The assumptions in Table D.5 regarding uncertainties and correlations shall be followed unless evidence is provided upon which to base another choice.

D.2 Uncertainty example calculations

D.2.1 Example description

These examples illustrate the following case where:

a) the NTF is derived on a test turbine on a site where no site calibration is required;

b) an IEC 61400-12-1 power curve is derived on the NTF test turbine;

c) the NTF is applied to a different turbine of the same type in the same terrain.

D.2.2 Example case – NTF uncertainty

Without a site calibration, all the contribution factors are equal to 1 (contribution at one stage) for the NTF uncertainty. In the example 2 % uncertainty is used for the flow distortion due to terrain. The calculation for $u_{FS,i}$ is:

$$u_{\mathrm{FS},i}=\sqrt{\begin{array}{l}(1)^2(0{,}01\times V_i\,[\mathrm{m/s}])^2+(1)^2(0{,}034\,\mathrm{m/s}+0{,}003\,4\times V_i\,[\mathrm{m/s}]')^2+(1)^2(0{,}01\times V_i\,[\mathrm{m/s}])^2\\+(1)^2(0{,}02\times V_i\,[\mathrm{m/s}])^2+(1)^2(0{,}03\,\mathrm{m/s})^2\end{array}} \tag{D.11}$$

$$=\sqrt{(0{,}024\times V_i\,[\mathrm{m/s}])^2+(0{,}034\,\mathrm{m/s}+0{,}003\,4\times V_i\,[\mathrm{m/s}]')^2+(0{,}03\,\mathrm{m/s})^2}$$

The calculation for $u_{N,i}$ is very similar:

$$u_{N,i}=\sqrt{\begin{array}{l}(1)^2(0{,}015\times V_i\,[\mathrm{m/s}])^2+(1)^2(0{,}01\times V_i\,[\mathrm{m/s}])^2+(1)^2(0{,}12\,\mathrm{m/s}+0{,}012\times V_i\,[\mathrm{m/s}]')^2\\+(1)^2(0{,}02\times V_i\,[\mathrm{m/s}])^2+(1)^2(0{,}03\,\mathrm{m/s})^2\end{array}} \tag{D.12}$$

$$=\sqrt{(0{,}027\times V_i\,[\mathrm{m/s}])^2+(0{,}12\,\mathrm{m/s}+0{,}012\times V_i\,[\mathrm{m/s}]')^2+(0{,}03\,\mathrm{m/s})^2}$$

The uncertainty resulting from the method is given by Equation (D.13):

$$u_{\mathrm{M\_NTF},i}=\sqrt{(1)^2(0{,}02\times V_i\,[\mathrm{m/s}])^2} \tag{D.13}$$

D.2.3 Example case – NPC uncertainty

In the example, the current and voltage transformers and the power transducer are all assumed to be of class 0,5.

The current transformers of class 0,5 (nominal loads of the current transformers are here designed to match the nominal power and not 200 % of nominal power). They have uncertainty limits, referring to IEC 61869-2, of ±0,5 % of the current at 100 % load.

At 20 % and 5 % loads, though, the uncertainty limits are increased to ±0,75 % and ±1,5 % of the current, respectively. For power performance measurements on wind turbines, the most important energy production is produced at a reduced power. Thus, we anticipate the uncertainty limits of ±0,75 % of the current at 20 % load to be a good average. The uncertainty distribution is assumed to be rectangular. It is assumed that the uncertainties of the three current transformers are caused by external influence factors such as air temperature, grid frequency, etc. They are therefore assumed fully correlated (an exception from the general assumption) and are summed linearly. As each current transformer contributes by one-third to the power measurement, it follows that the uncertainty of all current transformers is proportional to the power as follows:

$$u_{P1,i}=\frac{0{,}007\,5\times P_i\,[\mathrm{kW}]}{\sqrt{3}}\times\frac{1}{3}\times 3=0{,}004\,3\times P_i\,[\mathrm{kW}] \tag{D.14}$$

The voltage transformers of class 0,5, have uncertainty limits, referring to IEC 61869-3, of ±0,5 % of the voltage at all loads. The uncertainty distribution is assumed to be rectangular. The grid voltage is normally rather constant and independent of the wind turbine power. The uncertainties of the three voltage transformers are as for the current transformers assumed to be caused by external influence factors such as air temperature, grid frequency, etc. They are therefore assumed fully correlated (an exception from the general assumption) and are summed linearly. As each voltage transformer contributes by one-third to the power measurement, it follows that the uncertainty of all voltage transformers is proportional to the power as follows:

$$u_{P2,i} = \frac{0{,}005 \times P_i[\mathrm{kW}]}{\sqrt{3}} \times \frac{1}{3} \times 3 = 0{,}002\,9 \times P_i[\mathrm{kW}] \tag{D.15}$$

If current and voltage transformers are not operated within their secondary loop operational load limits, additional uncertainties shall be added. The power transducer of class 0,5, referring to IEC 60688, with a nominal power of 2 000 kW (200 % of the nominal power of the wind turbine) has an uncertainty limit of 10 kW. The uncertainty distribution is assumed to be rectangular. The uncertainty of the power transducer is thus:

$$u_{P3,i} = \frac{10\,\mathrm{kW}}{\sqrt{3}} = 5{,}8\,\mathrm{kW} \tag{D.16}$$

This leads to

$$\begin{aligned} u_{P,i} &= \sqrt{(1)^2(0{,}004\,3 \times P_i[\mathrm{kW}])^2 + (1)^2(0{,}002\,9 \times P_i[\mathrm{kW}])^2 + (1)^2(5{,}8\,\mathrm{kW})^2 + (1)^2(0{,}001 \times 2\,500\,\mathrm{kW})^2} \\ &= \sqrt{(1)^2(0{,}005\,2 \times P_i[\mathrm{kW}])^2 + (1)^2(5{,}8\,\mathrm{kW})^2} \end{aligned} \tag{D.17}$$

$u_{V,i}$ cannot be written in a simple mathematical form as it includes a category A uncertainty.

$$u_{T,i} = \sqrt{(1)^2(0{,}5\,\mathrm{K})^2 + (1)^2(2{,}0\,\mathrm{K})^2 + (1)^2(0{,}3\,\mathrm{K})^2 + (1)^2(0{,}001 \times 40\,\mathrm{K})^2} = 2{,}1\mathrm{K} \tag{D.18}$$

$$u_{B,i} = \sqrt{(1)^2(3{,}0\,\mathrm{hPa})^2 + (1)^2(0{,}34\,\mathrm{hPa})^2 + (1)^2(0{,}001 \times 100\,\mathrm{hPa})^2} = 3{,}0\,\mathrm{hPa} \tag{D.19}$$

$$u_{M,i} = \sqrt{\begin{matrix}(1)^2(0{,}005 \times P_i[\mathrm{kW}])^2 + (1)^2(0{,}01 \times P_i[\mathrm{kW}])^2 + \\ (1)^2(0{,}02 \times P_i[\mathrm{kW}])^2 + (1)^2(0{,}02 \times P_i[\mathrm{kW}])^2 + (1)^2(0{,}01 \times P_i[\mathrm{kW}])^2\end{matrix}} = 0{,}032 \times P_i[\mathrm{kW}] \tag{D.20}$$

Annex E
(normative)

Allowable anemometry instrument types

E.1 General

Anemometers that are used on a meteorological mast to establish a transfer function according to Annex D shall be of class 1,7A or better, as defined in the IEC 61400-50-1.

Anemometers that are used on the nacelle, are recommended to be of class 2,5B or better (as defined in IEC 61400-50-1) but can be any of the following type:

a) any form of cup anemometer,
b) any sonic anemometer,
c) any propeller anemometer.

No other type of anemometer (pitot tubes, hot wire anemometers, hot surface anemometers, etc.) shall be used either to establish the transfer function or to measure the nacelle power curve.

Cup anemometers shall be calibrated according to IEC 61400-50-1, cup anemometer calibration procedure.

Propeller anemometers shall be calibrated according to IEC 61400-50-1, cup anemometer calibration procedure.

The reporting of the calibration of all sensors shall follow the requirements as set out in IEC 61400-50-1, cup anemometer calibration procedure.

E.2 Recalibration of sonic anemometers

A sensor that has been used on the turbine to measure the transfer function shall be recalibrated after the measurement campaign. In-situ comparisons are an acceptable alternative. Maximum allowed deviation between calibration and recalibration is 1 % in wind speed range 4 m/s to 12 m/s. The in-situ calibration procedure as described in IEC 61400-50-1 shall be used when an in-situ calibration is done.

E.3 Uncertainty of sonic and propeller anemometers

The final sensor wind speed uncertainty can be calculated by quadratically combining the calibration uncertainty, the uncertainty from the rotation test and the uncertainty from the tilting test appropriately.

The final sensor wind direction uncertainty can be calculated by quadratically combining the uncertainty from the rotating test and the tilting test appropriately (see Annex B).

The tilting test is also highly recommended for a cup anemometer and propeller anemometer and should be considered for wind vanes, as well as a gust test for the anemometers to determine influence from turbulence.

Annex F
(informative)

Organisation of test, safety and communication

F.1 General

This annex gives recommendations on how a test can be organised regarding the assignment of roles and responsibilities, safety and communication between the involved parties. The term "involved parties" shall refer to all parties affected by the test in any way.

F.2 Responsibility for test

A chief of test shall be identified and communicated to the involved parties. The chief of test shall have responsibility for preparing the test plan, selecting all other test personnel, the interpretation of the test methods and procedures, assessment of the test data and preparation of a test report.

F.3 Safety during test

All testing personnel shall be site oriented, adequately familiar with and trained to work under the hazardous conditions that may prevail at the site and follow applicable safety regulations.

F.4 Communication

Any turbine under test shall be marked clearly as being under test, specifying also the planned duration of the test as well as the contact information for the chief of test and/or other safety representatives and emergency services. Any access to the turbine under test by any person shall be recorded in a log book and the chief of test shall be informed. Any remote change to the operating mode of the turbine under test shall also be reported to the chief of test.

F.5 Prior to test

All relevant drawings, documents, specifications, certificates and reports shall be placed at the disposal of the chief of test. Shortly before the start of tests the turbine under test shall be subjected to a thorough inspection to ensure that the agreed test conditions are met. A test plan shall be prepared before start of tests by the chief of test and be agreed upon by the involved parties. The test plan shall be distributed to the involved parties with ample time for consideration and agreement in writing. Where the test plan is not clear the provisions of IEC 61400-12-2 shall prevail. Where neither the test plan, nor this document is clear the interpretation by the chief of test shall prevail.

F.6 During test

The inspection report and any relevant observation during calibration of instruments, test preparation or test duration shall be recorded in writing by the chief of test, distributed immediately to the involved parties for written comment and included in the test report with the responses received. An observation shall be classified as relevant if any representative of a party considers it relevant.

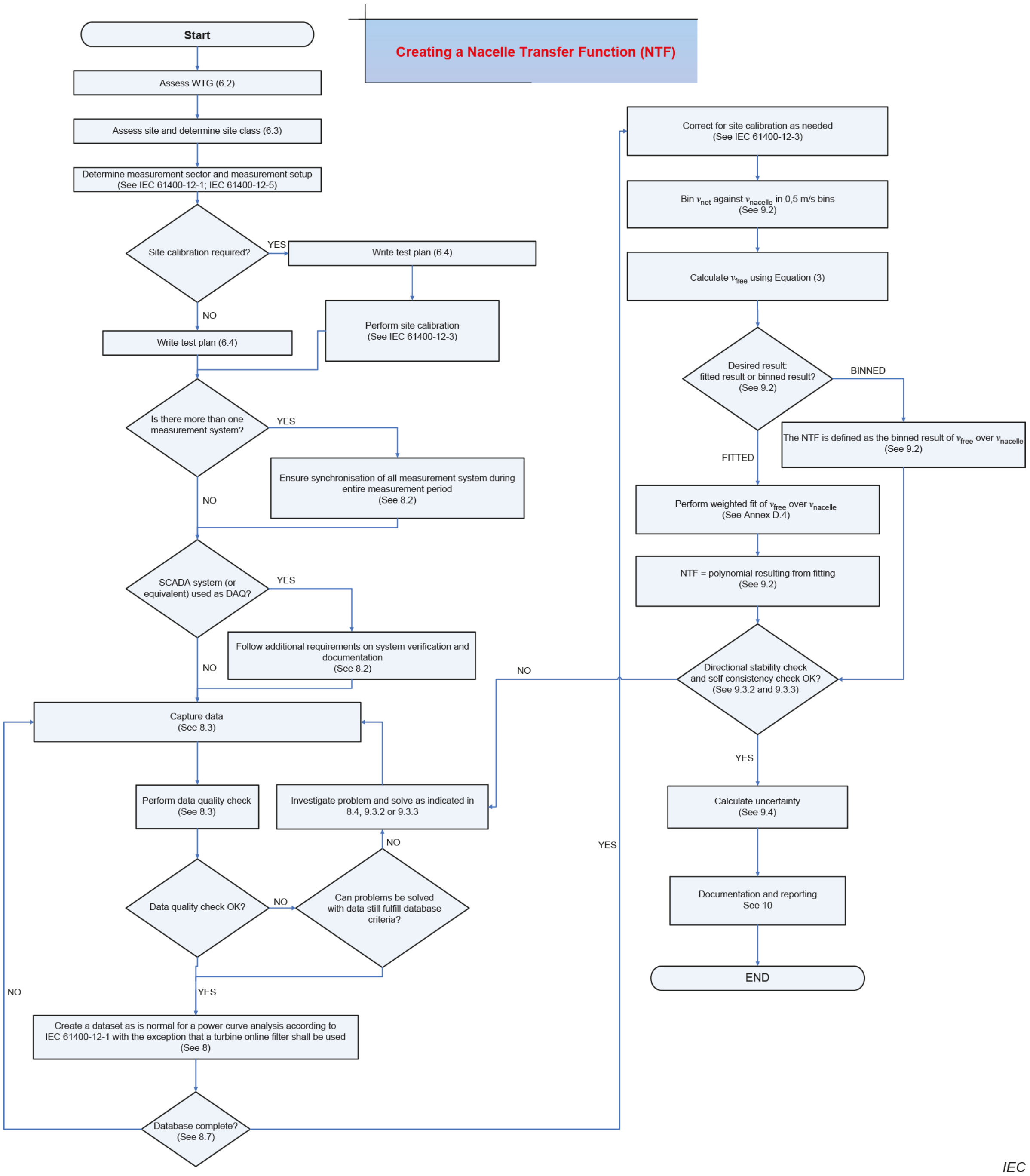
F.7 After test

If requested by any involved party, the turbine(s) under test shall be subjected to a post-testing inspection of identical scope to the pre-testing inspection. The chief of test shall prepare the final report within the time frame agreed in the test plan in draft format and distribute to the involved parties.

Annex G
(informative)

NTF flowchart

Figure G.1 gives a flowchart of the nacelle transfer function creation procedure.



IEC

Figure G.1 – NTF flowchart

Bibliography

[1] IEC 61400-2, *Wind turbines – Part 2: Small wind turbines*

(*Continued from second cover*)

International Standard	*title*
IEC 61400-50-1	Wind energy generation systems — Part 50-1: Wind measurement — Application of meteorological mast, nacelle and spinner mounted instruments
ISO/IEC Guide 98-3 : 2008	Uncertainty of measurement — Part 3: Guide to the expression of uncertainty in measurement

Only English language text has been retained while adopting it in this Indian Standard, and as such the page numbers given here are not the same as in the International Standard.

For the purpose of deciding whether a particular requirement of this standard is complied with, the final value, observed or calculated expressing the result of a test, shall be rounded off in accordance with IS 2 : 2022 ‘Rules for rounding off numerical values (*second revision*)’. The number of significant places retained in the rounded off value should be the same as that of the specified value in th

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