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Edition 1.0 2005-12

INTERNATIONAL STANDARD

Wind turbines –
Part 12-1: Power performance measurements of electricity producing wind turbines

IEC 61400-12-1:2005(E)

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WIND TURBINES –

Part 12-1: Power performance measurements of electricity producing wind turbines

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International Standard IEC 61400-12-1 has been prepared by IEC technical committee 88: Wind turbines.

This standard cancels and replaces IEC 61400-12 published in 1998. This first edition of IEC 61400-12-1 constitutes a technical revision. IEC 61400-12-2 and IEC 61400-12-3 are additions to IEC 61400-12-1.

The text of this standard is based on the following documents:

FDIS	Report on voting
88/244/FDIS	88/251/RVD

Full information on the voting for the approval of this standard can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

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IEC 61400-12 consists of the following parts, under the general title *Wind turbines:*

Part 12-1: Power performance measurements of electricity producing wind turbines

Part 12-2: Verification of power performance of individual wind turbines (under consideration)

Part 12-3: Wind farm power performance testing (under consideration)

The committee has decided that the contents of this publication will remain unchanged until the maintenance result date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed;
- withdrawn;
- replaced by a revised edition, or
- amended.

A bilingual version of this standard may be issued at a later date.

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INTRODUCTION

The purpose of this part of IEC 61400 is to provide a uniform methodology that will ensure consistency, accuracy and reproducibility in the measurement and analysis of power performance by wind turbines. The standard has been prepared with the anticipation that it would be applied by:

– a wind turbine manufacturer striving to meet well-defined power performance requirements and/or a possible declaration system;

– a wind turbine purchaser in specifying such performance requirements;

– a wind turbine operator who may be required to verify that stated, or required, power performance specifications are met for new or refurbished units;

– a wind turbine planner or regulator who must be able to accurately and fairly define power performance characteristics of wind turbines in response to regulations or permit requirements for new or modified installations.

This standard provides guidance in the measurement, analysis, and reporting of power performance testing for wind turbines. The standard will benefit those parties involved in the manufacture, installation planning and permitting, operation, utilization, and regulation of wind turbines. The technically accurate measurement and analysis techniques recommended in this standard 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 standard presents measurement and reporting procedures expected to provide accurate results that can be replicated by others. Meanwhile, a user of the standard should be aware of differences that arise from large variations in wind shear and turbulence, 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 contracting the power performance measurements.

A key element of power performance testing is the measurement of wind speed. This standard prescribes the use of cup anemometers to measure the wind speed. This instrument is robust and has long been regarded as suitable for this kind of test. Even though suitable wind tunnel calibration procedures are adhered to, the field flow conditions associated with the fluctuating wind vector, both in magnitude and direction, will cause different instruments to potentially perform differently.

Tools and procedures to classify cup anemometers are given in Annexes I and J. However there will always be a possibility that the result of the test can be influenced by the selection of the wind speed instrument. Special care should therefore be taken in the selection of the instruments chosen to measure the wind speed.

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WIND TURBINES –

Part 12-1: Power performance measurements of electricity producing wind turbines

1 Scope

This part of IEC 61400 specifies a procedure for measuring the power performance characteristics of a single wind turbine and applies to the testing of wind turbines of all types and sizes connected to the electrical power network. In addition, this standard describes a procedure to be used to determine the power performance characteristics of small wind turbines (as defined in IEC 61400-2) when connected to either the electric power network or a battery bank. The procedure can be used for performance evaluation of specific turbines at specific locations, but equally the methodology can be used to make generic comparisons between different turbine models or different turbine settings.

The wind turbine power performance characteristics are determined by the measured power curve and the estimated annual energy production (AEP). The measured power curve is determined by collecting simultaneous measurements of wind speed and power output at the test site 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 AEP is calculated by applying the measured power curve to reference wind speed frequency distributions, assuming 100 % availability.

The standard describes a measurement methodology that requires the measured power curve and derived energy production figures to be supplemented by an assessment of uncertainty sources and their combined effects.

2 Normative references

The following referenced documents are indispensable for the application 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 60044-1:1996, *Instrument transformers – Part 1: Current transformers*
Amendment 1 (2000)
Amendment 2 (2002)[1]

IEC 60688:1992, *Electrical measuring transducers for converting a.c. electrical quantities to analogue or digital signals*
Amendment 1 (1997)
Amendment 2 (2001)[2]

IEC 61400-2:1996, *Wind turbine generator systems – Part 1: Safety of small wind turbines*

ISO 2533:1975, *Standard atmosphere*

ISO Guide to the expression of uncertainty in measurement, 1995, ISBN 92-67-10188-9

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[1] There exists a consolidated edition 1.2 (2003) that includes edition 1 and its amendments 1 and 2.

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3 Terms and definitions

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

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

3.2
annual energy production
AEP
estimate of the total energy production of a wind turbine during a one-year period by applying the measured power curve to different reference wind speed frequency distributions at hub height, assuming 100 % availability

3.3
complex terrain
terrain surrounding the test site that features significant variations in topography and terrain obstacles that may cause flow distortion

3.4
data set
collection of data that was sampled over a continuous period

3.5
distance constant
indication of the response time of an anemometer, defined as the length of air that must pass the instrument for it to indicate 63 % of the final value for a step input in wind speed

3.6
extrapolated power curve
extension of the measured power curve by estimating power output from the maximum measured wind speed to cut-out wind speed

3.7
flow distortion
change in air flow caused by obstacles, topographical variations, or other wind turbines that results in a deviation of the measured wind speed from the free stream wind speed and in a significant uncertainty

3.8
hub height (wind turbines)
height of the centre of the swept area of the wind turbine rotor above the ground at the tower

NOTE For a vertical axis wind turbine the hub height is the height of the equator plane.

3.9
measured power curve
table and graph that represents the measured, corrected and normalized net power output of a wind turbine as a function of measured wind speed, measured under a well-defined measurement procedure

3.10
measurement period
period during which a statistically significant database has been collected for the power performance test

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3.11
measurement sector
a sector of wind directions from which data are selected for the measured power curve

3.12
method of bins
data reduction procedure that groups test data for a certain parameter into wind speed intervals (bins)

NOTE 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
net active electric power
measure of the wind turbine electric power output that is delivered to the electrical power network

3.14
obstacles
things that blocks the wind and creates distortion of the flow, such as buildings and trees

3.15
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

3.16
power coefficient
ratio of the net electric power output of a wind turbine to the power available in the free stream wind over the rotor swept area

3.17
power performance
measure of the capability of a wind turbine to produce electric power and energy

3.18
rated power
quantity of power assigned, generally by a manufacturer, for a specified operating condition of a component, device or equipment

NOTE Maximum continuous electrical power output which a wind turbine is designed to achieve under normal operating conditions.

3.19
standard uncertainty
uncertainty of the result of a measurement expressed as a standard deviation

3.20
swept area
for a horizontal axis turbine, the projected area of the moving rotor upon a plane normal to axis of rotation. For teetering rotors, it should be assumed that the rotor remains normal to the low-speed shaft. For a vertical axis turbine, the projected area of the moving rotor upon a vertical plane.

3.21
test site
location of the wind turbine under test and its surroundings

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3.22
uncertainty in measurement
parameter, associated with the result of a measurement, which characterizes the dispersion of the values that could reasonably be attributed to the measurand

4 Symbols and units

A	swept area of the wind turbine rotor	[m^2]
AEP	annual energy production	[Wh]
B	barometric pressure	[Pa]
$B_{10\text{min}}$	measured air pressure averaged over 10 min	[Pa]
C_h	pitot tube head coefficient	
$C_{\text{P},i}$	power coefficient in bin i	
C_QA	generalized aerodynamic torque coefficient	
C_T	thrust coefficient	
c	sensitivity factor on a parameter (the partial differential)	
$c_{\text{B},i}$	sensitivity factor of air pressure in bin i	[W/Pa]
$c_{\text{d},i}$	sensitivity factor of data acquisition system in bin i	
c_index	sensitivity factor of index parameter	
$c_{k,i}$	sensitivity factor of component k in bin i	
$c_{\text{m},i}$	sensitivity factor of air density correction in bin i	[Wm^3/kg]
$c_{\text{T},i}$	sensitivity factor of air temperature in bin i	[W/K]
$c_{\text{V},i}$	sensitivity factor of wind speed in bin i	[Ws/m]
D	rotor diameter	[m]
D_e	equivalent rotor diameter	[m]
D_n	rotor diameter of neighbouring and operating wind turbine	[m]
d	mast diameter	[m]
$F(V)$	the Rayleigh cumulative probability distribution function for wind speed	
f_i	the relative occurrence of wind speed in a wind speed interval	
H	hub height of wind turbine	[m]
h	height of obstacle minus zero displacement	[m]
I	inertia of cup anemometer rotor	[kgm^2]
k	class number	
k_b	blockage correction factor	
k_c	wind tunnel calibration factor	
k_f	wind tunnel correction factor to other tunnels (only used in uncertainty estimate)	
k_ρ	humidity correction to density	
$K_{\text{B,t}}$	barometer	
$K_{\text{B,s}}$	barometer gain	
$K_{\text{B,d}}$	barometer sampling	
$K_{\text{T,t}}$	temperature transducer	
$K_{\text{T,s}}$	temperature transducer gain	
$K_{\text{T,d}}$	temperature transducer sampling	
$K_{\text{p,t}}$	pressure transducer sensitivity	
$K_{\text{p,s}}$	pressure transducer gain	
$K_{\text{p,d}}$	pressure transducer sampling conversion	

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L	leg distance of three legged mast	[m]
L	distance between the wind turbine and the meteorological mast	[m]
L_e	distance between the wind turbine or the meteorological mast and an obstacle [m]	
L_n	distance between the wind turbine or the meteorological mast and a neighbouring and operating wind turbine	[m]
l_h	height of obstacle	[m]
l_w	width of obstacle	[m]
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 ≈ 8760	[h]
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	number of samples within sampling interval	
n	velocity profile exponent (n=0,14)	
P_0	porosity of obstacle (0: solid, 1: no obstacle)	
P_i	normalized and averaged power output in bin i	[W]
P_n	normalized power output	[W]
$P_{n,i,j}$	normalized power output of data set j in bin i	[W]
P_{10min}	measured power averaged over 10 min	[W]
P_w	vapour pressure	[Pa]
Q_A	aerodynamic torque	[Nm]
Q_f	friction torque	[Nm]
R	distance to mast centre	[m]
R_0	gas constant of dry air (287,05)	[J/(kgK)]
R_w	gas constant of water vapour (461,5)	[J/kgK]
r	correlation coefficient	
s	uncertainty component of category A	
s_A	category A standard uncertainty of tunnel wind speed time series	
$s_{k,i}$	category A standard uncertainty of component k in bin i	
s_i	combined category A uncertainties in bin i	
$s_{P,i}$	category A standard uncertainty of power in bin i	[W]
$s_{w,i}$	category A standard uncertainty of climatic variations in bin i	
$s_{\alpha,j}$	category A standard uncertainty of wind speed ratios in bin j	
T	absolute temperature	[K]
TI	turbulence intensity	
T_{10min}	measured absolute air temperature averaged over 10 min	[K]
t	mast solidity	
t	time	[s]
U	wind speed	[m/s]
U_d	centre-line wind speed deficit	[m/s]
U_{eq}	equivalent horizontal wind speed	[m/s]
U_h	free wind speed at height *h* of obstacle	[m/s]

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U_i	wind speed in bin i	[m/s]
U_t	threshold wind speed	[m/s]
$\vec{U}$	wind speed vector	
u	longitudinal wind speed component	[m/s]
u	uncertainty component of category B	
u_{AEP}	combined standard uncertainty in the estimated annual energy production	[Wh]
$u_{B,i}$	category B standard uncertainty of air pressure in bin i	[Pa]
$u_{c,i}$	combined standard uncertainty of the power in bin i	[W]
u_i	combined category B uncertainties in bin i	
u_{index}	category B standard uncertainty of index parameter	
$u_{k,i}$	category B standard uncertainty of component k in bin i	
$u_{m,i}$	category B standard uncertainty of air density correction in bin i	[kg/m^3]
$u_{P,i}$	category B standard uncertainty of power in bin i	[W]
$u_{V,i}$	category B standard uncertainty of wind speed in bin i	[m/s]
$u_{T,i}$	category B standard uncertainty of air temperature in bin i	[K]
$u_{\alpha,i,j}$	combined standard uncertainty of site calibration in wind speed bin i and wind direction bin j	[m/s]
V	wind speed	[m/s]
V_{ave}	annual average wind speed at hub height	[m/s]
V_i	normalized and averaged wind speed in bin i	[m/s]
V_n	normalized wind speed	[m/s]
$V_{n,i,j}$	normalized wind speed of data set j in bin i	[m/s]
V_{10min}	measured wind speed averaged over 10 min	[m/s]
v	transversal wind speed component	[m/s]
$\overline{v}$	mean flow air speed	[m/s]
w	vertical wind speed component	[m/s]
w_i	weighing function to define deviation envelope	
X_k	parameter averaged over pre-processing time period	
X_{10min}	parameter averaged over 10 min	
x	distance downstream obstacle to met mast or wind turbine	[m]
z	height above ground	[m]
z_0	roughness height	[m]
α	disturbed sector	[°]
α	angle of attack	[°]
α_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]
$\varepsilon_{max,i}$	maximum deviation for any wind speed bin i in the wind speed range	[m/s]
κ	von Karman constant 0,4	
λ	speed ratio	
ρ	correlation coefficient	
ρ	air density	
ρ_0	reference air density	[kg/m^3]
ρ_{10min}	derived air density averaged over 10 min	[kg/m^3]

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$\sigma_{P,i}$	standard deviation of the normalized 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	
ϕ	relative humidity (range 0 to 1)	
ω	angular speed	[s^{-1}]

5 Preparation for performance test

The specific test conditions related to the power performance measurement of the wind turbine shall be well-defined and documented in the test report, as detailed in Clause 9.

5.1 Wind turbine and electrical connection

As detailed in Clause 9, the wind turbine and electrical connection shall be described and documented to identify uniquely the specific machine configuration that is tested.

5.2 Test site

At the test site a meteorological mast shall be set up in the neighbourhood of the wind turbine to determine the wind speed that drives the wind turbine. The test site may have significant influence on the measured power performance of the wind turbine. In particular, flow distortion effects may cause the wind speed at the meteorological mast and at the wind turbine to be different, though correlated.

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

– choose the position of the meteorological mast;
– define a suitable measurement sector;
– estimate appropriate flow correction factors;
– evaluate the uncertainty due to wind flow distortion.

The following factors shall be considered, in particular:

– topographical variations;
– other wind turbines;
– obstacles (buildings, trees, etc.).

The test site shall be documented as detailed in Clause 9.

5.2.1 Location of the meteorological mast

Care shall be taken in locating the meteorological mast. It shall not be located too close to the wind turbine, since the wind speed will be influenced/changed/affected in front of the wind turbine. Also, it shall not be located too far from the wind turbine, since the correlation between wind speed and electric power output will be reduced. The meteorological mast shall be positioned at a distance from the wind turbine of between 2 and 4 times the rotor diameter D of the wind turbine. A distance of 2,5 times the rotor diameter D is recommended. In the case of a vertical axis wind turbine, D is equivalently defined as $2\sqrt{A/\pi}$, where A is the swept area of the rotor, and distance is defined as L+0,5D, where L is the distance between the centre of the turbine tower and the mast of an equivalent horizontal axis wind turbine.

Prior to carrying out the performance evaluation test and in helping to select the location for the meteorological mast, account should be taken of the need to exclude measurements from all sectors in which either the mast or the turbine will be subject to flow disturbance.

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In most cases, the best location for the meteorological mast will be upwind of the turbine in the direction from which most valid wind is expected to come during the test. In other cases, however, it may be more appropriate to place the mast alongside the turbine, for example for a wind turbine that is sited on a ridge.

5.2.2 Measurement sector

The measurement sector(s) shall exclude directions having significant obstacles and other wind turbines, as seen from both the wind turbine under test and the meteorological mast.

For all neighbouring wind turbines and obstacles, the directions to be excluded due to wake effects shall be determined using the procedure in Annex A. The disturbed sectors to be excluded due to the meteorological mast being in the wake of the wind turbine under test are shown in Figure 1 for distances of 2, 2,5 and 4 times the rotor diameter of the wind turbine. Reasons to reduce the sector might be special topographic conditions or unexpected measurement data achieved from directions with complicated structures. All reasons for reducing the measurement sector shall be clearly documented.

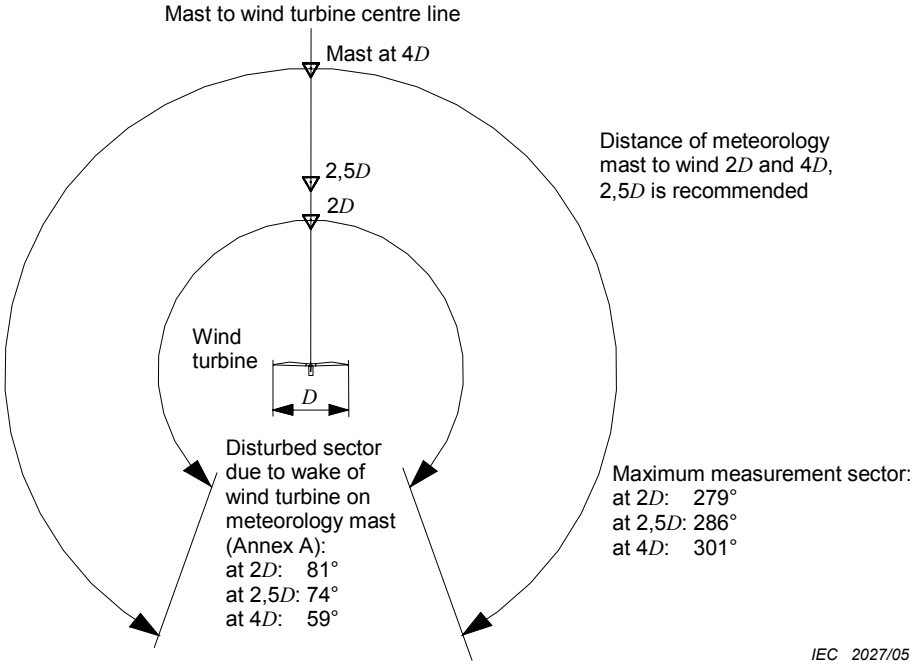

Figure 1 – Requirements as to distance of the meteorological mast and maximum allowed measurement sectors

5.2.3 Correction factors and uncertainty due to flow distortion originating from topography

The test site shall be assessed for sources of wind flow distortion due to topographical variations. The assessment shall identify whether the power curve can be measured without a required site calibration. If the criteria of Annex B are met, the wind flow regime of the site does not need a site calibration. However, in assuming that no flow correction factors are necessary, the applied uncertainty due to flow distortion of the test site shall be a minimum of 2 % of the measured wind speed if the meteorological mast is positioned at a distance between 2 and 3 times the rotor diameter of the wind turbine and 3 % or greater if the distance is 3 to 4 times the rotor diameter, unless objective evidence can be provided quantifying a different uncertainty.

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If the criteria of Annex B are not met, or a smaller uncertainty due to flow distortion of the test site is desired, then an experimental test site calibration shall be undertaken. If an experimental test site calibration is undertaken Annex C shall be used. The measured flow correction factors for each sector shall be used.

6 Test equipment

6.1 Electric power

The net electric power of the wind turbine shall be measured using a power measurement device (e.g. power transducer) and be based on measurements of current and voltage on each phase.

The class of the current transformers shall meet the requirements of IEC 60044-1 and the class of the voltage transformers, if used, shall meet the requirements of IEC 60186. They shall be class 0,5 or better.

The accuracy of the power measurement device, if it is a power transducer, shall meet the requirements of IEC 60688 and shall be class 0,5 or better. If the power measurement device is not a power transducer then the accuracy should be equivalent to class 0,5 power transducers. The operating range of the power measurement device shall be set to measure all positive and negative instantaneous power peaks generated by the wind turbine. As a guide, the full-scale range of the power measurement device should be set to –50 % to +200 % of the wind turbine rated power. All data shall be periodically reviewed during the test to ensure that the range limits of the power measurement device have not been exceeded. The power transducer shall be calibrated to traceable standards. The power measurement device shall be mounted between the wind turbine and the electrical connection to ensure that only the net active electric power (i.e. reduced by self-consumption) is measured. It shall be stated whether the measurements are made on the turbine side or the network side of the transformer.

6.2 Wind speed

Wind speed measurements shall be made with a cup anemometer that meets the requirements in Annex I. For power performance measurements an anemometer with a class better than 1,7A shall be used. Additionally, in terrain that does not meet the requirements of Annex B for not requiring a site calibration, it is recommended that a class better than class 2,5B or 1,7S be used. The wind speed to be measured is defined as the average magnitude of the horizontal component of the instantaneous wind velocity vector[2], including only the longitudinal and lateral, but not the vertical, turbulence components. Consequently, the angular response of the cup anemometer should be cosine shaped (see Annex J). All reported wind speeds, and all uncertainties connected to operational characteristics shall be related to this wind speed definition.

The cup anemometer shall be calibrated before and recalibrated after the measurement campaign. The difference between the regression lines of calibration and recalibration shall be within ±0,1 m/s in the range 6m/s to 12 m/s. Only the calibration before the measurement campaign shall be used for the performance test. Calibration of the cup anemometer shall be made according to the procedure of Annex F. During calibration the cup anemometer shall be mounted on a vertical tube configuration similar to the one being used during the power performance test.

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2 It is believed that, by using instruments that are able to measure the wind speed according to this definition consistent power curves will be obtained in most field conditions. Consistent in this context means that the power curves measured in inclined flow are essentially similar to the power curves measured under non-inclined flow conditions. Special care should be taken to achieve a proper mounting (align the instrument) and special care should also be taken to inspect the anemometer for distorted cups. Improper mounting or distorted cups may introduce severely biased results.

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As an inferior alternative to the recalibration, it shall be documented that the cup anemometer maintains its calibration over the duration of the measurement period. The procedure in Annex K should be used.

The cup anemometer shall be mounted at hub height of ±2,5 %, relative to the ground at the meteorological mast. The requirements given in Annex G with respect to mounting shall be used.

The uncertainty in wind speed measurement derives from three sources (see Table D.1): the calibration of the instrument, the operational characteristics of the anemometer and flow distortion due to instrument mounting effects. Uncertainty in calibration shall be derived from Annex F. Uncertainty due to operational characteristics shall be derived from Annex I on classification of anemometry. Uncertainty due to mounting effects shall be derived from Annex G.

6.3 Wind direction

Wind direction should be measured with a wind vane. A wind vane used for this purpose shall be mounted on the meteorological mast on a boom, as described in Annex G. The combined calibration, operation, and orientation uncertainty of the wind direction measurement should be less than 5º.

6.4 Air density

Air density shall be derived from the measurement of air temperature and air pressure using equation (1). At high temperatures, it is recommended also that relative humidity be measured and corrected for. The correction for the density effect of the air humidity shall be performed using equation (F.1).

The air temperature sensor, and the humidity sensor if used, shall be mounted within 10 m of hub height to represent the air temperature at the wind turbine rotor centre.

The air pressure sensor should be mounted on the meteorological mast close to hub height to represent the air pressure at the wind turbine rotor centre. If the air pressure sensor is not mounted close to the hub height, air pressure measurements shall be corrected to the hub height according to ISO 2533.

6.5 Rotational speed and pitch angle

Rotational speed and pitch angle should be measured throughout the test if there is a specific need for it, for example if there is a need to apply the measurements in connection with acoustic noise tests. If measured, the measurements shall be reported according to Clause 9.

6.6 Blade condition

The condition of the blades may influence the power curve particularly for stall regulated turbines. It may be useful in understanding the characteristics of the turbine to monitor the factors which might affect blade condition. These include precipitation, icing and bug and dirt accretion.

6.7 Wind turbine control system

Sufficient status signals shall be identified, verified and monitored to allow the rejection criteria of 7.4 to be applied. Obtaining these parameters from the turbine controller's data system, if available, is adequate[3]. The definition of each status signal shall be reported.

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[3] A status signal on generator cut-in is adequate to verify cut-out hysteresis control algorithm.

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6.8 Data acquisition system

A digital 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 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. As a guideline, the uncertainty of the data acquisition system should be negligible compared with the uncertainty of the sensors.

7 Measurement procedure

7.1 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 power performance characteristics of the wind turbine accurately. The measurement procedure shall be documented, as detailed in Clause 9, 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 measurement uncertainty, as described in Annex D. During the measurement period, data should be periodically checked to ensure high quality and repeatability of the test results. Test logs shall be maintained to document all important events during the power performance test.

7.2 Wind turbine operation

During the measurement period, the wind turbine shall be in normal operation, as prescribed in the wind turbine operations manual, and the machine configuration may not be changed. The operational status of the wind turbine shall be reported by the status signals as described in Clause 9. Normal maintenance of the turbine shall be carried out throughout the measurement period, but such work shall be noted in the test log. Any special maintenance actions, such as frequent blade washing, which ensure good performance during the test shall in particular be noted. Such special maintenance actions shall by default not be made, unless agreed by contractual parties prior to commencement of the test.

7.3 Data collection

Data shall be collected continuously at a sampling rate of 1 Hz or higher. Air temperature, air pressure, wind turbine status and precipitation, if measured, may be sampled at a slower rate, but at least once per minute.

The data acquisition system shall store either sampled data or statistics of data sets as follows:

– mean value;
– standard deviation;
– maximum value;
– minimum value.

Selected data sets shall be based on 10-min periods derived from contiguous measured data. Data shall be collected until the requirements defined in 7.6 are satisfied.

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7.4 Data rejection

To ensure that only data obtained during normal operation of the turbine are used in the analysis, and to ensure data are not corrupted, data sets shall be excluded from the database under the following circumstances:

– external conditions other than wind speed are out of the operating range of the wind turbine;
– turbine cannot operate because of a turbine fault condition;
– turbine is manually shut down or in a test or maintenance operating mode;
– failure or degradation (e.g. due to icing) of test equipment;
– wind direction outside the measurement sector(s) as defined in 5.2.2;
– wind directions outside valid (complete) site calibration sectors.

Any other rejection criteria shall be clearly reported.

The power curve shall capture the effect of hysteresis at the cut-in control algorithm, as well as the effect of parasitic losses below cut-in. The effect on the power curve of a large hysteresis loop in the cut-out control algorithm may be considerable. In case cut-out behaviour has been reached during the measurement period, two data sets shall therefore be presented. One data set shall include all data points in the database (database A). The other data set shall exclude all data sets where the turbine has stopped generating power due to cut-out at high wind speed (database B)[4].

Subsets of the database collected under special operational conditions (e.g. high blade roughness due to dust, salt, insects, ice) or atmospheric conditions (e.g. precipitation, wind shear) that occur during the measurement period may be selected as special databases.

If the grid frequency varies on the order of two or more hertz, it might be appropriate to select the power performance at different frequency levels as a special database. In this case, the grid frequencies should be divided into frequency bins, centred on integer values of the grid frequency.

7.5 Data correction

For the selected data sets wind speeds shall be corrected for flow distortion from site calibration (see 5.2) and air pressure shall be corrected if measured at a height other than close to hub height (see 6.4).

7.6 Database

After data normalization (see 8.1) the selected data sets shall be sorted using the “method of bins” procedure (see 8.2). The selected data sets shall at least cover a wind speed range extending from 1 m/s below 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 1m/s below cut-in to a wind speed at which "AEP-measured" is greater than or equal to 95 % of "AEP-extrapolated" (see 8.3). 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.

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[4] A power curve based on database A can be used to estimate the impact of cut-out behaviour of a turbine. While accurate for the location and period of the test, it may differ from the behaviour seen at other periods or locations. A power curve based on database B, which does not include power loss due to cut-out hysteresis, can be used to compare or verify power curves in a more generic way.

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

– each bin includes a minimum of 30 min of sampled data;
– 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 has to be fulfilled by using these two measures: AEP measured by 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 8.3).

The database shall be presented in the test report as detailed in Clause 9.

8 Derived results

8.1 Data normalization

The selected data sets shall be normalized to two reference air densities. One shall be the sea level air density, referring to ISO standard atmosphere (1,225 kg/m^3). The other shall be the average of the measured air density data at the test site during periods of valid data collection, rounded to the nearest 0,05 kg/m^3. No air density normalization to actual average air density is needed when the actual average air density is within 1,225 ± 0,05 kg/m^3. Alternatively, the other normalization may be carried out to a nominal air density pre-defined for the site. The air density may be determined from measured air temperature and air pressure according to the equation:

$$\rho_{10\,\mathrm{min}} = \frac{B_{10\,\mathrm{min}}}{\mathrm{R}_0 \cdot T_{10\,\mathrm{min}}} \tag{1}$$

where

$\rho_{10\,\mathrm{min}}$ is the derived 10 min averaged air density;

$T_{10\,\mathrm{min}}$ is the measured absolute air temperature averaged over 10 min;

$B_{10\mathrm{min}}$ is the measured air pressure averaged over 10 min;

R_0 is the gas constant of dry air 287,05 J/(kg × K).

For a stall-regulated wind turbine with constant pitch and constant rotational speed, data normalization shall be applied to the measured power output according to the equation:

$$P_\mathrm{n} = P_{10\mathrm{min}} \cdot \frac{\rho_0}{\rho_{10\mathrm{min}}} \tag{2}$$

where

P_n is the normalized power output;

$P_{10\mathrm{min}}$ is the measured power averaged over 10 min;

ρ_0 is the reference air density.

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For a wind turbine with active power control, the normalization shall be applied to the wind speed according to the equation:

$$V_{\mathrm{n}} = V_{10\mathrm{min}} \left(\frac{\rho_{10\mathrm{min}}}{\rho_0} \right)^{1/3} \tag{3}$$

where

V_{n} is the normalized wind speed;

$V_{10\mathrm{min}}$ is the measured wind speed averaged over 10 min.

8.2 Determination of the measured power curve

The measured power curve is determined by applying the "method of bins" for the normalized data sets, using 0,5 m/s bins and by calculation of the mean values of the normalized wind speed and normalized power output for each wind speed bin according to the equations:

$$V_i = \frac{1}{N_i} \sum_{j=1}^{N_i} V_{\mathrm{n},i,j} \tag{4}$$

$$P_i = \frac{1}{N_i} \sum_{j=1}^{N_i} P_{\mathrm{n},i,j} \tag{5}$$

where

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

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

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

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

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

The measured power curve shall be presented as detailed in Clause 9. In case cut-out behaviour has been reached during the measurement period two power curves shall be presented. Power curve A shall be based on database A and power curve B shall be based on database B, as described in 7.4. Both power curves shall be presented as detailed in Clause 9.

8.3 Annual energy production (AEP)

Generic AEP is estimated by applying the measured power curve to different reference wind speed frequency distributions. A Rayleigh distribution, which is identical to a Weibull distribution with a shape factor of 2, shall be used as the reference wind speed frequency distribution. AEP estimations shall be made for hub height annual average wind speeds of 4, 5, 6, 7, 8, 9, 10 and 11 m/s according to the equation:

$$AEP = N_{\mathrm{h}} \sum_{i=1}^{N} \left[F(V_i) - F(V_{i-1}) \right] \left(\frac{P_{i-1} + P_i}{2} \right) \tag{6}$$

where

AEP is the annual energy production;

N_{h} is the number of hours in one year ≈ 8760;

N is the number of bins;

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

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

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and

$$F(V) = 1 - \exp\left(-\frac{\pi}{4}\left(\frac{V}{V_{\text{ave}}}\right)^2\right) \quad (7)$$

where

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

V_{ave} is the annual average wind speed at hub height;

V is the wind speed.

The summation is initiated by setting V_{i-1} equal to V_i – 0,5 m/s and P_{i-1} equal to 0,0 kW.

For a specific development, nominal site conditions specifying the wind climate of the site may be known. If so, a site specific AEP may, additionally, be reported and computed based on this site specific information.

The AEP shall be calculated in two ways, one designated "AEP-measured", the other "AEP-extrapolated". If the measured power curve does not include data up to cut-out wind speed, the power curve shall be extrapolated from the maximum complete measured wind speed up to cut-out wind speed.

AEP-measured shall be obtained from the measured power curve by assuming zero power for all wind speeds above and below the range of the measured power curve.

AEP-extrapolated shall be obtained from the measured power curve by assuming zero power for all wind speeds below the lowest wind speed in the measured power curve and constant power for wind between the highest wind speed in the measured power curve and the cut-out wind speed. The constant power used for the extrapolated AEP shall be the power value from the bin at the highest wind speed in the measured power curve.

AEP-measured and AEP-extrapolated shall be presented in the test report, as detailed in Clause 9. For all AEP calculations, the availability of the wind turbine shall be set to 100 %. For given annual average wind speeds, estimations of AEP-measured shall be labelled as "incomplete" when calculations show that the AEP-measured is less than 95 % of the AEP-extrapolated.

Estimations of measurement uncertainty in terms of standard uncertainty of the AEP according to Annex D, shall be reported for the AEP-measured for all given annual average wind speeds.

The uncertainties in AEP, described above, only deal with uncertainties originating from the power performance test and do not take into account uncertainties due to other important factors relating to actual energy production for a given installation.

8.4 Power coefficient

The power coefficient, C_{P}, of the wind turbine shall be added to the test results and presented as detailed in Clause 9. C_{P} shall be determined from the measured power curve according to the following equation:

$$C_{\text{P},i} = \frac{P_i}{\frac{1}{2}\rho_0 A V_i^3} \quad (8)$$

where

$C_{\text{P},i}$ is the power coefficient in bin i;

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

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

A is the swept area of the wind turbine rotor;

ρ_0 is the reference air density.

9 Reporting format

The test report shall contain the following information:

a) An identification and description of the specific wind turbine configuration under test (see 5.1), including:
   1) turbine make, type, serial number, production year;
   2) rotor diameter and a description of the verification method used or reference to rotor diameter documentation;
   3) rotor speed or rotor speed range;
   4) rated power and rated wind speed;
   5) blade data: make, type, serial numbers, number of blades, fixed or variable pitch, and pitch angle(s);
   6) hub height and tower type;
   7) description of the control system (device and software version) and documentation of status signals being used for data reduction;
   8) description of grid conditions at the wind turbine, i.e. voltage, frequency and their tolerances, and a drawing indicating where the power transducer is connected, specifically in relation to an internal or external transformer and self-consumption of power.

b) A description of the test site (see 5.2), including:
   1) photographs of all measurement sectors preferably taken from the wind turbine at hub height;
   2) a test site map showing 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, meteorological mast, significant obstacles, other wind turbines, and measurement sector;
   3) results of site assessment, i.e. the limits of the valid measurement sector(s);
   4) if site calibration is undertaken the limits of the final measurement sector(s) shall also be reported including the rationale for any changes from the results of the site assessment.

c) A description of the test equipment (see Clause 6):
   1) identification of the sensors and data acquisition system, including documentation of calibrations for the sensors, transmission lines, and data acquisition system;
   2) description of the arrangement of cup anemometers on the meteorological mast, following the requirements and descriptions in Annex G;
   3) sketch of the arrangement of the meteorological mast showing principle dimensions of the tower and instrument mounting fixtures;
   4) description of method how to maintain the anemometer calibration over the duration of the measurement period and documentation of results that show that the calibration is maintained.

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d) A description of the measurement procedure (see 5.1 and Clause 7):

1) documentation of the procedural steps, test conditions, sampling rate, averaging time, measurement period;

2) a 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;

3) identification of any data rejection criteria beyond those listed in 7.4.

e) Presentation of measured data (see 7.3 to 7.6):

data from each selected data set shall be presented in both tabular and graphical formats, providing statistics of measured power output as a function of wind speed and of important meteorological parameters including:

– scatter plots of mean, standard deviation, maximum, and minimum power output as a function of wind speed (plots must include information on sample frequency). An example is shown in Figure 2;

– scatter plots of mean wind speed and turbulence intensity as a function of wind direction;

– scatter plots of the turbulence intensity as a function of wind speed, and the average turbulence intensity in each wind speed bin shall be presented;

– special databases consisting of data collected under special operational or atmospheric conditions should also be presented as described above;

– if measured, rotational speed and pitch angle shall be presented with a scatter plot including binned values versus wind speed and a table with the binned values;

– definition of status signals, and plots of status signals during the measurement period.

f) Presentation of measured power curve for air density at sea level (see 8.1 and 8.2):

1) the power curve shall be presented in a table similar to Table 1. For each wind speed bin, the table shall list:

– normalized and averaged wind speed;

– normalized and averaged power output;

– number of data sets;

– calculated C_p value;

– standard uncertainties of category A (see Annexes D and E);

– standard uncertainties of category B (see Annexes D and E);

– combined standard uncertainty (see Annexes D and E);

2) the power curve shall be presented in a graph similar to Figure 3. The graph shall show as a function of normalized and averaged wind speed:

– normalized and averaged power output;

– combined standard uncertainty;

3) the C_p curve shall be presented in a graph similar to Figure 4;

4) both the graph and the table shall state the sea level air density 1,225 kg/m^3, used for the normalization;

5) in case cut-out wind speed has been reached during the measurement period the power curve and C_p curve, or the parts of the curves influenced by the cut-out hysteresis, shall be presented in a similar way to items 1), 2), 3) and 4).

g) Presentation of measured power curve for site specific air density (see 8.1 and 8.2):

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if the site average air density is not within 0,05 kg/m^3 of 1,225 kg/m^3, or if a pre-defined nominal air density is required, then a second presentation of the measured power curve shall be made. This presentation shall be the same as for sea level air density but shall show the power curve results obtained by normalization to the site specific air density.

h) Presentation of measured power curves collected under special operational and atmospheric conditions (see 7.5):

power curves, derived from subsets of the database for special operational or atmospheric conditions, may also be reported. If this is the case, a power curve should be reported as for sea level air density, but with clear indication in all plots and tables of the special operational and/or atmospheric conditions.

i) Presentation of estimated annual energy production for air density at sea level (see 8.3):

1) a table that for each annual average hub height wind speed shall include:
   - AEP-measured;
   - standard uncertainty of AEP-measured (see Annexes D and E);
   - AEP-extrapolated;
2) the table shall also state:
   - reference air density;
   - cut-out wind speed;
3) if at any annual average wind speed AEP-measured is less than 95 % of AEP-extrapolated, the table shall also include the label, “incomplete” in the column of values of AEP-measured;
4) in case cut-out wind speed has been reached during the measurement period the estimated annual energy production, including the cut-out hysteresis, shall additionally be presented similar to items 1), and 3); the table shall also state the reference air density.

j) Presentation of estimated annual energy production for site specific air density (see 8.3):

if the site average air density is not within 0,05 kg/m^3 of 1,225 kg/m^3, or if it is desired that a pre-defined nominal air density be used, then a second table of AEP shall be presented. This presentation shall be the same as for sea level air density, but shall show AEP results obtained by normalization to the site specific air density.

k) Presentation of measured power coefficient (see 8.4):

measured power coefficient should be presented as a function of wind speed in a table and a graph in which the swept area of the rotor shall be indicated.

l) Presentation of results of site calibration (see Annex C):

1) if a site calibration is undertaken, it shall be presented in the report as a table and a graph;
2) the table shall for each wind direction bin present:
   - minimum and maximum wind direction limits;
   - the bin-averaged wind direction;
   - the bin-averaged ratio of wind speeds;
   - number of hours of data;
   - combined standard uncertainty of the wind speed ratio for 6, 10 and 14 m/s;
3) the graph (see Figure 5) shall present:
   - the bin-averaged ratio of wind speeds with standard deviation $S_{\alpha,j}$ versus wind direction.

m) Uncertainty of measurement (see Annex D):

uncertainty assumptions on all uncertainty components shall be provided.

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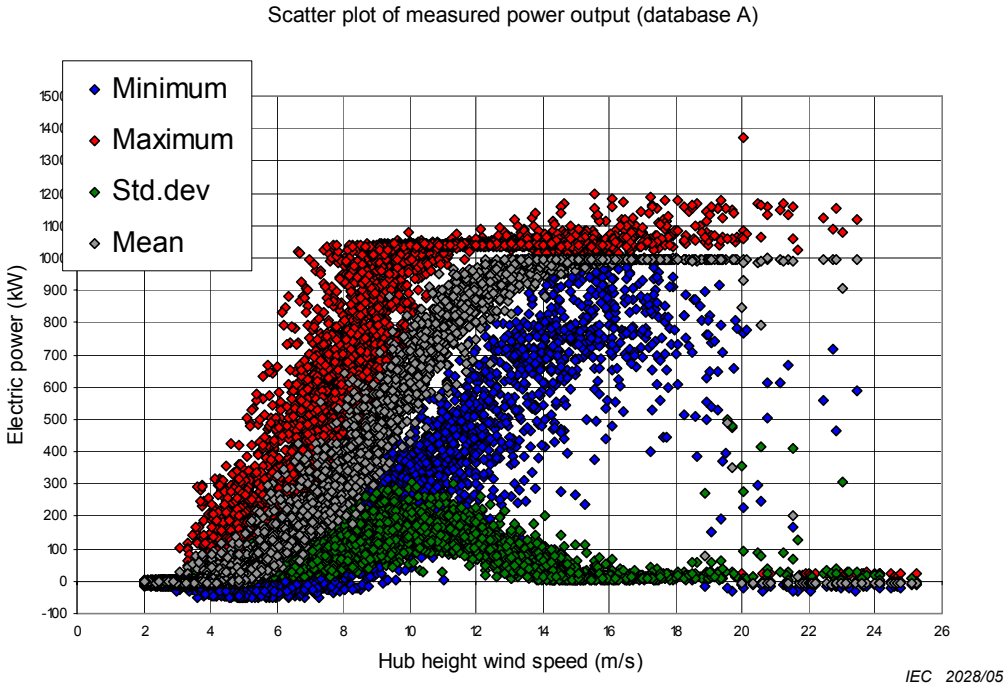
n) Deviations from the procedure:

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



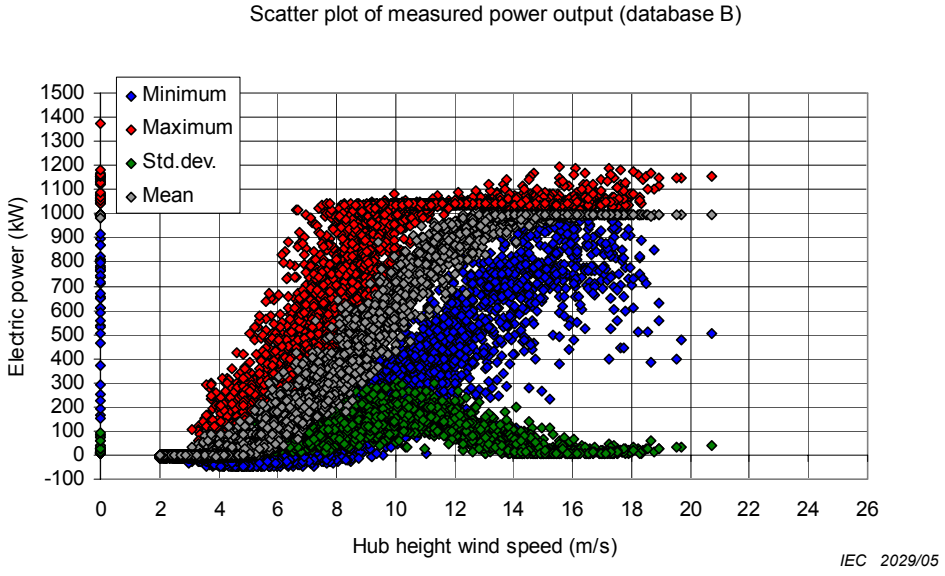


Figure 2 – Presentation of example database A and B: power performance test scatter plots sampled at 1 Hz (mean values averaged over 10 min)

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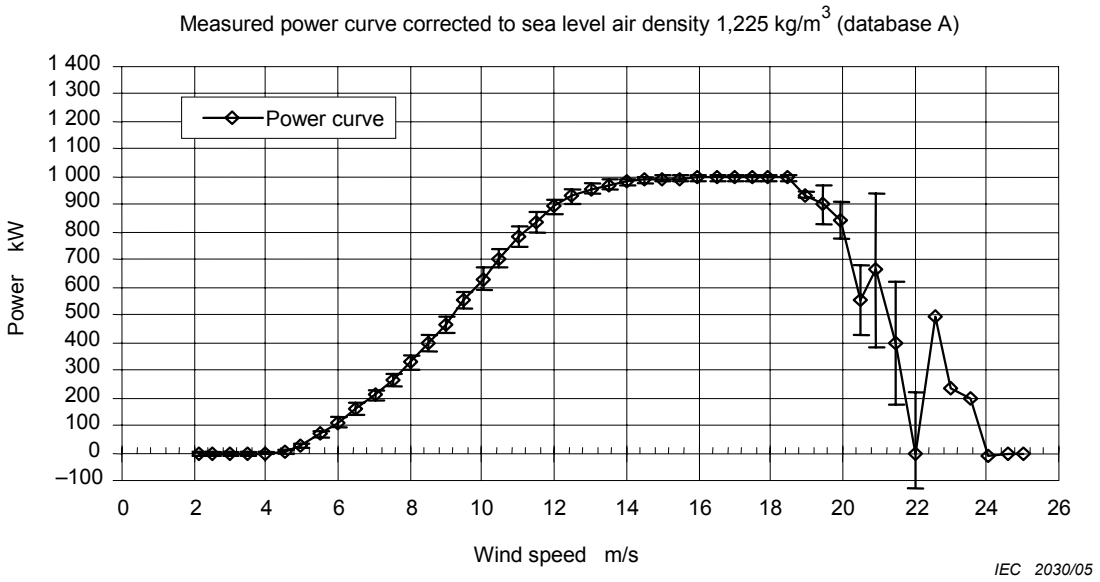

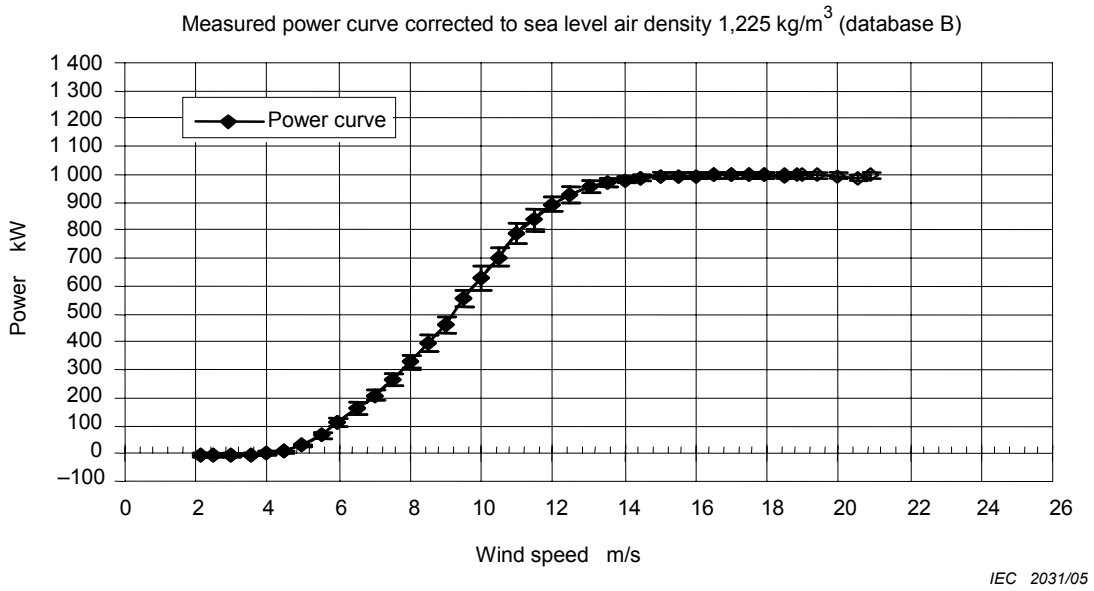

Figure 3 – Presentation of example measured power curve for databases A and B

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