Development of Power Curve Measurement Standards

H. Mellinghoff; DEWI GmbH, Wilhelmshaven

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Summary
Starting from observations of various power curve warranties, this article discusses the motivation for refined measurement procedures and presents in an overview the discussions reflected by two IEC standards recently released rsp. under revision. This is the standard measurement approach with an upwind measurement of the wind conditions as laid out in the IEC 61400-12-1. The current version introduced in 2005 is under revision and will see major methodological changes, the most prominent one being the introduction of the equivalent wind speed concept. The second is the measurement of the wind conditions using the nacelle anemometer approach.

Introduction

Since 2005 the current version of the IEC 61400-12-1 [1] is the most often used measurement procedure when assessing the power curve of a wind turbine. The classic approach measures the wind speed at hub height with a cup anemometer and derives a power curve after selection of a measurement sector based on the evaluation of wind speed, wind direction, air density, status signals and the net electric power to the turbine. In cases where the terrain exceeds certain conditions a previous site calibration campaign is required. With the growth of the machines, their installation in a bandwidth of climatic conditions onshore, offshore, in complex terrain, deserts and in cold climate conditions the demands to the standards of measuring a power curve have risen.
While the -12-1 standard is undergoing a major revision [2] the -12-2 [3] is aiming at measuring the power curve based on nacelle anemometry. This presentation is intended to give an overview of the upcoming changes and is intended for project developers planning installations in the next 2 to 4 years. The discussion is motivated by first looking at warranty conditions observed in sales contracts of wind turbines.

Warranty contract formulations

Previous practice
The warranty formulation of a wind turbine power curve in sales contracts has seen a significant degree of refinement over the past years. This initially has to do with the fact that the IEC 61400-12-1 defines a method how to report a standardized annual energy production (AEP) but leaves it open to the contract negotiations to define the details when a certain machine, quite often representing a full wind energy project, has passed the test. The earlier warranty formulations basically asked for a measured AEP calculated for a defined wind speed regime that should exceed a certain fraction, quite often 95%, of the measured AEP. The warranted power curve

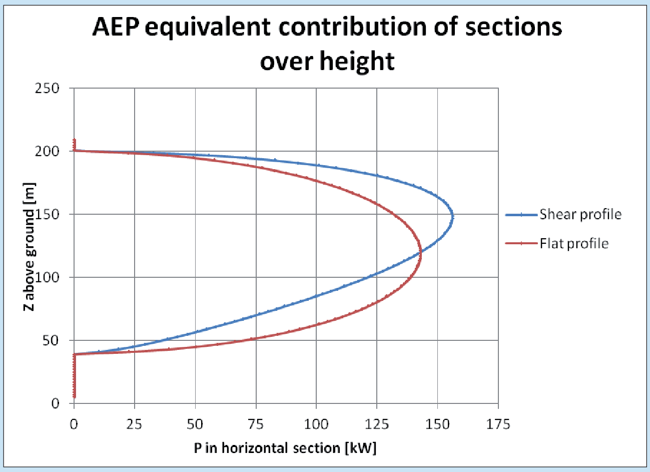

Fig. 1: Power in horizontal stripes of 2 meters height for a turbine with 120 m hub height, 160 m rotor diameter, α=+0.25, 9.0 m/s wind speed at hub height. The impact of shear onto the net power in the rotor plane is a function of hub height and rotor diameter.

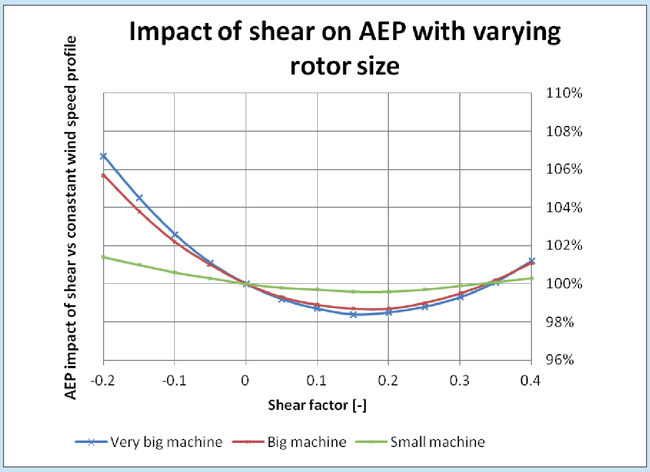

Fig. 2: Relative shear impact

and the reference wind regime at the site were parts of the sales contract. The measurement in general followed the IEC 61400-12-1. Often it was required to define further details of the test procedure prior to the beginning of the test as they appeared to be open. Site calibrations were generally allowed and the uncertainty of the AEP calculation was not necessarily considered in the warranty formulation. The measurement duration for a site calibration - if required - and consecutive power curve test could be estimated with three months each as a rule of thumb.

Recent warranty procedures

Current sales contract define the individual measurement conditions in more detail naming a list of additional requirements for example:

- *Data base filtered for grid coupled status signal.* This takes out the so called cut-out hysteresis from the power curve at high wind speeds. Also, turbines with a serious availability problem would not show that in the measured power curve.
- *Turbulence filters.* Depending on the wind speed range, turbulence can increase or decrease the power curve of a wind turbine. Filters aim at reducing the accepted range to conditions which are usually observed in flat and open terrain.
- *Wind shear filters.* The degree to which the wind speed changes with height has a significant impact on the power curve that grows with the size of the rotor. This will be discussed in more detail in the next section.
- *Limitation of tilted inflow.* Cup anemometers and wind turbines respond to tilted inflow in different manner. For sites in complex terrain it becomes therefore a standard demand to measure the vertical component of the wind vector as well.
- *Site calibration using advanced correlation schemes for wind speed at hub height but also wind shear and turbulence.* The current standard assumes a linear correlation between the wind speed at hub height and the wind speed at the reference tower depending only on wind direction but do not take effects like wind speed or time of day into account. Yet, with growing complexity of the terrain, such site impacts grow.
- *The uncertainty of AEP measured reduces the warranted energy yield.* Depending on the site conditions and maximum wind speeds observed the uncertainty of a power curve measurement can easily exceed 5 % in AEP measured. The formulations for such cases range from an equal share between turbine producer and manufacturer to leaving the uncertainty to the expenses of the manufacturer.

The bottom-line of such formulations is that the site conditions that can be demanding on the turbine and can affect the energy yield are not taken into account when calculating the measured AEP. The approach of using filters can limit the evaluated subset to a fraction of less than 10 % of the complete measured data. As a consequence the power curve test can take rather long. The filtering may even be so restrictive that a power curve measurement is not possible at all. One of the ideas if the revised IEC 61400-12-1 is therefore to use shear information to normalize the data so that filtering is no longer required.

Shear Impact

The following consideration is meant to show the impact on the power in the rotor plane that results just from theoretical considerations at the wind speed profile over height. We assume three different turbine sizes. A small machine with a rotor diameter of 40 m and a hub height of 60 meters. Secondly, a big machine with a hub height of 80 meters and a rotor diameter of 100 meters and a very big machine with a hub height of 120 m and a diameter of 160 meters. We keep the wind speed at hub height at a fixed value and vary the shear factor and look at the relative influence on rotor power compared to a profile with no shear (α=0) to get the above Fig. 2. The relative AEP is up to 1.6% smaller compared to the case with no shear. Furthermore we see that highly negative shear actually increases the AEP output relative to standard situations. The same happens for shear factors α>0.35. Yet, for the range most frequently observed in the field the AEP is reduced from the impact of shear relative to the constant wind speed with height.

The second conclusion from the plot is that the assumption to describe the wind regime in a rotor plane works with acceptable accuracy with a point measurement for the turbine dimensions that were common 10 to 15 years ago. Nowadays with rotor areas growing, the assumption introduces a significant bias. It grows with rotor size and with relatively short towers.

The development of the IEC 61400-12-1

General

The maintenance cycle report for this standard had been sent out in the summer of 2008. Since then 13 meetings by the expert group have been held with team sizes between 25 to 40 persons attending. The document grew from 90 pages to now 200 in the current second CD version under discussion. Next to the methodological developments there is quite some material on measurement technologies and there has been extensive work on the annexes. There are also several new annexes with the following items:

- Annex L Application of remote sensing
- Annex M Normalization of the power curve for turbulence
- Annex N Wind vane calibration
- Annex O Cold climate power performance
- Annex P Wind shear normalization
- Annex Q Rotor equivalent wind speed considering wind veer

The major methodological development is the introduction of the *rotor equivalent wind speed* concept. Wind speed is no longer measured at hub height only but at an odd number of heights over the full rotor plane. The values are used then to determine a single wind speed figure named rotor equivalent wind speed that takes the wind profile into account. The preferred approach to measure the wind profile is remote sensing technology which currently means LIDAR or SODAR systems. Yet, tall towers spanning the full rotor height are also discussed. The equivalent wind speed concept is introduced in the standard as one of two general approaches to describe the wind conditions. The classic power curve using the *hub height wind speed* will continue to be an option.

Other major developments are the definition of the power curve itself which will not only be depending on wind speed and air density but also consider influences of wind veer and turbulence.

Extensive work has gone into the site calibration procedure which discusses various types of terrain and methods to assess the quality of the correlation between turbine and met tower to detect flow separation scenarios. Depending on the site analysis the site calibration will be using a matrix of factors based on shear and direction or a linear regression approach based on wind direction.

Wind measurement options

The rotor equivalent wind speed approach requires having wind information over the full rotor height. The current discussion is such that measurements in complex terrain will not be allowed with remote sensing methods. Instead there is the option to measure the wind with tall towers spanning the full rotor height and measuring the wind profile using side mounted booms. This is actually a limitation that may be overcome with future developments in remote sensing technology.

Two other approaches are proposed in flat terrain which allow to utilize the strength of the remote sensing technology. The combination of a hub height met mast with a remote sensing device is probably the setting that is of greatest interest already today. It allows hub height wind speed evaluations of power curves as well as doing the rotor equivalent wind speed evaluations on top. At the same time it stays in line with the requirements on the setting that the current IEC 61400-12-1 defines. This is a setup that the author suggests to use especially in prototype testing of turbines with 100 meters rotor diameter and more.

The second combination of interest is the use of a short tower in combination with a remote sensing device. Here the mast acts as a reference to check the performance of the remote sensing system against the mast and to either determine a hub height wind speed or a rotor equivalent wind speed value from it. This setup is considered to be of commercial interest for power performance testing because putting up a small tower of 40 to 60 meters is relatively easy and will become even more interesting, when turbines grow even further. This setup is new to the revised standard and not applicable if the current IEC 61400-12-1 requirements should be met as well.

Yet, it is common to all four approaches of wind speed measurements to have a met tower at the site. This is also reflecting the fact that traceability of the remote sensing data in the sense of the IEC/ISO 17025 can only be achieved by comparison against a cup anemometer.

As a consequence the classification of remote sensing instruments will be done in the form of a field verification test which will study the impact of various meteorological variables on the accuracy of the reading at various heights. Variables of interest are shear, turbulence, precipitation, wind direction, air temperature, air density, temperature profile, wind veer profile and flow inclination. Such classification tests will be conducted next to tall towers with an advanced instrumentation. The duration of such a campaign is proposed to be at least three months to ensure that a range of seasonal fluctuations has been observed.

The Development of the IEC 61400-12-2

General

The work on this standard started as early as in 2006 and it was finally published in March 2013. The major aim of developing the standard was to offer a method for cases in which the standard approach to power curve measurements was not available or economically not feasible. This would be turbines in complex terrain for which a site calibration was not available or, more recently, offshore wind turbines. As a guiding principle the standard had been developed trying to stay as close to the ideas of the current IEC 61400-12-1 from 2005 as possible. As a consequence it is a hub height power curve, yet there are limitations. The rotor must be turning in order to gain meaningful data from a nacelle anemometer over a ten minute averaging period. Effectively this means a grid coupled turbine.

Requirements and application

Tilted inflow of winds to a nacelle structure can have unpredictable effects on the reading of a nacelle mounted anemometer. The behavior depends on a number of factors, among them type of sensor and its exact location, that may only be assessed by empirical comparison. As a consequence the current draft proposes a scheme that classifies the terrain in five

groups in which the turbine is placed and allows only limited transfer to neighbouring terrain classes.
Since the mounting of a wind speed sensor is critical it has been required that a nacelle transfer function can only be applied if a number of factors including rotor, blade type, controller settings, calibration of the anemometer, mounting of the sensor must be identical and well documented. The signal chain form the anemometers raw signal to the data acquisition system shall be described in detail, independent of the turbine control and tested against a calibrated reference source by injecting known signals at the point of connection of the nacelle anemometer.
A limitation of the method is that it may not be applied in wind directions that are in the wake of another turbine. Partial and full wake situations are not covered.

A typical application case

The interesting feature of a nacelle transfer function (NTF) is that it can be gathered relatively easy during a classic power curve test. With a bit more time invested in documentation of the anemometer mounting and especially calibration of the anemometer the data base can be obtained at relatively low cost as a side product. The decision to measure the NTF should be made prior to the beginning of the power curve test to allow for the necessary documentation. It requires avoiding disturbing influences which can be detected at the beginning relatively easy like flashlights mounted in the vicinity of the anemometer, lightning catcher structures directly upwind or mounting of anemometers on massive bars that have a significant near field impact on the reading.
The typical application would then be using this transfer function on one or all turbines standing free and with the same technical frame conditions. The advantage is that the power curve test can be performed on several turbines, probably more than would have been tested with the classic mast design. Secondly it can be applied in complex terrain without knowing the site calibration for the turbine under test. The uncertainty calculation should basically benefit from the larger number of samples in a batch. Yet, since the uncertainty of a Nacelle Power Curve (NPC) has generally higher uncertainties, the net result depends largely on which assumptions can be considered regarding the cancellation of uncertainties.

Measurement of the NTF

The Nacelle Transfer Function determination uses the ten minute average values recorded at the met tower hub height anemometer and the nacelle anemometer at the same time. Ideally the signals should be going to the same data acquisition system to avoid any ambiguity about data synchronization. The signal on the turbine may be coming from three different sensor types including cup and sonic anemometers who are most often used in current designs for the nacelle anemometer. Most turbines have more than one nacelle anemometer, so it needs to be documented which of the sensors is used in the particular setup. The signals of turbine yaw and turbine wind vane shall be recorded as well. They do not directly enter the NTF calculation but have an impact on sector determination. As an option, the standard discusses determining a transfer function of the nacelle wind direction signal in relation to wind speed. The wind speed data does not require undergoing air density normalization which assumes that the measurement behaviour of allowed anemometer types is independent of air density. The only correction that may be required to the free wind data is the application of a site calibration in complex terrain.
The final NTF is a binned relation of the free wind over the nacelle anemometer after filtering. An alternative presentation of the function is the offset per wind direction bin or in the form of any analytical function. Compared to the discussions in the IEC 61400-12-1 the NTF approach has the limitation that it will not give a corrected figure for the turbulence intensity in the free wind and it is also not meant to give statements on wind shear.

Summary and Outlook

The IEC 61400-12-1 power curve measurement standard is undergoing an extensive revision aiming to meet the requirements of large turbines and reducing the site effects that turbines are exposed too as the wind energy use advances into more demanding sites. The wind speed description based on equivalent wind speed definition is the major methodological development. The step is motivated by the fast development of remote sensing technologies in the past decade. Consequently the technical revisions of the standard deal with refinements of the classification scheme for all allowed wind measurement technologies. This includes not only remote sensing but also the point measurement with cup anemometers and sonics, adding a procedure for the calibration of wind vanes as well. The standard is reflecting a progress in transition from the currently used hub height wind speed to the expected rotor equivalent wind speed concept. Consequently, it allows to use both for the measurement of power curves. Where profile information is not taken into account, an estimation on the uncertainty contribution to the hub height wind speed power curve shall be provided.
The IEC 61400-12-2 is a currently released power curve measurement standard that may be the only option if a site calibration had not been performed prior to turbine erection. Furthermore the application under offshore conditions may be interesting as putting up offshore masts is very expensive.
The future will likely bring a combination of the ideas in the revised IEC 61400-12-1 and the IEC 61400-12-2: Horizontally forward looking Lidars will measure the free wind at hub height upstream in distances of 2.5 rotor diameters without the need to correct for effects introduced downwind by the turbines rotor. DEWI has actually started doing first offshore power curve measurements on a commercial basis with this approach.
The demands to take site effects more into account are reflected by the recent warranty formulations that manufacturers use in their sales contracts on top of the requirements of the current IEC [1]. Checking the implications of the requirements on the instrumentation of a power curve measurement and the feasability of its timeline is recommended prior to beginning of the test.

References

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

[2] IEC 61400-12-1, Ed. 2, CD2, 2013, Power performance measurements of electricity-producing wind turbines

[3] IEC 61400-12-2; Ed.1, 2013/03, Power performance of electricity-producing wind turbines based on nacelle anemometry