Power Curve Working Group Agenda

Impact of 'non-standard' inflow

6th Meeting Minutes, Wednesday 1st April 2014, DTU Risø Campus, Roskilde, Denmark

Theme: The 1st meeting gave a clear statement of the problem. The 2nd meeting examined possible solutions. The 3rd meeting put some of those solutions into practice. The 4th meeting consolidated the learning to date by examining new datasets. The 5th meeting focused on validating the candidate correction methods against real data. The 6th meeting broadened the validation to additional datasets, examined the limitations of the correction methods and probed the Type B effects associated with these limitations.

Attending: Mathew Colls (Prevailing), Richard Whiting (DNV GL), Anna Marsh (DNV GL), Erik Tuexen (DNV GL), Carla Ribeiro (DNV GL), Peter Stuart (RES), Alex Clerc (RES), Alan Derrick (RES), Dan Bernadette (AWS TruePower), Jørgen Højstrup (Højstrup Wind Energy), Samuel DAVOUST (Avent), Axel Albers (WindGuard), IÑAKI LEZAUN MAS (Gamesa), Tomas Blodau (Senvion), David Malins (Scottish Power), Diego Azofra (Barlevento), Michael Pram Nielsen (Vestas), Per Nielsen (EMD), Ralph Torr (ORE Catapult), Florin Pintille (Sgurr), Ioannis Antoniou (Siemens), Alejandro Gonzalez (Siemens), Postolos Piperas (Siemens), Julija Tastu (Siemens) Daniel Marmander (Natural Power), Barry Logue (Vaisala), David LANGOHR (Leosphere), Rozenn Wagner (DTU), Paula Gómez Arranz (DTU), Rebeca Rivera Lamata (Dong). Richard Gale (EON), Matthew Meyers (EON), chris.slinger (Zephir), Frank Klinto (Suzlon), Joerg Wwanink (GE), Gaetan Martellozzo (EDF), Brian Davison (Edinburgh Napier University) & Herbert Schwartz (Anemos-Jacob).

Key Outcomes:

- There is substantial merit in the turbulence renormalisation method, but it is important to be aware of its limitations. Further work is required to better understand the limitations of the turbulence renormalisation method.

- There is broad agreement that while there is substantial merit in the existing correction methods (Density, Rotor Equivalent Wind Speed and Turbulence Renormalisation) they do not fully explain all the available observations. Further work is required to investigate the limitations of these methods and the sources of possible "Type B effects".

Summary of Actions:

- **Complete Rotor Equivalent Wind Speed (Veer) Exercise.**
- **Develop Guideline Document on the Presentation of Power Curve Information**
- **Develop Guideline Document on the Application of the Turbulence Renormalisation Method**
- **Engage with research institutions to test Type B hypotheses using 'open-source' rotors.**
- **Develop proof of concept for the 'Black Box Model' approach.**
- **Release python implementation of consensus analysis as open source.**
- **Investigate the possibility of hosting a PCWG event in the US.**

Presentations:

- “01 Introduction” Peter Stuart (RES)
- “02 Validation Analysis - Turbulence Correction” Alex Clerc (RES)
- “03 REWS & TI Correction Methods Vs Real Performance Trends - Diego Azofra (Barlevento)”
- “04 A Study of Turbine performance under cold weather driven stable atmospheric conditions in Scandinavia - Carla Ribeiro (DNV-GL)”
- “05 Analyses of the mechanisms of amplitude modulation of aero-acoustic wind turbine sound - Andreas Fischer (DTU)”
- “06 Steps towards comparison of turbine performance across varying turbine geometries - Matthew Colls (Prevailing)”
- “07 Calculating site specific power curve loss estimtates - Dan Bernadett (AWS Truepower)”
- “08 Illustrating the Importance of Site Specific Power Curves - Alan Derrick (RES)”
- “09 Power curves - Use of spinner anemometry - Troels Friis Pedersen (DTU)”
- “10 Rotor Equivalent Wind Speed - IÑAKI LEZAUN MAS (GAMESA)”
- “11 Challenges accompanying the use of the Rotor Equivalent Wind Speed (Siemens)”
- “12 Probabilistic Atmospheric characterization Relevant Shear and Turbulence Intensity statistics - Mark Kelly (DTU)”
- “13 Type B Effects Introduction - Erik Tüxen (DNV GL)”

Presentation Clarifications

One group member sought clarification regarding the presentation “04 A Study of Turbine performance under cold weather driven stable atmospheric conditions in Scandinavia - Carla Ribeiro (DNV-GL)”. The member wanted to know if DNV-GL had applied the turbulence renormalisation method from the draft IEC power performance standard or some other method. DNV-GL responded that they had used the turbulence renormalisation method from the draft standard and added that the formula $P = 1/2\rho(u)3(1+3TI2)ACp$ was presented purely for illustration (it wasn’t formerly used in their analysis).

Minutes of Discussion

The Merits of the Turbulence Renormalisation Method

The group discussed the merits and applicability of the turbulence renormalisation method.

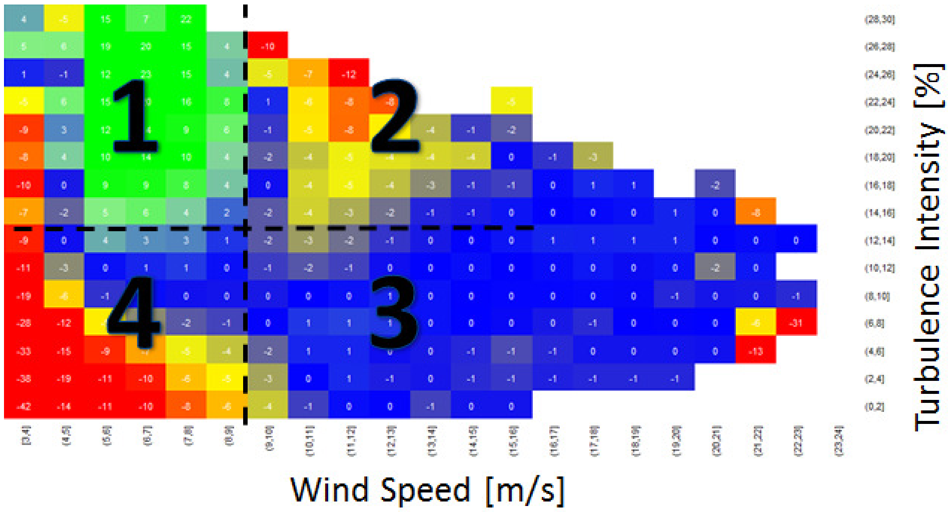

Figure 1. Power deviations as a function of wind speed and turbulence intensity ('power matrix'). The 'quadrants' have been numbered 1 to 4. The 4th Quadrant (strong negative deviations associated with low wind speed, low turbulence and high shear) has received particular attention from the working group.

One consultant commented that there was definitely value in the turbulence renormalisation method, however it was important to know its limitations. The consultant added that in his view the turbulence renormalisation method was one tool by which power curves can be adjusted e.g. other corrections can be applied based on the power performance track record of the turbine model under consideration. A developer added that he believed that even an imperfect model can be very useful if applied properly.

One consultant suggested that shear may be the primary reason for the power degradation in the 4th Quadrant (angles of attack variations due to shear) and asked if any of the manufacturers present have individual pitch control in their turbines. Two manufacturer responded by saying that all of their machines are collective pitch. One manufacturer suggested that the hypothesis could easily be tested using models, but added that their expectation was that the result would not be a 'game changer'.

Another consultant said that he felt that it was necessary to revert to empirical methods within the 4th quadrant and rely on the analytical turbulence renormalisation methods in the other quadrants. One developer said that they weren't convinced that the performed on the method in the 4th quadrant was the key issue and added that their analysis indicated that the performance near the knee (Quadrants 2 and 3) was more of an issue.

One developer commented that his work suggested that the turbulence renormalisation method shows similar performance to the density correction method. Another developer commented that people do not tend to apply the density correction method if the correction is too large (for example a >3% density change may be considered too much). A consultant commented that the best way to reduce the uncertainty in the turbulence renormalisation was to start with a power curve whose reference turbulence is as close to the site turbulence as possible.

One working group member suggested that analysis of 'fast data' (e.g. 1 Hz data) may be helpful in further developing the turbulence correction. Another working group member mentioned the $P \alpha (u)^3(1+3TI^2)$ relationship from the DNV-GL presentation as a well-known method for describing the power available in turbulent wind. One manufacturer made the point that the turbine does not respond in the same way at the ankle and the knee and that it may be necessary to change the wind speed definition to describe the effects of turbulence, but added that this would be a big step.

In conclusion the group agreed that there is substantial merit in the turbulence renormalisation method, but also that it was important to be aware of its limitations. The group also agreed that further work is required to better understand the limitations of the method.

<u>Use of ten-minute averages</u>

A LiDAR manufacturer commented on the use ten-minute averages for power performance analysis. The LiDAR manufacturer compared the power curve situation to a choice commonly encountered in processing LiDAR data i.e. to fit the data to a non-linear function and then average or to average the data and then fit. The LiDAR manufacturer stated that in their experience it was best to average and then fit e.g. the "Line of Site Average First" method used in Nacelle LiDARs. The LiDAR manufacturer suggested it would be advantageous for power curve analysis to log non-linear quantities for each ten minute bin e.g. average square of wind speed over ten minutes, average cube of wind speed over ten minutes etc.

<u>Guidelines for the Presentation of Power Curve Information</u>

The group discussed a proposal to develop a set of guidelines explaining how power curve information should be presented. One developer said that he believed there would be benefit in developing a set of guidelines that would explain how to present power curve so that correction methods could be applied unambiguously e.g. by explicitly stating that the power curve is referenced to either hub height, rotor equivalent wind speed or both. A consultant added that he felt that it was definitely helpful to unify how data is sent and received.

<u>Turbulence Renormalisation Method Guidelines</u>

The group briefly discussed the potential to develop guidelines on how to calculate the uncertainty associated with the turbulence renormalisation method e.g. what is the reduction in the uncertainty associated with applying the method. One consultant commented that he was very keen to see such guidelines developed, however another consultant said that he wasn't convinced that the method always added certainty. A consultant commented that a consideration of the uncertainty reduction associated with the application of the rotor equivalent wind speed method is already part of the draft IEC standard. In the end the group concluded that the guideline document on the uncertainties associated with the turbulence renormalisation method was not feasible in the short term and should be revisited when the limitations of the method are better understood.

One developer made an alternative suggestion that the group should develop a guideline document on how to apply the turbulence renormalisation method (without addressing uncertainty). This could capture the lessons learnt from the round robin exercises and make use of the consensus analysis. The group agreed to work towards developing a guideline document on the application of the turbulence renormalisation method.

Rotor Equivalent Wind speed (Veer) Round Robin

The group agreed to work towards the end of April as a deadline for the 3rd Round Robin Exercise (Rotor Equivalent Wind Speed with Veer).

Open Source Python Implementation of Consensus Analysis

One developer indicated that the python code it has developed which implements the consensus methodology of Rotor Equivalent Wind Speed and Turbulence Renormalisation could be made available to the group[1]. The group was receptive to the concept of using a shared code base to develop to group's ideas. It was agreed that the existing Excel consensus analysis would serve as a bench mark for the python code.

It was suggested that the open-source code may provide a platform for enhanced data sharing whereby individual PCWG members can analyse their proprietary datasets and shared their results in an anonymised standard format. One developer commented that in their experience it was only when a relatively large amount of power curve data was assembled that patterns start to clearly emerge. One developer questioned whether data sharing of this type was feasible to which one manufacturer responded that they have already shared anonymised data with the group in the form of their 'power matrices'.

Type B Effects Discussion

Previously the group had discussed that corrections should be applied for 'non-standard' conditions which are different to those for which a power curve is representative. These corrections fall into two categories:

- **Type A**: Adjustments made to reflect changes in the energy available for conversion across the rotor in a ten minute period due to 'non-standard conditions'.
- **Type B**: Adjustments made to reflect changes in the conversion efficiency due to 'non-standard conditions'

Erik Tüxen from DNV GL introduced the topic of Type B effects with his presentation "13 Type B Effects Introduction". In his presentation Erik introduced a new perspective by showing a schematic alternative form of power curve which relates electrical power to the wind's kinetic power (instead of electrical power to wind speed). The group was receptive to the concept. One developer stated that the "power matrix" could be adapted to express a similar concept by showing efficiency (electrical power normalised to kinetic power) as a function of wind speed and turbulence.

[1] Since the meeting the code has been made available via the GitHub code sharing platform https://github.com/peterdougstuart/PCWG

The group then discussed possible causes of Type B effects. It was proposed that the vertical wind profile could be the source of at least two Type B effects (in additional to the Type A effects described by Rotor Equivalent Wind Speed):

- Changes in conversion efficiency due to angle of attack variations: Either by the angle of becoming sub-optimal and/or tip stall.
- Changes in conversion efficiency due to change in tip speed.

The "ratio of wind speed" metric from the presentation "06 Steps towards comparison of turbine performance across varying turbine geometries - Matthew Colls (Prevailing)" was discussed in the context of Type B effects. One consultant commented that the ratio of wind speed metric may provide a useful tool for empirical investigations of Type B effects.

The likelihood of tip stall due to shear induced angle of attack variations was briefly discussed. One developer posed the question: "how close are turbines to stall in high shear scenarios?". The same developer mentioned the possible parallels with the work presented in "05 Analyses of the mechanisms of amplitude modulation of aero-acoustic wind turbine sound - Andreas Fischer (DTU)".

The group briefly discussed 'Type B' effects associated with turbulence. One consultant commented that the current turbulence renormalisation method assumes an instantaneous turbine response when in reality the turbine will always lag a little behind i.e. the lag potentially represents a Type B loss.

One manufacturer made the point that it should be possible to test these hypothesises on Type B effects using models. The same manufacturer said that this could be done using currently available 'open–source' rotors (e.g. NREL rotor) and BEM (blade element momentum) models e.g. testing the effect of cyclic pitch on Type B effects. One manufacturer commented that once things are better understood it may be possible to create a different formulation of the equivalent wind speed which would build in Type B effects.

The group briefly discussed how new measurement technology such as nacelle LiDARs may change our perception of type B losses. One group member made the comment that these new forms of measurements mean than we now have more information available than when the current draft IEC power performance standard was written.

The group discussed the relationship between the 'power matrix' approach and Type B effects. One manufacturer commented that the 'power matrix' approach will inherently include all Type B effects. Another manufacturer commented that the 'power matrix' approach was a good intermediate step and added that it may be possible to define an 'extreme shear' power curve for the 4th quadrant. A manufacturer commented that some of the effects observed in the power matrices would not be replicated in BEM calculations. It was suggested that the 'power matrix' approach could be coded up and added to the PCWG python code.

The group briefly discussed if there could be a mechanism by which electrical losses would increase during periods of non-standard conditions e.g. high shear. One developer made the comment that if electrical losses were a significant source of loss then one would expect a large temperature increase in the turbine (electrical power converted to heat) which is not the case. The group agreed that electrical losses were unlikely to be a significant cause of degradation and the source was more likely to be aerodynamic.

‘Black Box Model’ Discussion

The group revisited the topic of a black box model i.e. manufacturers could supply a model of turbine performance to developers who could use the model without knowing what’s in the box. Several group members expressed interest in the idea and the group agreed to work towards a proof of concept demonstration[2].

[2] An initial proof concept of the ‘power curve black box’ based on JSON (JavaScript objection notation) and Python is now available at http://peterdougstuart.pythonanywhere.com/?powerCurveID=T001-A&hubWindSpeed=10.5&hubTurbulenceIntensity=0.12&hubDensity=1.224. Example python code to read the value from the JSON web service here: Dropbox\PowerCurveWorkingGroup\BlackBox\Example.py