Paper: wes-2016-16
Title: Monitoring offshore wind farm power performance with SCADA data and advanced wake model
Authors: Niko Mittelmeier et al.

Answers to comments of anonymous Referee #3 by

Niko Mittelmeier et al. July 26, 2016

Dear Referee,

Thank you very much for your interest and taking the time to review our paper. Your comments and suggestions are very helpful and highly appreciated. Below we have addressed each comment and our responses are marked as ***/ response/***.

Dear Authors,
thank you for a interesting and novel idea for the detection of underperforming wind turbines. While I agree with the overall tenet of the paper, there are a few issues I would like to have clarified. Particularly, the SCADA system delivers data at a much higher rate than the 10-min averages. What would happen if you'd make use of the 1-sec resolution available from the data? 130 values would suddenly be 2 minutes instead of 21 hours, if every assumption stays unchanged - which it probably doesn't.

/That is a very good question. And you are right, SCADA data can be recorded with 1-sec resolution. For our particular case, we have used two years of measurements to obtain a fairly good average result for the tuned wake model. And for this period only 10-min data was available. We see the problem with the higher resolution in the increasing scatter of the measurement. Particularly for 1-sec data wind direction and wind speed measured behind the rotor has a very large variation. As we are using this variation to determine the uncertainty of the measurement we would obtain a much higher uncertainty for the detection of underperformance. Type A uncertainties will decease faster but Type B uncertainties will increase. /

How do you deal with intra-10-min variability? Do you require a relatively stable weather situation or at least wind direction to be able to do it?

***/ We are working with 10-min averages and we need N values of 10-min to be averaged, before we can highlight underperformance. Therefore we think that intra-10-min variability is averaged out in most cases. The intra-10-min variability of the wind direction is supposed to be covered by the Gaussian averaging method proposed by Gaumond et al. (2014).
The model is tuned for the annual average weather conditions. In weather conditions, where the model systematically under-, or over-predicts the wake effects the underperformance indicator η will be biased. This has not been explicitly tested, but we think that n(n-1) calculations would reveal turbines which deviate compared to the fleet.
A degradation of the whole wind farm will probably be a slow process and would therefore be much closer at annual averaged conditions for which the wake model is tuned.

References:
Gaumond, M., Réthoré, P., Ott, S., Pena, A., Bechmann, A. and Hansen, K. S.: Evaluation of the wind direction uncertainty and its impact on wake modeling at the Horns Rev offshore wind farm, Wind Energy, 17, 1169–1178, doi:10.1002/we.1625, 2014.

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More detailed comments:
Page 2 Line 1: Offshore met masts are very expensive. Are people really putting up met masts offshore to verify the turbine performance? Or onshore?

/ The installation of an offshore met mast purely for power curve verification has probably not happened yet. But there are already quite a number of offshore met masts installed which are used for performance and research investigations. Just to mention a few: Fino1-3, Nordsee Ost, Amrumbank, Horns Rev etc. /

P3L17: I think this is debatable. Since you need quite a number of values / quite some time to detect the deviations, the method is not really real time anyway, so it could also be analysed retroactively every now and then. It also could be run on a larger highperformance
computer based on downloaded SCADA data. Besides, the connection between higher computational cost and accuracy of the wake models is sketchy at best, see e.g. the results presented in WindBench.

***/You are right, this whole paragraph has been revised as follow:
"The performance monitoring model (Fig. 1) is based on two dimensional LUTs. The user can choose any wake model or even a combination of different model results to provide power output $P_{\pi_{i,j}}$ values for different wind speed bin i and wind direction bin j. The predicted power output P_{π} is derived from the LUTs with linear interpolation knowing the measured wind speed and wind direction. "/***

2.1.1: I wonder why you do not use the same correction method on all the wind farms wind vanes? It just requires SCADA data and some computer power, so it would not be too difficult. Also, when you're calculating a mean wind direction for the whole farm, aren't you relying on a smaller size farm far away from the coast? For example, if you have a location like Anholt, then you have wind and direction gradients due to the proximity of the land across the wind farm. How would that influence your method and its accuracy?

***/This is a very valid point. In our model, the wind direction should be representative for the selected turbines. The variation among the individual wind vanes is used to come up with an uncertainty estimate. With larger wind farms, we expect this variation to increase which will lead to an increase of the uncertainties. We would recommend to divide very large wind farms in smaller groups. One way of defining a quality criteria could be to ensure, that the standard deviation of the single wind directions compared to the average wind direction is smaller or equal to 3.6° (values we have obtained).
We will add the following wording in the paper, to better describe the wind direction correction and estimation:

"The first step is to derive a wind direction ϑ for each 10 min interval. For our monitoring model we are using the absolute wind direction signal from each turbine which is defined as

$$\vartheta = nacelle\ position + wind\ vane\ position \tag{4}$$

The nacelle position is the angle between the rotor axis and a marking for true north. This marking is calibrated as part of the commissioning. But often this signal is not maintained well during operation, because it has no effect on turbine performance. This causes the necessity to apply an offset correction to this signal before using it for reanalysis purposes. The wind vane position indicates the angle of the flow to the rotor axis. It directly provides a value for the yaw error. The turbine controller uses this signal to control the yaw activity.
Within the Pre-Process (Fig.1) of the monitoring model we estimate the north marking offset for one turbine by checking the location of the maximum wake deficit with respect to the true north. Then we compare the average wind direction between corrected turbines and neighbouring turbines to estimate the remaining offset for all turbines. After applying this offset correction, the wind direction from all wind vanes are averaged in the complex plane to account for the wind direction discontinuity at the beginning/end of the value range, after removing outliers outside ±1.5 IQR (interquartile range)."

We are using the wake "centre check" only at one turbine because of the observed "wake drift" (We will give more explanation to this term three comments later) /***

P4L1: Is that one reference turbine for the whole farm, or one particular one for each of the other turbines? If it is one for the farm, how is it defined?

/ we take one turbine (turbine under observation) and use every single turbine in the farm as reference. (One after each other) Then we take the next turbine to observe. In this way, we obtain n(n-1) results. In this way we increase the confidence in underperformance detection cause a real underperforming turbine will be highlighted multiple times. /

P7L23: So the Type A uncertainties do not multiply in a multipe wake situation?

***/ It certainly makes a difference in the Type A uncertainties in which wake situation you are and this is reflected by the prediction accuracy of this wake itself. We use the standard deviation of N differences between the modelled power and the measured power and divide it with the square root of N.

We have changed the wording to be more precise:
"For the predicted power P_{π}, we are using a combined uncertainty with statistical type A uncertainties, being the experimental standard deviation of the mean from the difference between wake model predictions and measurements and type B uncertainties which conclude from the instrument devices to estimate wind speed and wind direction. "/***

P10L15-22: This is quite interesting. Has this behaviour been observed anywhere else? Another explanation could be that the overall wind flow is skewed at the Ormonde location, which judging by the map is not impossible, seeing that the wind farm is wedged between land and a larger offshore wind farm. Or do I understand this wrong, and it is an effect from Fuga which is described here? Did you switch on the meandering mechanism in Fuga?

***/ The effect we are describing here is not modelled in Fuga. During our wake model results validation, we have also looked into the meandering option, but we obtained better results with the Gaussian averaging method. It might also be possible, that the neighbouring wind farms have an effect and play a role on the observed behaviour. But we can also provide some publications below which have observed and tried to explain a similar wake behaviour.

These studies have the general aim to investigate active wake control but they also provide examples for 0°yaw error. Fleming (2013) shows in his baseline simulation (no yaw error) a small wake shift to the right when looking downwind. In the LES study of Vollmer et al. (2016) it can be observed, that the wake deflection increases from neutral (Vollmer et al. 2016, Fig. 5) to stable conditions (Vollmer et al. 2016, Fig. 9). These Figures provide simulated results also for a turbine with 0° yaw angle. In both cases the maximum wake deficit is found to be on the right side of the centre line (looking downstream).
Gebraad (2014, p86) gives an explanation for the observations from the simulations by Fleming (2013). The flow reacting on the rotation of the rotor causes the wake to rotate counter clockwise (looking downstream). Higher wind speeds from the upper layer are transported downwards (on the left side) and lower wind speeds from the lower layer are pushed upward on the right side of the wake. As a result the velocity deficit at the right part of the wake increases, so the wake deflects to the right.
Marathe et al. (2015) could show in their field measurement campaign with dual-doppler radar, that in the near wake region, the wake is drifting to the right, as expected by the theory. But in the far wake they registered a contradicting movement. The authors state the hypothesis that this phenomenon may be caused by atmospheric streaks. An offshore field experiment by Beck et al. (2015) provides further evidence that wakes are moving out of the centre line.

References:

Beck, H., Trujillo, J. J., Wolken-möhlmann, G., Gottschall, J., Schmidt, J., Peña, A., Gomes, V., Lange, B., Hasager, C. and Kühn, M.: Comparison of simulations of the far wake of alpha ventus against ship-based LiDAR measurements, in RAVE Conference., 2015.

Fleming, P. A., Gebraad, P. M. O., Lee, S., van Wingerden, J. W., Johnson, K., Churchfield, M., Michalakes, J., Spalart, P. and Moriarty, P.: Evaluating techniques for redirecting turbine wakes using SOWFA, in ICOWES2013 Conference., 2013.

Gebraad, P. M. O.: Data-Driven Wind Plant Control, 2014.

Marathe, N., Swift, A., Hirth, B., Walker, R. and Schroeder, J.: Characterizing power performance and wake of a wind turbine under yaw and blade pitch, , doi:10.1002/we, 2015.

Vollmer, L., Steinfeld, G., Heinemann, D. and Kühn, M.: Estimating the wake deflection downstream of a wind turbine in different atmospheric stabilities: An LES study, Wind Energy Sci. Discuss., (March), 1–23, doi:10.5194/wes-2016-4, 2016.

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Figure 5: A map of the location would be good here (see above).

***/ New Figure with orientation and scales provided

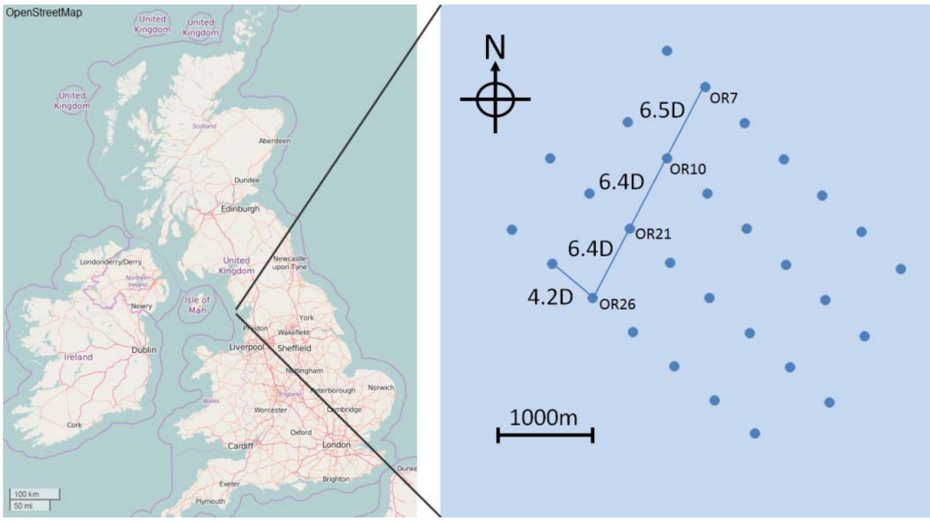

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Figure 7: There seems to be a shift in wind direction between the SCADA system and the calculations - any idea where that is coming from?

***/ The wake model results used in this plot are directly taken from the Fuga Output. No wake model tuning/corrections as proposed in the pre-process step of the monitoring method (Fig. 1) has been applied. The corrected model has an 2.5° offset for all single wake case, 3.5° offset for the double wake cases and a 4.5° offset for the triple wake case for wind directions 207° ±15°. In Fig.7 the offset of the wind direction at 207° (the four demonstration turbines in a column) is approximately 2.2°. At the wind directions 132° and 312° , with the largest wake effects along the four rows of 7 to 8 turbines, the offset is approximately 5°. This fact supports the theory, that with every additional wake added to the flow, the overall "wake drift" increases. We will add this information into the caption of the plot.

"Figure 7: Wind farm averaged wind speed with wake effects normalised with wind farm averaged wind speed without wake effects plotted versus averaged wind farm wind direction. Black dots show the measurements from SCADA and the green solid line represents the results from Fuga with a Gauss averaging for standard deviation of 4°. An offset of the wind direction between model and SCADA can be observed. At 207° the offset is approximately 2.2° and it increases up to 5° for wind directions (132° and 312°) with the largest wake effects. An explanation and correction for this "wake drift" is proposed in section 2.2." /***

Table 2: Is the source of that the IEC Annex D uncertainty estimation, or own values?

/The values are based on the example given in IEC 61400-12-1 (2005) Annex E. We will add this information in the caption of Table 2./

Textual issues:

P1L9: The presented method or the present method?

/We will change the sentence to: " The method, presented in this paper, estimates…/

P1L18: "The common [...] definition defines that the system is ready to operate" might not be exactly what is in the availability standard. Please rephrase.

***/Thanks for the advice, here is our new sentence:
“In wind industry, the common standard IEC TS 61400-26-1 (2011) defines different categories of turbine conditions and describes the calculation of availability”/***

P1L23: What’s the difference between IEC 61400 and IEC TS 61400?

***/ TS stands for “Technical Specification”.
Both Documents (IEC TS 61400-26-1 and IEC TS 61400-26-2) are technical specifications. An “International Standard” has a higher degree than a “technical specification”. Work is ongoing to bring these TS to the level of an “International Standard”
We have revised the references accordingly./***

P2L25: To lower uncertainties, ... ??

***/We have rephrase the whole paragraph:
“Mittelmeier et al. (2013) presented a new method where not the absolute values between model and measurement are compared, but the relations between an observed turbine and all other turbines in the farm. In this way, the uncertainty of the measurement chain could be reduced. The model is also based on pre-calculated power matrices which we call from now on “lookup-tables” (LUTs). Different wake models or even combinations of wake model results can be used to provide results for these LUTs. But the model relies on measurements from a met mast which is often not available. Furthermore, with increasing size of wind farms, the assumptions of one measurement position being representative for the whole offshore wind farm is not valid (Dörenkämper, 2015). Further investigations are necessary to obtain a reliable and automated method to detect underperformance at individual turbines in a wind farm.”/***

P6L15: You might want to explain what you mean by "wake drift".

***/Sure. We understand the need to provide more explanation and references on this topic. The last paragraph of section 2.2 has been revised as follow:
“The third tuning parameter is applying a simple offset on the wind direction of the LUTs to account for a drift of the wake. We call this phenomena from here on “wake drift”. Fleming (2013) has studied the effects of active wake control and in his baseline simulation (no yaw error) a small wake drift to the right can be observed when looking downwind. In the LES study of Vollmer et al. (2016) the wake drift increases from neutral to stable conditions also for 0° yaw angle. Gebraad (2014, p86) gives an explanation for the observations from the simulations by Fleming (2013). The flow reacting on the rotation of the rotor causes the wake to rotate counter clockwise (looking downstream). Higher wind speeds from the upper layer are transported downwards (on the left side) and lower wind speeds from the lower layer are pushed upward on the right side of the wake. As a result the velocity deficit at the right part of the wake increases, so the wake deflects to the right.
Marathe et al. (2015) could show in their field measurement campaign with a dual-doppler radar the wake drifting to the right, as expected by the theory. But in the far wake they registered a movement to the left. The authors state the hypothesis that this contradicting phenomenon may be caused by atmospheric streaks. In an offshore field experiment by Beck et al. (2015) further evidence is provided that wakes are moving out of the centre line. This wake drift is currently not modelled in Fuga and therefore applied in a further step of the pre-process (Fig. 1).“

References for this paragraph:
Beck, H., Trujillo, J. J., Wolken-möhlmann, G., Gottschall, J., Schmidt, J., Peña, A., Gomes, V., Lange, B., Hasager, C. and Kühn, M.: Comparison of simulations of the far wake of alpha ventus against ship-based LiDAR measurements, in RAVE Conference., 2015.

Fleming, P. A., Gebraad, P. M. O., Lee, S., van Wingerden, J. W., Johnson, K., Churchfield, M., Michalakes, J., Spalart, P. and Moriarty, P.: Evaluating techniques for redirecting turbine wakes using SOWFA, in ICOWES2013 Conference., 2013.

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/***

P9L9/L15: "of demonstration wind farm" could be deleted without detriment.

/ Thanks for pointing this out. We will delete that part. /

P9L13: This value is used_for the uncertainty...

/ Thanks. It is corrected./

P10L5: I would drop the brackets around the version number of Fuga.

/ Agreed./

P10L14: I don't think I've seen zeta_naught introduced before?

***/ This value is directly used as an input parameter in Fuga. The theory behind it is described in Ott and Nielsen (2014). We will add "Secondly, the **Fuga** parameter to model the effect of atmospheric stability ζ_0…"

References:

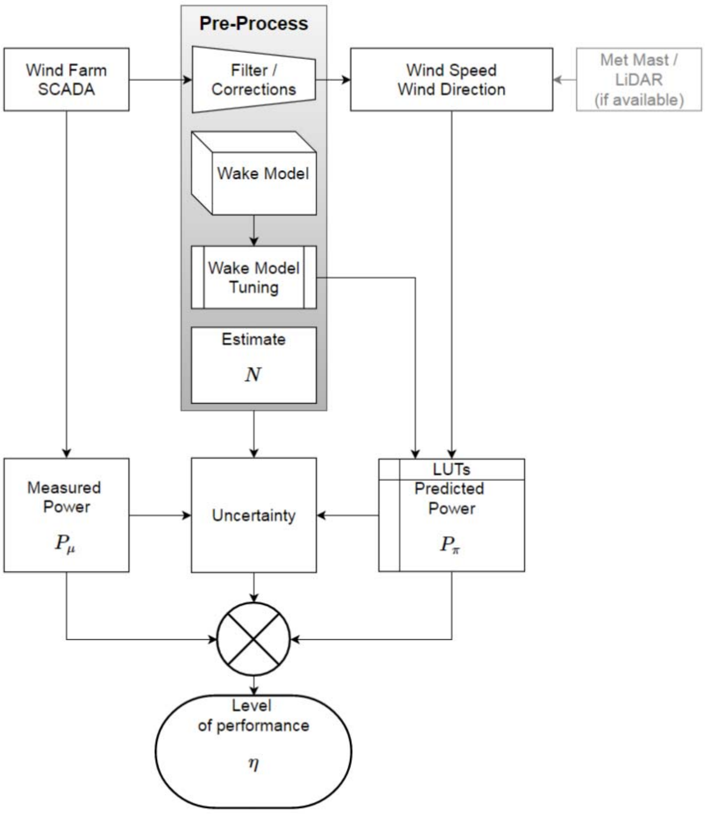
Ott, S. and Nielsen, M.: Developments of the offshore wind turbine wake model Fuga, Report E-0046, DTU Wind Energy., 2014. /***

P10L15: While wind and nautical terms can easily be construed to have a connection, not everyone is familiar with "starboard".

***/ Sorry, being offshore tempt us to use nautical terms.
"Starboard" replaced by "right"
"Port" replaced by "left" /***

Figure 1 center: Should that really be called Uncertainty, or rather something like Deviation?

/ We have updated Fig. 1. (see below). We are calculating an uncertainty value for each 10-min SCADA measurement. And the input for this calculation comes from the SCADA power, the N and the LUTs. This uncertainty is a variable threshold for the model. Only if the deviation between the ratio π and the ratio μ is higher than the uncertainty, then underperformance is highlighted. For this reason we will keep the wording "uncertainty" in Fig.1. /



Pre-Process
Wind Farm SCADA
Filter / Corrections
Wind Speed Wind Direction
Met Mast / LiDAR (if available)
Wake Model
Wake Model Tuning
Estimate
N
Measured Power
P_μ
Uncertainty
LUTs
Predicted Power
P_π
Level of performance
η

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