Authors reply to comments from referee D.P. Held

Dear D. P. Held, thank you very much for your thorough review. I will go into the comments in detail below.

RC1. *Section 2.2 needs information on how the wind direction was measured.*

AC. In section 2.2 a paragraph is added explaining the instrumentation used to measure the inflow:

> The analyses in this article were carried out on the basis of measurements at a met mast. In (Bromm M, et al. Field investigation on the influence of yaw misalignment on the propagation of wind turbine wakes. Wind Energy. 2018;1-18.) measurements from the same device were used. As described there, the height of the met mast is 91.5 m. The wind direction was measured by a wind vane of type 4.3150.00.212 (manufactured by Thies GmbH) at a height of 89.4 m. Additionally, the met mas was equipped with three cup anemometers of type 4.3351.00.000 from the same company, installed at heights of 34.6 m, 89.3 m and 91.5 m. The cup anemometer at 91.5 m was used for filtering the available data as mentioned in Section 2.4 in the manuscript.

RC2. *Regarding the bias of wind direction measurement in Section 3.1 alternative measurement devices need to be discussed.*

AC. I completely agree that the risk for a considerable bias should be minimized by additional measurement devices. A paragraph is added to the discussion that addresses this point:

> The consideration of the aerodynamic interactions in wind farm control has some critical requirements that must be met as best as possible. This includes the absolute orientation of the wind turbine and a bias in the measurements. While the absolute orientation of the wind turbine is not important for turbine control, it plays a decisive role in wind farm control, as it is required to derive the aerodynamic interactions of the turbines. A bias in wind direction measurement has negative implications for both wind turbine and wind farm control. For this reason, the risk of a significant bias needs to be minimized. Therefore, great care must be taken during installation and alignment of the wind vane. If possible, additional measuring instruments for determining the wind direction should be considered, such as nacelle-mounted lidar or the consideration of blade loads for the determination of the inflow as described in (C.L. Bottasso, C.E.D. Riboldi, Estimation of wind misalignment and vertical shear from blade loads, Renew. Energy. 62 (2014) 293–302).

RC3. *Regarding the controller proposed in Section 3 (Fig.10), is the yaw angle changed every iteration? If so, this is not feasible for a utility-scale turbine as was also mentioned in the manuscript earlier.*

AC. In Section 3 (Fig.10) the concept of a yaw-controller is introduced. In this concept the yaw-angle of the turbine is adjusted in every iteration, but one iteration takes exactly 5 minutes. Experience from turbine data shows that this is a realistic yaw adjustment rate. This simplified concept of a yaw-controller was used here to be able to validate a large set of data in a manageable fashion.

I fully agree with the referee that constantly adjusting the yaw angle of a utility scale turbine is not feasible. Therefore, the robust yaw control should be carefully integrated into the existing yaw control of the turbine. The reason that only a simplified concept was presented in this research is, that the details of the yaw control of a wind turbine are strongly adapted to the type of wind turbine and are commonly kept confidential.

Minor comments at specific places in the manuscript:

RC4. *p.2 ll.20: "and" missing before 3)*

AC. Thanks for the comment. It will be corrected.

RC5. *p.2 ll.30 "A more elaborate..." is not a complete sentence*

AC. The word "For" at the beginning of the sentence is missing and the comma is wrong.

RC6. *p.4 ll.2: hysteresis is not the same as dead-band. Please correct. (Also p.14 ll.12)*

AC. The wind energy handbook (Burton 2011) broadly describes the yaw controller of a utility scale wind turbine and refers to it as a dead-band controller. The controller uses a threshold before reacting to the deviation of yaw angle and measured wind direction. In literature I did not find that the word hysteresis is clearly defined. In some uses of the term a hysteresis could include a dead-band (e.g. bang-bang control or Schmitt-Trigger) and in other uses dead-band and hysteresis are clearly distinct, in that at a hysteresis there is always movement and no dead-zone. To be clear in the article I will rephrase the respective paragraphs as follows:

> p.3 ll.19f: The turbulent changes in the wind direction are in contrast to the slowly reacting yaw mechanism of utility-scale wind turbines. The deviation of the wind direction and the yaw angle of the turbine is usually averaged over several minutes and a threshold for the deviation is used to keep the turbine from constantly yawing (Burton, 2011). This has the effect that the turbine is in standstill mode most of the time (Kim and Dalhoff, 2014).

> p.4 ll.2: "Although the details of the yaw control depends on the manufacturer and is commonly kept confidential, in our experience....."

> p.14.ll: "...to simulate additional inaccuracies like for example measurement uncertainties, yaw deviations through the thresholds of the yaw control and alignment errors."

RC7. *p.9 ll.9: Shouldn't* $\pm 2\sigma$ *cover* 95 % *of the normal distribution?*

AC. 95 % is the commonly used rounded amount, which more accurately the $\pm 1.96\sigma$ region. The more precise $\pm 2\sigma$ region covers 95.45 % of the standard normal distribution.

RC8. *p.9 ll.31 "In the blue graph* ($\sigma = 4°$)*, the yaw misalignment is considerably reduced compared to the first case". This is only true for wakes onto T11 and T13. For the closest turbines there is no reduction in yaw misalignment compared to the first case. I suggest rephrasing the sentence.*

AC. That is correct, the reduction in yaw misalignment for the closest turbines is not well noticeable in the graph. I will rephrase the sentence and address this point

> In the blue graph ($\sigma = 4°$), the yaw misalignment is reduced compared to the first case. This applies in particular for wind directions where the downstream wind turbine is further away (e.g. at around 159° T11 and 201° T13)

RC9. *p.11 ll.3: Why was* 172° *chosen? Intuitively, I would think that 90deg or 270 deg gives the largest wake effects.*

AC. It is correct, that the strongest wake effects are at wind directions of 90° and 270°, followed by the wakes at 0° and 180°. There are several reasons why we chose 172° for the exemplary case: First, at 90° and 270° the distance is 3D, although this turbine spacing is sometimes chosen for utility scale turbines, this is only the case for wind directions that occur very rarely. Therefore, this constellation is not very representative. Second, the example at about 180° was used to explain the results of the various robustness parameters and also serves as an example of the passive wake deflection. Third, the particular value of 172° was selected because the results of the optimization for the different robustness parameters show a clear tendency to which direction the wake is deflected and they differ from each other and the baseline.

RC10. *Fig. 9: What if you calculate* $\int_0^{2\pi} \rho(\varphi) P_{\mathit{diff}} d\varphi$ *for the robustness factors? Is this measure positive of negative, i.e. do you get an overall improved performance of not?.*

AC. This is a very good question, which gives the opportunity to explain the results of the optimization in a bit more detail. The optimization is designed to give the best result for a given wind direction distribution, so the optimization with $\sigma = 0°$ should give the highest result for the dirac-delta distribution at 172°. For this simple case we can just look at Fig.9 at the graph at 172°. The black graph shows the highest value of 0.09987 of normalized power, which is slightly higher than the blue graph ($\sigma = 4°$) with 0.09711. The red graph ($\sigma = 8°$) achieves 0.05479. Now, if we weight the depicted graph with a normal distribution with the expected value at 172° and a standard deviation of 4° the results are: black ($\sigma = 0°$) 0.04840, blue ($\sigma = 4°$) 0.05150 and red ($\sigma = 8°$) 0.03419. So for this case the blue graph achieves the highest result, as it was designed for. Finally if we weight the graph with a normal distribution with an expected value of 172° and a standard deviation of 8° the results are: black ($\sigma = 0°$) -0.01841, blue ($\sigma = 4°$) -0.00789 and red ($\sigma = 8°e$) 0.00646. As expected the robust optimization with $\sigma = 8°$ achieves the best result since it was optimized for exactly that case. Furthermore, the results of a certain robustness parameter are always positive for its respective distribution, since the optimization is searching yaw settings that improve the power output compared to the baseline case.

RC11. *p.19 ll.4 missing bracket.*

AC. Thank you for noticing.

RC12. *p.19 ll.13: In the manuscript perfect accuracy (no bias) and imperfect precision (Gaussian error that is introduced in section 3.3) is assumed. Please rephrase*

AC. Thank you for the remark, that in the common technical understanding the word accuracy is synonymous with the word trueness. I will rephrase the sentence as follows

> The method takes dynamic wind direction changes and imprecision in the determination of the wind direction into account within a statistical framework in the optimization.

RC13. *p.19 ll.14 control instead of contgrol.*

AC. Of course this was on purpose ;).