

Wake Measurements at alpha ventus - Dependency on Stability and Turbulence Intensity

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Abstract. Wind and power deficit in the wake are assessed for the offshore wind farm Alpha Ventus. Operational data are evaluated for the power deficit in the wake of a single wind turbine and in a row of wind turbines. The wake of a single wind turbine is described by the maximum power deficit and expansion width of the wake. The impact of atmospheric stability in respect to vertical wind shear and turbulence intensity is assessed showing that wake effects are more pronounced under stable conditions.

1. Introduction

Wake measurements are necessary for the verification of wake models. For an energy yield assessment the uncertainty of the wake model has a contribution to the uncertainty of a few percent. This is important especially offshore where due of the size of the wind farms, the farm efficiency is low compared to onshore sites and often takes values of 85% only or even below. So, uncertainties of wake models can quickly lead to a wrong prediction of the energy yield of a few percent. This makes the validation and improvement of wake models necessary. But not only for energy yield assessments precise wake models are needed but also for other applications like wind farm monitoring, guarantee agreements or energy forecasting [1].

Up to now wake models are mostly validated on Danish wind farms that were built at the beginning of the last decade, e.g. there are thorough wake assessments from the Danish wind farms Horns Rev and Nysted (e.g. [2]-[5] and more). In addition Alpha Ventus can serve for the validation of wake models, as in the mean time the rotor diameter of offshore wind turbines has grown from 80m to about 120m. Alpha Ventus is situated far away from the coast (~50km) and therefore has a pronounced maritime meteorology with high wind speed conditions and low turbulence intensity. In Alpha Ventus the power deficit can be measured up to the 3rd wind turbine in a row of wind turbines of the same type. As the power reduction between wind turbines for the first wind turbines in a row is highest, the results are valuable and can be of benefit for larger wind farms as well.

This evaluation is the continuation of an assessment of the wake effects at FINO1 [6] and an assessment of operational data [1] done earlier. The evaluation of the wake effects was done with special emphasis on the influence of thermal stability on the wake effects.

For reasons of confidentiality no evaluation includes both wind turbine types, the single wake assessments are done with data of Repower 5M wind turbines and the power-loss in a row is assessed from data of AREVA M5000 wind turbines.

2. Data Base

Alpha ventus consists of 12 wind turbines in a 3x4 configuration (**Figure 1**). The wind turbines are 5 MW class wind turbines of two types. Row 1 and 2 (AV1-AV6) consist of wind turbines of the type



Repower 5M with a rotor diameter of 126m and a hub height of 92m LAT¹. Row 3 and 4 (AV7-AV12) consist of AREVA M5000 wind turbines with a rotor diameter of 116m and a hub height of 91.5m LAT. West of Alpha Ventus at a distance of 405m to the nearest wind turbine the offshore platform FINO1 is located. A LIDAR was temporarily placed at the substation south-east of Alpha Ventus.

The data were evaluated as 10-minute average values. Data of the periods 2011-01-01 to 2012-06-30 (operational data) and 2010-07-01 – 2012-06-30 (FINO1 wind data) have been evaluated.

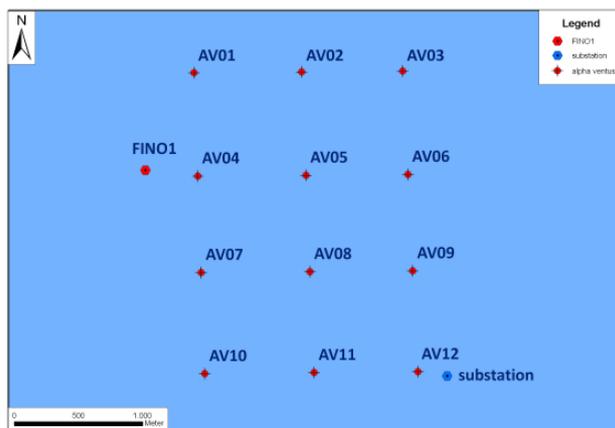


Figure 1. Layout of the offshore wind farm Alpha Ventus with the positions of the offshore met mast FINO1 and the substation which was basis of a LIDAR device (Coordinate system of the map: GK3, Rauenberg, Bessel, coordinates of FINO1: 6°35'15.5''E; 54°0'53.2''N).

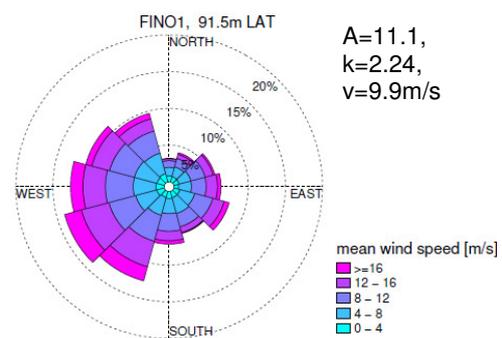


Figure 2. Wind distribution during 2010-07-01 – 2012-06-30.

Wind speed and wind direction data measured at the offshore platform FINO1 at a height of 91.5m LAT are used in the following. The wind measurements at FINO1 are disturbed by the mast structure itself and additionally by the wind farm Alpha Ventus. For both effects corrections have been performed. The wind speed data have been corrected for the mast effects based on the “uniform ambient flow mast correction scheme” (UAM-scheme) [8][9]. The wind direction measurements at FINO1 are also influenced by the mast structure. Based on comparisons with a temporarily installed LIDAR at the FINO1 platform [10] the wind direction measurements at 91.5m LAT have been corrected. Then the north mark has been aligned based on wake measurements in the wind farm of Alpha Ventus.

Since 2009-08-12 the first wind turbines of Alpha Ventus are in operation. For easterly wind directions the wind measurements at FINO1 are disturbed by the wind farm. To continue free flow measurements from easterly directions a LIDAR-device was installed in April 2011 on the substation of Alpha Ventus which is located about 233 m south-east of wind turbine AV12 [11]. For the period before the LIDAR installation and to fill data gaps the undisturbed FINO1 wind data from easterly directions were re-established with nacelle anemometer data of AV3 and AV12 after a calibration with LIDAR or FINO1 data. Minor data gaps were filled by FINO1 data corrected according to CFD simulations [6]. **Figure 2** shows the wind distribution of FINO1, 91.5m LAT, during 2010-07-01 – 2012-06-30 after application of all corrections.

¹ LAT = lowest astronomical tide

The data have been classified to different thermal stabilities with a simplified approach using the vertical wind shear. The wind shear is defined according to IEC standard 61400-1 [12] by $v(z) = v(z_r) \cdot (z/z_r)^\alpha$, where $v(z)$ and $v(z_r)$ denote the wind speed at two height levels and α is the wind shear exponent. Most corrected data of FINO1 from the heights 41.5, 51.5, 61.5, 71.5, 81.5 and 91.5m LAT are considered.

The stability limits are chosen based on the data of FINO1. The chosen limits of the classes are shown below in **Table 1**. The table shows the share of each stability class on the total number. The focus was on the identification of data sets with stable or unstable stratification. “Neutral” rather denotes the remaining data sets. **Figure 3 left** shows the wind shear exponent α versus the wind speed for the 2-year period 2010-07-01 – 2012-06-30 for the wind direction sector 255° - 280° ². It shows as well the chosen limits for the stability classification.

Table 1. Used stability classification in respect to wind shear for FINO1 during the 2-year period 7/2010-6/2012.

	Wind shear exponent α	Share of data [%]
unstable	$\alpha < 0.07$	53%
neutral	$0.07 < \alpha < 0.15$	20%
stable	$\alpha > 0.15$	27%

Additionally the wake effects have been assessed with respect to the turbulence intensity. The turbulence intensity has been assessed as $TI = \sigma_v / \bar{v}$ from 10min mean values \bar{v} and standard deviation σ_v of the wind speed. **Figure 3 right** shows the turbulence intensity versus the wind speed for the wind direction sector 255° - 280° . **Figure 4** shows the scatter plots of turbulence intensity and wind shear and visualizes the close connection between both parameters. Stable conditions are characterized by high wind shear and low turbulence intensity and unstable conditions have low wind shear and high turbulence. Later in this paper the wake effects have been assessed for different turbulence intensity classes; the chosen limits are shown in **Figure 4** as green lines.

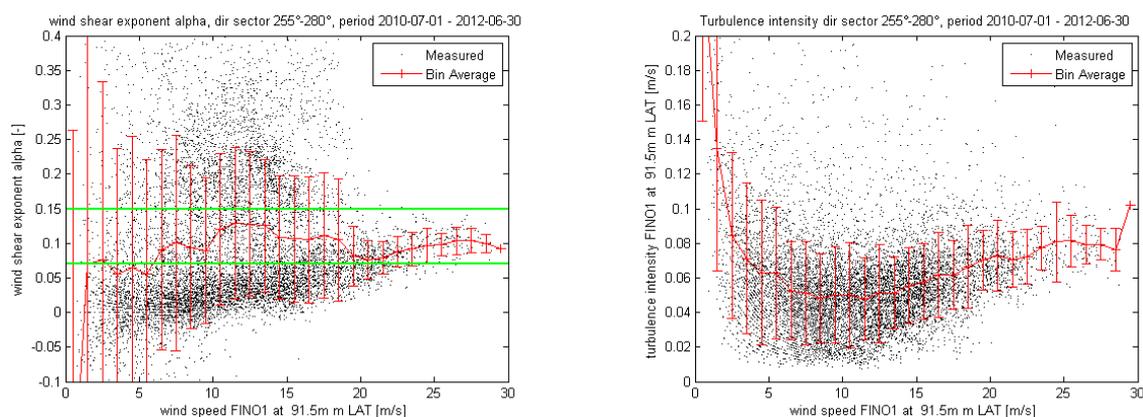


Figure 3. Wind shear exponent α at FINO1 (left) and Turbulence intensity (right) at FINO1, 91.5m LAT for the period 2010-07-01 - 2012-06-30 and wind direction sector 255° - 280° . The stability limits in respect to wind shear are marked as green lines.

² The wind direction sector $270^\circ \pm 15^\circ = 255^\circ$ - 285° is evaluated in detail in the following. Here the sector is restricted to 255° - 280° , to omit the FINO1 data in the direct mast shadow.

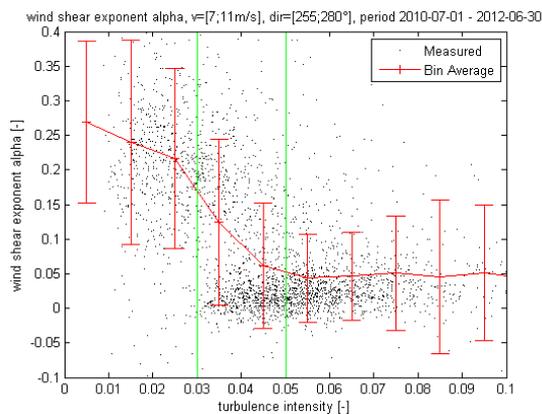


Figure 4. Wind shear exponent α versus turbulence intensity at FINO1, 91.5m LAT for the wind speed bin [7;11m/s] and the wind direction sector 255°-280°. The stability limits in respect to TI are marked as green lines.

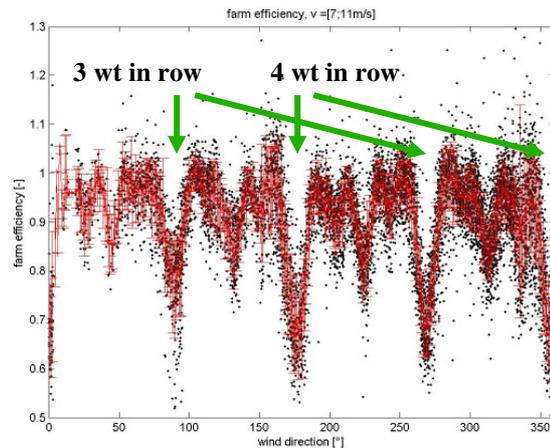


Figure 5. Farm efficiency of Alpha Ventus at free wind speeds in the range of 7-11m/s.

3. Farm efficiency

A data base consisting only of measurements during which all wind turbines of Alpha Ventus were in operation was generated. It covers the period 2011-01-01 to 2012-06-30 and contains 27880 data sets. As status signal the generator speed has been used.

The farm efficiency $P_{\text{farm}}/P_{\text{free}}$ as a measure of the losses in a wind farm due to wakes has been assessed for each 10-min data set. A crucial point is to estimate the free power output of the wind farm (without wake losses) P_{free} . For this, the power output of the upwind wind turbines was averaged for each wind turbine type as an estimate for the free power output. For example for wind from the west the mean power output of AV1 and AV4 was used as free power of the Repower 5M wind turbines and the mean power of AV7 and AV10 served as free power of the type AREVA M5000. As Alpha Ventus consists of wind turbines of two types this procedure is not possible for all wind directions. There are cases where no wind turbine of one type is in free flow (at wind from the north or south). For these beforehand a mean power curve of the upwind wind turbines for each of the two wt types has been generated. This measured power curve then was combined with the corrected wind speed data of FINO1 to get an estimate of the free power.

As Alpha Ventus consists of 12 wt only, the average farm efficiency is quite high. A farm efficiency of 95.2% has been assessed for 2011. Plotting the farm efficiency over the wind direction for wind speeds in partial load 7-11m/s shows the distinct wind farm axes (**Figure 5**). At wind speeds above 15m/s all wt run with nominal power.

4. Single Wake

The power deficit of a wind turbine which is in the wake of a second one has been assessed as $\eta=(1-P_{\text{wake}}/P_{\text{free}})$ with P_{wake} as the power to wind turbine that experiences the wake and P_{free} as the average power of all wind turbines of the same type in free flow for each 10-minutes data set.

Figure 6 shows the power deficit of AV5 in the wake of AV4 for wind speeds in partial load, 7-11m/s averaged in 2° wind direction bins. The data were fitted similar to [2] with a function of the wind direction Θ : $f(\Theta)=(a_1+a_2\Theta+a_3\Theta^2)*\exp(-a_4\Theta^2)$. The wake width is defined as the 95% confidence level of the fit. For this distance (=6.7D) and this wind speed bin [7;11m/s] the maximum deficit was 0.49 and the wake width was 22°. **Figure 7 left** shows the fitted function of power deficit for different thermal stratifications according to the classification with the wind shear α . Under stable conditions the wake is broader with a wake width of 27° but has a smaller maximum of 0.44. Under unstable

conditions the wake is narrower (width 19°), but the maximum power deficit in the wake centre is larger with 0.55. The comparison of data sets with different turbulence intensity gave consistent results (**Figure 7 right**) connected to the high agreement of the two data sets (**Figure 4**).

The wind speed deficit in the wake is larger under stable conditions compared to unstable conditions as was measured at FINO1 [6]. Corresponding to higher wind speed deficit larger power deficits would be expected under stable conditions. At Alpha Ventus this is not the case in about $7D$, where the relationship reverses in the wake centre³. For the offshore wind farm Horns Rev, which has approximately the same wt spacing of $7D$, but a different turbine size and a different offshore meteorology, a higher power deficit for stable stratification was documented for the whole wake region [2]. For this subject further studies are necessary. Additionally the maximum power deficit was compared. In the respective wind speed interval 7-11m/s it was at Horns Rev lower (36-41%) than at Alpha Ventus (49%) [3].

The difference between power deficit in unstable and stable conditions is shown in **Figure 8** at the bottom of the figure; the difference varies strongly with the wind direction but on average the difference between stable and unstable in the dir sector $[240;300^\circ]$ is 4%. Thus, for this spacing and for wind speeds in the range of 7-11m/s (partial load) under stable conditions on average a 4% higher power deficit has been assessed compared to unstable conditions. Under stable conditions not only the power deficit in the wake is higher, but as well the power curve itself is lower compared to unstable conditions. Bégué [7] found a difference of 4% in AEP (annual energy production) when considering only wind speeds in the partial load. In order to evaluate this issue on a different data base the power curve of the Repower 5M was compared in respect to the stability. **Figure 9** shows the normalized power curves of all upwind wind turbines for the Repower 5M for different stabilities. For wind speeds in the partial load the difference in power is on average about 4%.

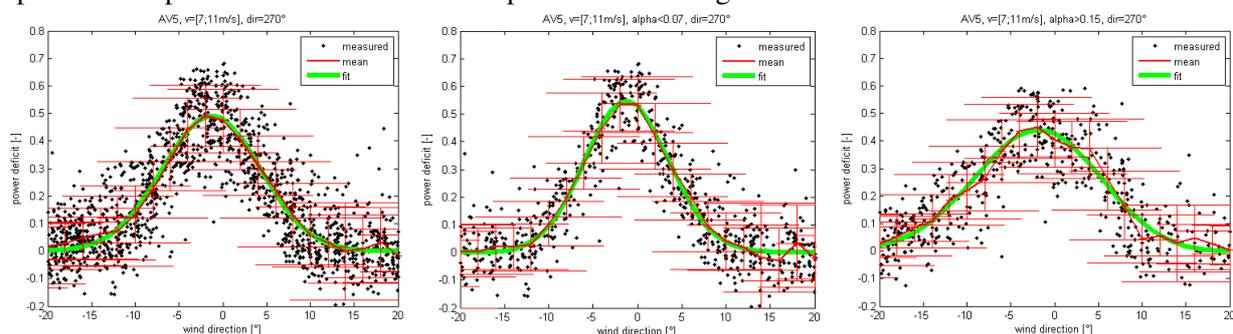


Figure 6. Power deficit of the AV5 in the wake of AV4 in $6.7D$ distance for $v=[7,11\text{ms}]$ for different stability conditions in respect to wind shear: all data sets (left), unstable with $\alpha < 0.07$ (centre) and stable stratification with $\alpha > 0.15$ (right).

³ A later study showed that this effect was observed only at wind from West in the wake of AV4. When AV5 was in the wake of AV2 or AV6 (wind from North or East) a higher power deficit for stable stratification was observed for the whole wake region [13].

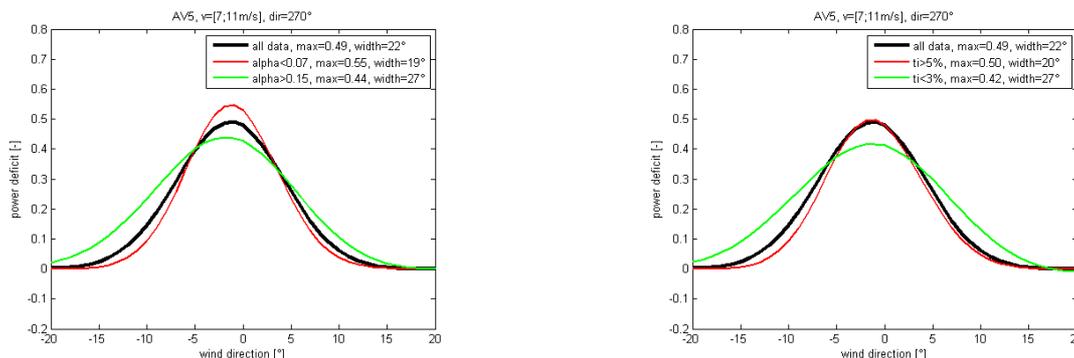


Figure 7. Power deficit of the AV5 for $v=[7,11\text{ms}]$ for different stability conditions in respect to wind shear (left) and for different turbulence intensity classes (right).

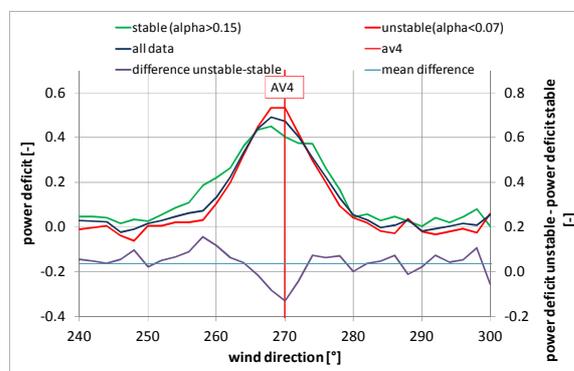


Figure 8. Power deficit of AV5 for $v=[7,11\text{ms}]$ with enlarged direction domain $[240^\circ;300^\circ]$. The direction from AV5 to the wind turbine AV4 is given as red line.

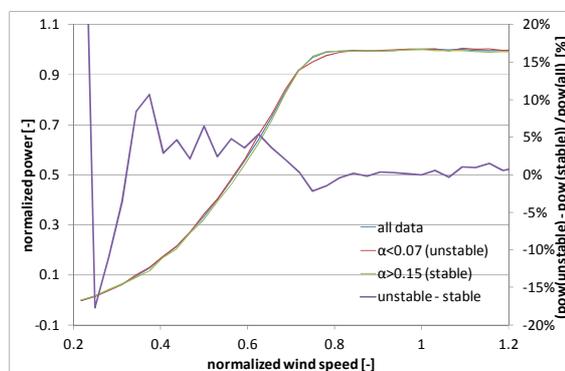


Figure 9. Normalized mean power curve of upwind wind turbines of the wt type Repower 5M, dir $210^\circ\text{-}280^\circ; 0^\circ\text{-}30^\circ$, 01/2011-06/2012.

5. Wake deficit along a row

The power reduction along the row3 in Alpha Ventus was assessed and compared with published results for Horns Rev, which has a similar spacing of 7D [2]. In **Figure 10** the power reduction in row 3 consisting of the three 116m diameter (D) wind turbines AV7, AV8 and AV9 is depicted. The spacing between the wind turbines is 7.3D. The production data were evaluated for the wind direction intervals of $\pm 15^\circ$, $\pm 7.5^\circ$ and $\pm 2.5^\circ$ bin width and for the wind speed 8, 9 and 10m/s $\pm 0.5\text{m/s}$.

The power deficit for the wind direction sector of $\pm 15^\circ$ is about 21-24% at the second wind turbine and about 1% more at the third wind turbine in a row. These results are in broad agreement with the results documented for Horns Rev. For a smaller wind direction sector of $\pm 2.5^\circ$ a power deficit at the second wind turbine of about 43-50% has been observed, which is therefore higher than the respective power deficit observed in Horns Rev of about 35% [3]. The wind farm Horns Rev consists of wind turbines with a distinct smaller rotor diameter of 80 m only. Next to different size and type of wind turbine this might be connected with a different offshore meteorology with higher turbulence intensity at Horns Rev.

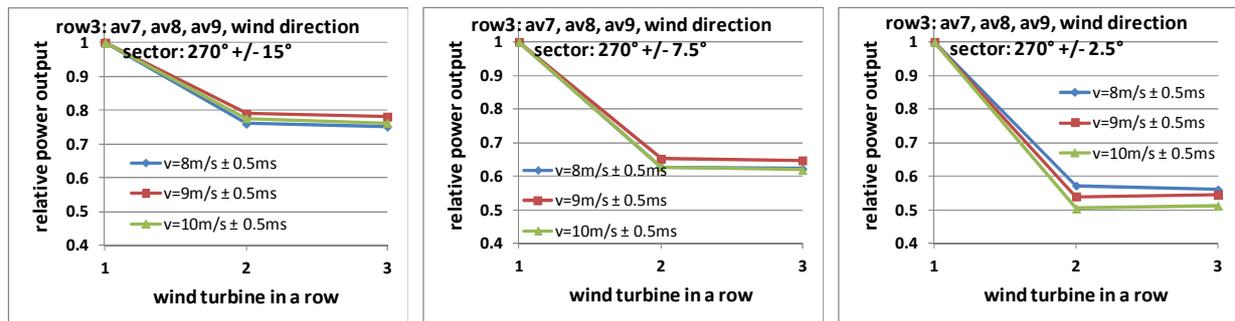


Figure 10. Power deficit along row3 consisting of AV7, AV8 and AV9 for different wind direction intervals of $\pm 15^\circ$, $\pm 7.5^\circ$ and $\pm 2.5^\circ$ bin width and different wind speed intervals.

6. Wind speed reduction at FINO1

At the position of FINO1 the wind speed deficit caused by the wakes of alpha ventus was measured and compared with CFD simulations. The CFD calculations were in overall agreement with the measurements for the nearest wind turbines. It turned out that a formerly observed mismatch of the measured and simulated shape of the wake was caused by the usage of wrong coordinates of FINO1 in the CFD simulations. The CFD calculations were performed with coordinates of FINO1, which were in line with the wind turbines in the second row, AV4-AV6. But in reality FINO1 is located 50 m to the North ($6^\circ 35' 15.5''\text{E}$; $54^\circ 0' 53.2''\text{N}$). **With the correct coordinates of FINO1 the measured shape of the wake of AV4-AV6 is reproduced by the CFD simulations (Figure 11).**

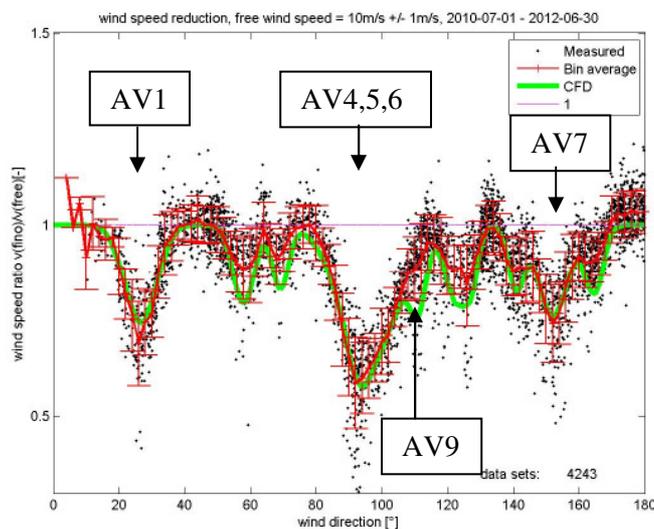


Figure 11. Wind speed deficit at FINO1, only data with all wt in operation.

7. Conclusions

Operational data are evaluated to assess the power reduction in the wake of a single wind turbine. The impact of atmospheric stability and turbulence intensity was assessed showing that wake effects are more pronounced under stable conditions. The single wake was broader under stable stratification. For wind speeds in the range of 7-11 m/s (partial load) under stable conditions the power deficit was about 4% larger compared to unstable conditions. Additionally for this wind speed bin stable stratification led to 4% lower power output of the free wind turbine. As soon as the wind speed is higher than the wind speed of the nominal power the stability does not play a role anymore. Generally, the consideration of atmospheric stability can improve wake modeling and wind farm monitoring.

One aspect of the evaluation was to compare the power reduction in Alpha Ventus with published results of other wind farms to test whether the power deficit can be scaled up when the wind turbines become larger. In comparison to Horns Rev which has approximately the same wind turbine spacing of $7D$, the maximum power deficit in the wake of a single wind turbine as well as the power deficit along a row for small wind direction sectors showed larger values at Alpha Ventus. Next to different size and type of wind turbine this might be connected with a different offshore meteorology with higher turbulence intensity at Horns Rev. Wake models often were validated with data of Horns Rev. The assessment indicates the results cannot be simply used and that a validation with wind farms with a larger rotor diameter are necessary when the wake models shall apply on present-day wind farms.

Acknowledgements

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