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**Friis Pedersen, Troels; Gottschall, Julia; Kristoffersen, Jesper Runge; Dahlberg, Jan-Åke**

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# Yawing and performance of an offshore wind farm

Troels Friis Pedersen, Julia Gottschall, Risø DTU
Jesper Runge Kristoffersen, Jan-Åke Dahlberg, Vattenfall
Contact: trpe@risoe.dtu.dk, +45 2133 0042

**Abstract**

Optimization of yaw misalignment may improve energy output of wind farms. An analysis was made of the potential power loss of the Horns Reef wind farm due to yaw error. The method for the estimate was to measure the yaw error on an identical V80 onshore wind turbine and to extrapolate these findings to all turbines in the wind farm. The yaw errors were measured to be significant, and in average about 10° on the onshore V80 turbine. The flow inclination angle was measured to be significantly influenced by wake rotation from the neighboring wind turbines. The average power loss factor in the wind speed range 3-15m/s was found to be 0,971. Adjusting for a realistic yaw error interval the estimated power loss was 2,7%. When considering the wind distribution at the Horns Reef site and only considering the power below rated wind speed we end up with an estimated power loss of 1,6%, which corresponds to the production from 1,3 wind turbines in the Horns Reef wind farm.

**Objectives**

The objectives of this paper are to estimate the yawing errors and performance losses of the wind turbines in a wind farm. The target wind farm is the offshore Horns Rev wind farm west of Esbjerg, which consists of 80 Vestas V80 2MW wind turbines that have been in operation since 2002.

**Methods**

The method for estimation of yaw errors and performance losses on Horns Rev wind farm are based on measurements and analysis on one onshore V80 wind turbine, configured exactly like the wind turbines at Horns Rev wind farm. The onshore wind turbine is located as turbine no 5 in a small wind farm of 8 wind turbines at Tjæreborg, see Figure 2, all of the same size as the V80 wind turbine. Coordinates of the wind farm together with the met mast 1,5D southwest of the V80 wind turbine are shown in Figure 3, and data for the wind farm are shown in Table 1.

The inflow to the rotor centre is measured with a spinner anemometer [1-4], see Figure 1, on V80 wind turbine no 5. The output of the spinner anemometer is the local wind speed at the spinner nose, the yaw error and the flow inclination angle. The yaw error was calibrated by yawing the wind turbine in and out of the wind ±60°. The wind speed was calibrated relative to the met mast with a stopped rotor. In this way the spinner anemometer measures the actual flow wind speed and direction at the spinner. During operation the rotor induces a wind speed at the spinner, so that the spinner anemometer no longer measures the free wind speed. Figure 4 shows the spinner anemometer wind speed relative to the met mast cup anemometer on the boom in the 247° wind direction from the open sector 212°-252° during operation. It is clearly seen that the spinner anemometer wind speed is reduced in the range 4-12m/s. The induced wind speed in the rotor centre is quantified by the induction factor as shown in Figure 5. The induction factor is seen to have a maximum value of about 12%.

The ratio between the spinner anemometer and the hub height cup anemometer is shown in Figure 6 for all directions for half a year of measurements. In this figure the wakes of the turbines on the mast measurements and on the spinner anemometer measurements are indicated by the colored labels. Two open sectors, where both turbine 5 and the met mast see free flow, are identified: 212°-252° and 320°-35°. The wakes of the closest turbine no 6 on turbine 5 in the direction 201° and on the mast in the direction 173° is clearly seen, as well as the wakes from the other turbines.

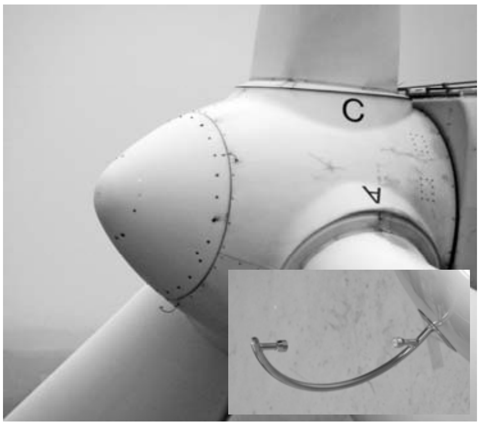


Figure 1 Spinner anemometer mounted on V80 turbine no 5


Figure 2 Tjæreborg wind farm site

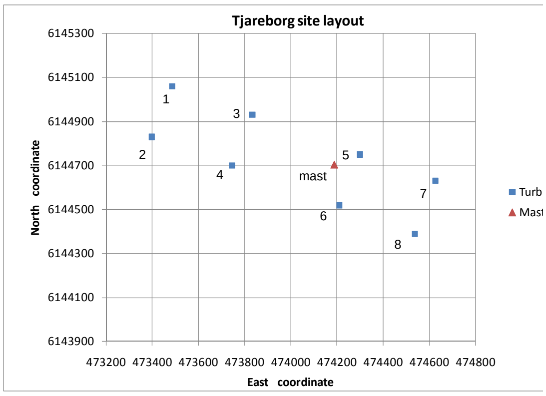


Figure 3 Positions of turbines and mast

Table 1 Relative distances and directions

| WT # | Distance to WT #5 (xD of V80) | Direction to WT #5 (deg) |
|---|---|---|
| 1 | 10,9 | 291 |
| 2 | 11,3 | 275 |
| 3 | 6,3 | 291 |
| 4 | 7,0 | 265 |
| 5 | 0,0 | - |
| 6 | 3,2 | 201 |
| 7 | 4,3 | 110 |
| 8 | 5,4 | 147 |
| | Distance to met mast (xD of V80) | Direction to met mast |
| 1 | 9,8 | 297 |
| 2 | 10,0 | 279 |
| 3 | 5,3 | 302 |
| 4 | 5,6 | 270 |
| 5 | 1,5 | 67 |
| 6 | 2,3 | 173 |
| 7 | 5,5 | 100 |
| 8 | 5,8 | 132 |

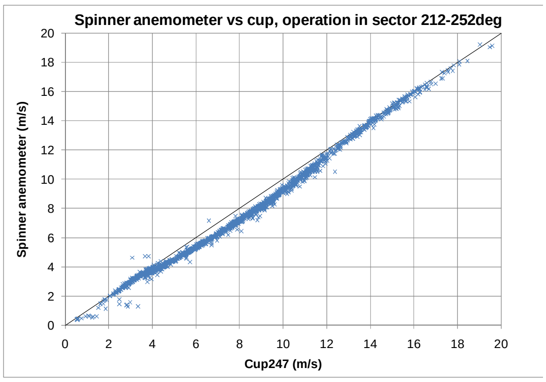


Figure 4 Spinner wind speed relative to cup

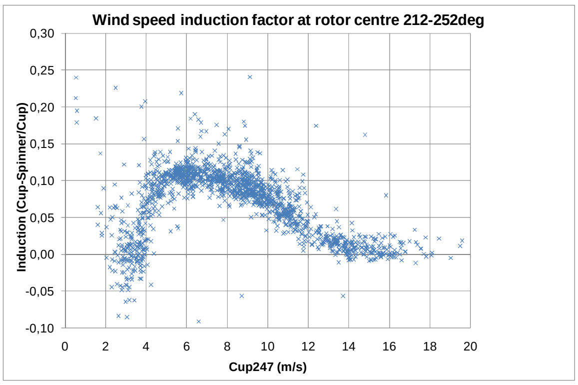


Figure 5 Induction factor at rotor centre

### Results of yaw error and flow inclination angle measurements

The yaw error measurements for a two month period with the spinner anemometer are shown in Figure 7. The average yaw error is almost 10° and the spreading of data is about 5°. Only for one wind direction, which is in the wake of turbine 6, the yaw error is spreading more, from -10° to 14°.

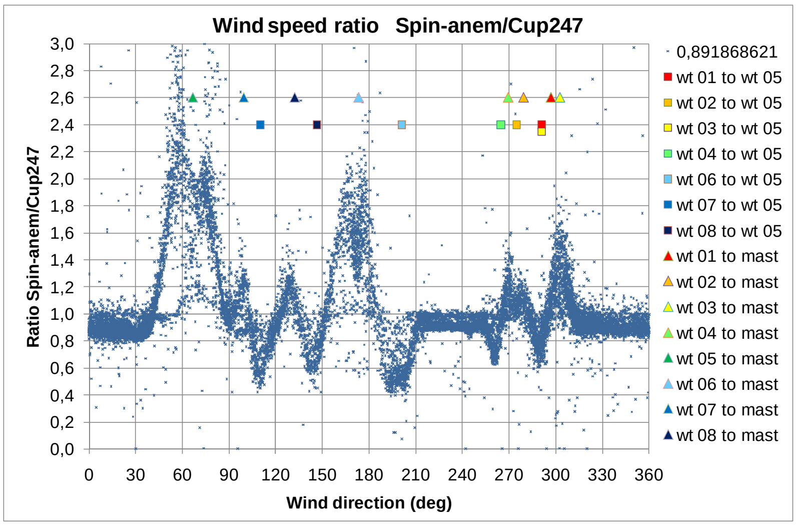


Figure 6 Spinner anemometer wind speed relative to cup wind speed from various directions

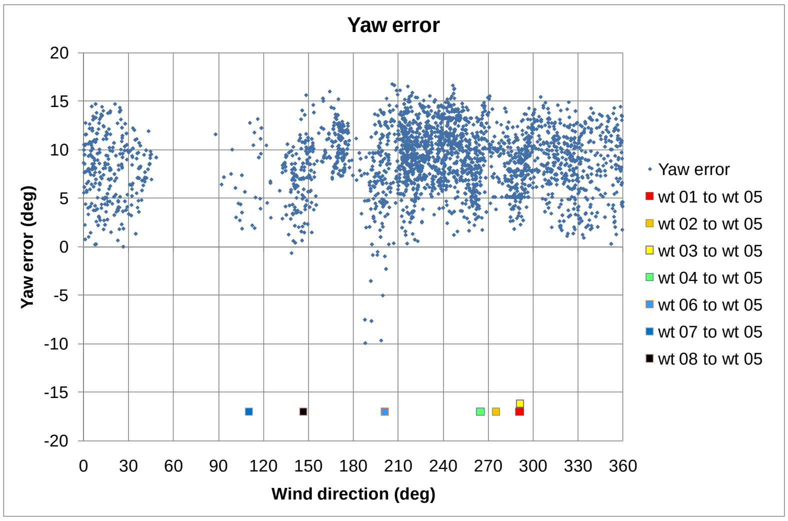


Figure 7 Yaw error measurements from various directions

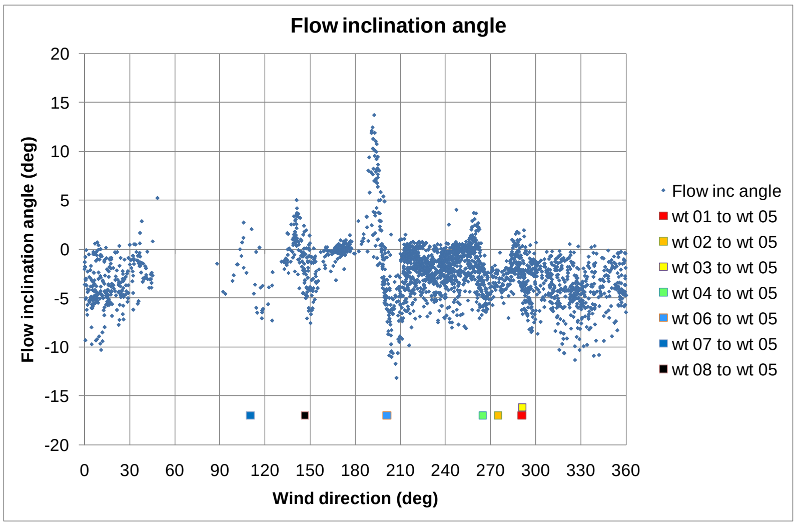


Figure 8 Flow inclination measurements from various directions

The flow inclination angle is shown in Figure 8. From most of the directions the flow inclination angle is between 5° and 0°. A dramatic change of inflow angle is seen in the wake of turbine 6. At 192° the inflow angle is almost 14° while at 207° the inflow angle is -13°. Between these points there is a linear change of inflow angle. This inflow angle pattern is due to the rotation of the wake of turbine 6. The wake rotation from turbine 6 is opposite the rotation direction of the rotor. This corresponds well with the measurements.

### Power loss estimate of onshore V80 turbine

The estimate of the power loss due to yaw error is estimated using the following assumptions. First, it is assumed that the power is proportional to the cosine squared of the yaw angle. Second, the power loss is only considered relevant in the wind speed range from 4m/s to 12m/s. Above 12m/s the power is regulated down so a power loss is taking place anyway. Third, it is assumed the power can be improved by better yawing having zero yaw error. This is, however, not a realistic assumption. In practice the yaw error can be targeted to be within ±5°, in which case the power loss is maximum 0,4%, and if it is spreading equally over the range the average is 0,2%. The power loss factor is calculated from the yaw error measurements in Figure 8 and is shown in Figure 9. The power loss factor is seen to vary from 1.00 down to about 0.93. The average power loss factor of all data is 0,971. This corresponds to a power loss due to yaw error of 2,9%. If we extract the 0,2% due to the targeted yaw error range we get 2,7% power loss.

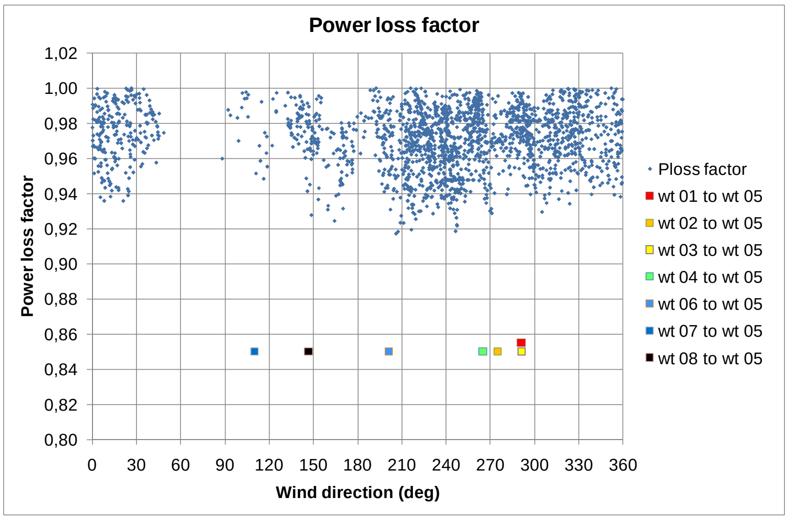


Figure 9 Power loss factor of onshore V80 turbine in the wind speed range 4-12m/s

**Power loss estimate of Horns Reef wind farm**

The Horns Reef wind farm has been operated for several years and a database of SCADA data has been gathered. These data consists of power data, nacelle wind speed and wind direction data, and yawing direction data. A parametric analysis was made based on yawing directions, and position of the turbines in the wind farm. The yawing directions showed quite large variations, indicating that yaw errors could be significant. For one whole day of production with a good wind from the west (26/8-2005) the average power and yaw direction of each of the 80 turbines was determined. The average power of each turbine is shown if Figure 10 as function of the deviation in yaw direction from the overall average yaw direction. The front row turbines in the top of the plot are seen to have a significant higher production than the rest. If the rest of the turbines were having yaw errors corresponding to these variations then the power would be visibly reduced, following the $\cos^2$ law, for the turbines having large yaw errors (apparent yaw error). From Figure 10 it can be seen that this is not the case. The large variations in yaw direction are not due to yaw errors. It may be assumed that they are due to the yaw direction sensors not being calibrated relative to each other. This is confirmed when looking at longer term statistics.

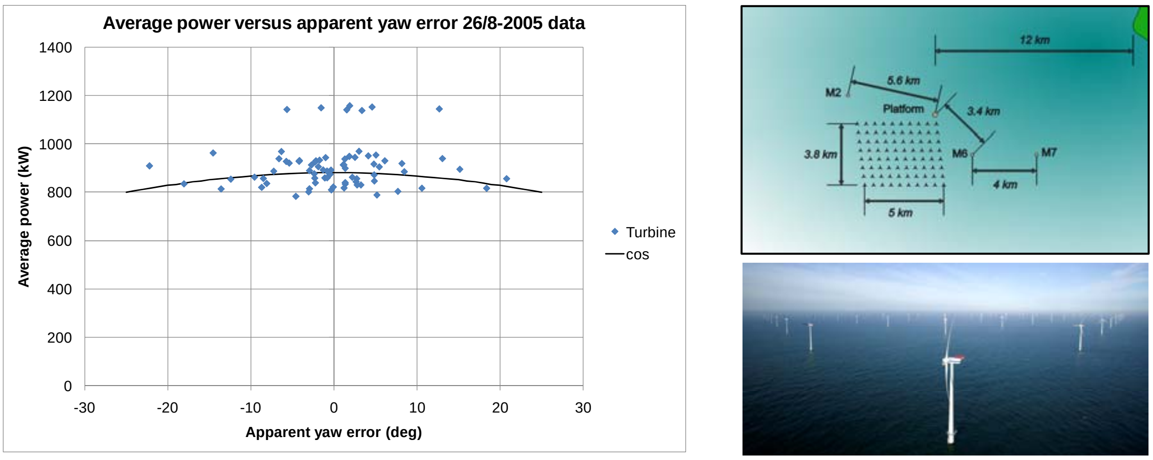


Figure 10 One day average power versus apparent yaw error in Horns Reef wind farm

In estimating the power loss of the Horns Reef wind farm due to yawing error the V80 onshore measurements can be used. We then have to make further assumptions. First, we assume all turbines to have the same amount of yaw error as the V80 onshore turbine. Second, we assume that power losses are only relevant for the 3-15m/s wind speed range. For the wind distribution at Horns Reef we can assume that about 60% of the power production should be considered in the power loss model. We thus end up with an estimate of 1,6% power loss of the wind farm due to yaw errors. This corresponds to the production from 1,3 wind turbines.

## Conclusions

An analysis was made of the potential power loss of the Horns Reef wind farm due to yaw error. The yaw errors on an identical V80 onshore wind turbine were measured to be significant, and in average about 10°. The flow inclination angle was measured to be significantly influenced by wake rotation from the neighboring wind turbines. The average power loss factor in the wind speed range 3-15m/s was found to be 0,971. Adjusting for a realistic yaw error interval the estimated power loss for the wind speed range was found to 2,7%. Considering the wind distribution at the Horns Reef site and only considering power below rated wind speed then an estimated power loss of 1,6% was found. This corresponds to the production from 1,3 wind turbines.

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