Spinner anemometer: wind speed and Spinner Transfer Function seasonal robustness in an offshore wind farm

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Spinners: wind speed and Spinner Transfer Function seasonal robustness in an offshore wind farm

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Abstract. This work presents the first, long-term, demonstration case of the use of spinner anemometers for power curve measurements in an offshore wind farm. The stability of the spinner anemometer wind speed and its STF during a 22-month measurement period was quantified, using a nacelle lidar as reference. Power curves and annual energy productions (AEPs) were obtained using this long-term data set, to assess the spinner anemometer wind speed stability. Next, several STFs were obtained at a reference turbine in different periods (four two-months periods) to assess the STF seasonality. Finally, the AEPs of three neighbouring turbines were analysed using the STFs generated at the reference turbine.

1. Introduction

The spinner anemometer is an instrument installed on a wind turbine spinner that measures wind inflow angles and horizontal wind speed in the center of the turbine rotor. Since it measures inside the turbine induction zone, it requires a Spinner Transfer Function (STF, the equivalent of the NTF for nacelle-mounted sensors [1]) to obtain the “free wind speed”. I.e. a wind speed that (ideally) is not affected by the flow distortion caused by the wind turbine, which is the input to power curves and Annual Energy Production (AEP) calculations.

The Performance Transparency Project (PTP), funded by EUDP (project partners ROMO Wind and DTU Wind Energy), aims to demonstrate the seasonal and terrain wise robustness of the STF in different terrains and turbine types.

PTP has produced 22 months of data from one nacelle lidar and iSpin® systems (spinner anemometer produced by Romo Wind) in an offshore wind farm. Previously, we presented preliminary results from the reference turbine in this wind farm [2]. In the present work, we reviewed our previous analysis and studied the seasonal stability of the spinner anemometer wind speed and STF in a longer dataset. Moreover, we investigated the reproducibility of the spinner anemometer power curves and the suitability of the STF derived from the reference turbine, which was applied to several turbines in the wind farm.
2. Objectives
The main objective of the present work was to analyze the stability, over more than one year, of the spinner anemometer wind speed measurements with respect to the lidar and the nacelle anemometer, using a long-term STF. Another goal was to evaluate the seasonal stability of the STF and its impact on AEP. Finally, we investigated the reproducibility of the spinner anemometer power curves and AEPs from several neighboring wind turbines.

3. Method
3.1. Overview
The first part of the analysis focused on the reference turbine. We obtained a $k_1$ factor and a STF [3] from the full campaign dataset and derived the wind speed differences, power curves, and AEPs from iSpin, nacelle anemometer (SCADA), and lidar for two-month sub-sets. In the second part, we generated STFs and $k_1$ factors from shorter periods, and compared these “season” STFs to the previous STF. At the reference turbine, we also compared the AEPs obtained on a bi-monthly basis from these STFs. Finally, we compared the AEPs from several neighbouring wind turbines.

3.2. Database and filters
The dataset consisted of ten-minute data from several V112-3.0MW turbines. iSpin® measurements and turbine SCADA data were available in all the turbines included in this study. The spinner anemometers were calibrated and installed following best practices [4]. Additionally, a four-beam nacelle lidar (Wind Iris v2) was installed on the reference turbine.

Table 1 shows the applied filters to select valid data for the analyses. They are grouped by lidar, spinner anemometer, and turbine filters. The lidar filter No. 2 was defined based on a note from the manufacturer for this specific unit and firmware version. Filter No. 3 was defined in order to exclude extreme events where a fog layer would affect only top or bottom Lines-of-Sight (LOS) measurements, which may produce an incorrect wind speed. In comparison to previous results in [2], the additional filter No. 6 was defined to use valid iSpin measurements for a non-operating turbine in low wind speeds. Hence, the number of valid data points increased for low wind speeds. The filter No. 8 defines the reference turbine wake-free sector, which was verified by analyzing the lidar LOS turbulence with respect to wind direction. It shall be noted, that no lidar data was recorded during July 2019, due to a full memory disc.

| No. | Filter description |
|-----|-------------------|
| Wind Iris v2 | 1. Data availability: 1 |
|  | 2. CNR lower than -5dB for all LOS |
|  | 3. Difference between CNR from top and low LOS lower than 5dB. I.e. $|\text{CNR}_0-\text{CNR}_2|<5\text{dB}$ and $|\text{CNR}_1-\text{CNR}_3|<5\text{dB}$. |
| iSpin ® | 4. Valid iSpin measurements based on quality code [8] |
| V112-3.0MW | 5. Turbine operating according to angular rotor speed limits |
|  | 6. Turbine pointing into the wind for low wind speeds with yaw misalignment lower than 30° |
|  | 7. Power signal is larger than 0 [kW] and SCADA data is valid |
| Wind direction | 8. Reference turbine in wake-free condition (155°-300°) |
3.3. Spinner transfer function

The spinner anemometer wind speed calibration includes two final steps [3]: (1) to correct measurements to free wind speed by applying a calibration factor $k_1$, and (2) to correct the non-linear induction effects at the rotor with a spinner transfer function (STF). An example is given in the next two plots. Figure 1 presents the raw iSpin and lidar wind speed measurements in no-wake conditions. First, the data in very low and very high wind speeds in Figure 1 was fitted to a forced-through-zero line (ignoring non-linear effects from the operating turbine rotor induction). The obtained gain coefficient is $k_1$. Next, a STF was obtained using the $k_1$-corrected iSpin data, by computing the average difference between iSpin and lidar speed, in 0.5m/s bins [5] (see example in Figure 5).

![Figure 1](image1.png)  
**Figure 1.** Spinner anemometer wind speed before applying the calibration factor $k_1$ and STF, as function of the lidar wind speed.

![Figure 2](image2.png)  
**Figure 2.** Spinner anemometer wind speed corrected with the calibration factor $k_1=0.69$ and STF$_1$ as function of the lidar wind speed.

As part of the seasonality study, five different $k_1$ calibration factors and STFs were obtained, following the procedure in [4] but using the lidar wind speed (at a distance of 2.3 times the rotor diameter) as the reference ($w_{ref}$) instead of a mast-mounted cup anemometer. For each case, we performed the self-consistency test prescribed in Annex D.8 of [1], and selected STFs that fulfilled the pass criteria, as previously done in [2]. Table 2 summarizes the start and end dates of the selected periods, the number of valid data points, and the $k_1$ calibration factors (rounded to two decimals).

| Name   | Description | Measurement period | Number of valid data points | $k_1$ factors |
|--------|-------------|--------------------|-----------------------------|--------------|
| STF$_1$| full period | 2018-02-07 to 2019-12-04 | 27116 | 0.69 |
| STF$_2$| spring      | 2018-03-01 to 2018-05-01 | 2394  | 0.69 |
| STF$_3$| summer      | 2018-07-01 to 2018-09-01 | 1984  | 0.68 |
| STF$_4$| autumn      | 2018-09-01 to 2018-11-01 | 3736  | 0.69 |
| STF$_5$| winter      | 2018-11-01 to 2019-01-01 | 2190  | 0.69 |

Table 2. Overview of Spinner Transfer Function periods, number of data and calibrations
3.4. Wind speed deviation

Wind speed deviation $\Delta w_s$ was defined in [2] as:

$$\Delta w_s = \frac{w_s - w_{s\text{ref}}}{w_{s\text{ref}}} \cdot 100\%$$ (1)

where $w_{s\text{ref}}$ is the lidar wind speed, and $w_s$ stands for either the spinner anemometer wind speed (corrected with calibration factor $k_1=0.69$ and STF$_1$), $w_{i\text{Spin}}$, or the nacelle anemometer wind speed (from SCADA), $w_{nac}$.

3.5. AEP uncertainty assessment

The uncertainties of the lidar and spinner anemometer power curves based on the full dataset, and their AEPs, were calculated based on [5]. The lidar uncertainties were determined following the present IEC draft for the use of nacelle-mounted lidars for wind speed measurements [6]. The spinner anemometer uncertainties were assessed according to [1]; the inputs and uncertainty method were described in [7]. Where available, the input values for the assessment were taken from calibration certificates and installation documents. In other cases, we assumed typical values, based on our experience or common practice. The lidar calibration uncertainty was based on the preliminary post-calibration (ongoing).

The wind speed uncertainty is expressed in eq. 2, and the input values as given in Table 3. The values assumed for other uncertainty components are given in Table 4.

$$u_{V,i} = \left( u_{V_{S,i}}^2 + u_{\text{terr},i}^2 + u_{M,i}^2 \right)^{1/2}$$ (2)

| Uncertainty component | Values |
|------------------------|--------|
| Instrument uncertainty $u_{V_{S,i}}$ | Lidar [6] | Spinner anemometer [7] |
| $u_{V_{p\text{h},WFR,\text{inputs,i}}}$ | $0.12\ m/s$ | Calibrations: |
| $u_{V_{\text{los,3}}} \cos \alpha_H^{-1} \cos \beta_Y^{-1} = 0.12\ m/s$ | | • Wind tunnel calibrations: |
| $u_{V_{\text{h,operational,i}}} \approx 0$ | | $u_{V_{N1,V_{1,i}}} = 0.0052V_{1,i} + 0.012\ m/s$; |
| $u_{V_{\text{h,WFR,\text{internal,i}}} \approx 0}$ | | $u_{V_{N1,V_{2,i}}} = 0.0053V_{2,i} + 0.010\ m/s$; |
| Other: $u_{V_{\text{measH}}} = (\langle z_{hub} + u_d \rangle^2 z_{hub}^{-s} - 1) \cdot 3^{1/2} \cdot V_i$ | | $u_{V_{N1,V_{3,i}}} = 0.0050V_{3,i} + 0.017\ m/s$ |
| Other ≈ 0 | | • Angular calibration: $0.1k_a$ |
| Flow distortion (terrain) $u_{\text{terr},i}$ | $u_{\text{terr},i} = 1\%V_i$ | |
| Method uncertainty $u_{M,i}$ | Lack of shear and veer normalization: $u_{M,\text{shear-veer},i} = 0.5\% (*)$ | Other ≈ 0 |
Table 4. Summary of other power curve uncertainty components and input values. Values indicated with (*) are assumptions.

| Uncertainty component | Values |
|-----------------------|--------|
| Electrical power      | \( u_{P,i} = (u_{P,CT,i}^2 + u_{P,PT,i}^2 + u_{d,P,i}^2)^{1/2} = \left( (0.005 \cdot 3^{1/2} \cdot P_i)^2 + (0.0075 \cdot 3^{1/2} \cdot 1.4 P_{nom}^2 \right)^{1/2} \) |
| Air temperature       | \( u_{T,i} = (u_{T,cal,i}^2 + u_{T,shield,i}^2 + u_{T,mnt,i}^2 + u_{dT,i}^2)^{1/2} = 0.5^\circ C(\ast) \) |
| Air pressure          | \( u_{B,i} = (u_{B,cal,i}^2 + u_{B,mnt,i}^2 + u_{dB,i}^2)^{1/2} = 0.6 hPa(\ast) \) |
| Relative humidity     | \( u_{RH,i} = (u_{RH,cal,i}^2 + u_{RH,mnt,i}^2 + u_{dRH,i}^2)^{1/2} = 0.5\%(\ast) \) |

4. Results

4.1. Long-term STF analysis (reference turbine)

The following section focuses on presenting results from the reference turbine, that were gained by applying the long-term STF to spinner anemometer measurements. First, wind speed deviation are defined and compared. In the second part, an uncertainty assessment is carried out to finally show AEP evaluations.

4.1.1. Wind speed deviations

The full data set was split into 21 two-month subsets. For each subset we calculated the wind speed deviation, \( \Delta w_s \), for the spinner and the nacelle anemometer measurements. The results are shown as boxplots in Figure 3. The whiskers in each boxplot represent the two-sigma region of the dataset and the box indicates the first and the third quartile, including the median as horizontal line inside each box. The starting date is indicated in the x-axis, which represents the selected two-month period, e.g., ‘2018-02’ contains measurements in the period from 2018-02-01 to 2018-03-30.

The main body of each boxplot containing iSpin® measurements were within the ±2% error band (grey in top plot), showing a good agreement with the reference (lidar). The nacelle anemometer (SCADA) exceeded the ±2% deviation band in most measurement periods.
Figure 3. Distribution of wind speed deviation (top) and number of valid data points (bottom) for spinner anemometer (iSpin®) and nacelle anemometer (SCADA) in 21 two-month periods.

4.1.2. AEP and uncertainty of lidar and iSpin

The AEP was calculated using the full-period lidar and spinner anemometer power curves. The reference hub height annual wind speeds were 6m/s and 8m/s, with a Rayleigh probability density function. The reference air density was 1.225kg/m³. The results are shown in Table 5; the measured AEP values were normalized to the lidar AEP at the given wind speed.

Table 5. Measured AEP and uncertainty from full period data set

|                  | V = 6m/s                     | V = 8m/s                     |
|------------------|------------------------------|------------------------------|
|                  | Measured AEP, $AEP_{meas}$   | Measured AEP, $AEP_{meas}$   |
|                  | Standard uncertainty in AEP, $u(AEP_{meas})$ | Standard uncertainty in AEP, $u(AEP_{meas})$ |
| Lidar            | 100.0%                       | 100.0%                       |
|                  | 4.7% $AEP_{meas,lidar}$      | 3.1% $AEP_{meas,lidar}$      |
| Spinner anemometer| 100.0%                       | 100.1%                       |
|                  | 6.7% $AEP_{meas,iSpin}$      | 4.4% $AEP_{meas,iSpin}$      |

The lidar AEP result at V=8m/s was used as the reference for the analysis in next sub-section.

4.1.3. AEP comparison

Power curves and AEPs were obtained from each two-month data set, from the lidar, spinner anemometer (iSpin®), and nacelle anemometer (SCADA). The method and normalizations used are described in [5]. A Rayleigh probability density function was assumed with a reference annual mean wind speed of 8m/s. Figure 4 presents the AEP values normalized to the AEP of the lidar power curve obtained from the full period (black dashed line). The iSpin® AEPs show small variations around the reference, of similar magnitude as the lidar, whereas the nacelle anemometer (SCADA) AEPs deviations from the reference are greater than 2% or 4% in most cases. Due to the lidar data loss in July 2019 an abrupt change in the AEPs is observed at point ‘2019-06’.
Figure 4. AEPs from spinner anemometer (iSpin®), lidar and nacelle anemometer power curves in two-month periods. Normalized by AEP of lidar power curve obtained from the full period (black dashed line).

4.2. STF seasonality analysis

The STFs obtained from the five datasets in Table 2 (section 3.3) are shown in Figure 5. The STF is expressed as the wind speed difference $w_{ref,n,i} - w_{ispin,n,i}$, where “$n$” indicates the STF period, and “$i$” indicates the wind speed bin index.

Figure 6 displays the difference relative to the one-year STF (STF$_1$), expressed as eq. 3. In this figure, we plotted only wind speed bins where there was data in all STFs. We interpolated the values $(w_{ref,n,i} - w_{ispin,n,i})$ to the abscissa values in STF$_1$ ($w_{ref,1,i}$)

$$\Delta STF = \left( (w_{ref,n,i} - w_{ispin,n,i}) - (w_{ref,1,i} - w_{ispin,1,i}) \right) w_{ref,1,i}^{-1}$$

(3)

Figure 5. (left) STFs from the different periods. (Right) Number of data in the STFs.
4.2.1. Effect of STF on AEPs (reference turbine)

Next, we investigated how the differences in STF affect the AEP. We evaluated the difference in AEP due to the application of the season STFs, i.e. STF_{n=2..5} (n=2..5), with respect to the application of the full-period function, STF_1. For each STF_{n=2..5}:

- we applied STF_n to the iSpin data,
- grouped the data in twenty-one two-month datasets and applied air-density normalization,
- calculated the iSpin power curve and AEP for each two-month dataset, AEP_{n,m} (m=1..21),
- obtained the difference between the AEPs based on the season STF and the one-year STF: \( \Delta AEP_{n,m} = (AEP_{n,m} - AEP_{1,m}) / AEP_{1,m} \times 100\% \).

**Figure 6.** Wind speed difference between each STF and the full-period STF in absolute (m/s) and relative (%) units, as shown in subplots left and right, respectively.

**Figure 7.** Difference between the AEPs based on the season STFs and the full-period STF, evaluated in two-month periods.
Changes in AEP due to the different STFs were within 1%, as shown in Figure 7.

4.3. *AEPs of neighbouring turbines*

We selected three neighbouring turbines: the two immediate neighbours of the reference turbine, and an additional one. The setting for filter No. 8 in section 3.2 was reduced (to 180°, 240°), to select a common sector where the four turbines were free of wakes. This was verified with the turbulence measurements from spinner anemometer of each turbine, as shown in Figure 8.

Power curves and AEPs were obtained from spinner anemometer wind speeds (corrected by $k_1$ and STF), using the air density correction and methods in [1]. The annual average wind speed was assumed 8m/s with a Rayleigh distribution ($k=2$). The results are shown in Figure 9; the AEPs were normalized to the AEP from the reference turbine obtained with the full-period STF.

Due to the proximity between the turbines, on average they were subject to similar wind conditions. Then, the comparison of these turbines AEPs might be, on the one hand, an indication of the reproducibility of the spinner anemometer speeds and the suitability of the STF derived from the reference turbine. On the other hand, it remains unclear whether the difference, which is close to 2%, between the turbines AEP (for a given STF), might be due to differences in the turbine performance, or differences in measurement equipment (specifications of power measurement equipment were not available).

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**Figure 8.** Turbulence intensity measurements from spinner anemometer at each turbine.

**Figure 9.** AEP for neighboring turbines normalized to the AEP obtained at the reference turbine for the full-period STF.
5. Conclusions

This work complemented and extended our previous work in [2], and confirmed our previous conclusions. In particular, for the present analysis, we obtained the following conclusions:

The analysis using a long-term STF showed that:
- The two-month-average wind speed differences between the spinner anemometer and the lidar were within ±2% of the reference wind speed, over a year.
- The variation in AEP calculated from short periods (two months) of spinner anemometer and lidar wind speeds showed a similar degree of variability. I.e. the calculated AEPs from lidar and iSpin lied between ±2% of the full-period lidar AEP.
- The spinner anemometer and lidar power curves and AEPs were consistent, considering their uncertainty intervals (calculated following IEC standards).

The analysis using several STFs from different periods showed that:
- Differences between the full-period STF and the season STFs were within -2.5% and 1% of the reference wind speed.
- The AEPs from season STFs differed from the AEPs based on the full-period STF in less than 1%, in the reference turbine.

The comparison of several turbines AEPs, on the one hand, might support the suitability of the STF derived from the reference turbine. On the other hand, it remains unclear whether the observed differences between turbine AEPs (for a given STF) might be due to differences in the turbine performance, or differences in measurement equipment.

6. References

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