ISPIN

Review of the Spinner anemometer from ROMO Wind iSpin

ROMO Wind A/S

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Table of contents

1 EXECUTIVE SUMMARY

ROMO Wind is a technology and engineering company, established in 2011 by a group of people with extensive experience from the wind industry. ROMO Wind is, in general, focusing on assisting wind farm owners in optimising the energy output from their wind farms. However, during recent years the business is focused on providing services related to the iSpin spinner anemometer. The iSpin aims to improve energy production from turbines by correcting yaw misalignments.

ROMO offers both permanent installation of the iSpin and short measurement campaigns for detecting and making a one-off correction of potential yaw misalignments.

The technology of the spinner anemometer was originally invented and developed at the Department of Wind Energy (formerly Risø) of the Technical University of Denmark (DTU) and the spinner anemometer marketed by ROMO is, to a very large extent, based on the work performed by Risø DTU. DNV GL has reviewed some of the work performed by Risø DTU and finds that the technology of the spinner anemometer is based on sound theoretical analyses and practical testing.

ROMO Wind undertakes calibration of the iSpin using a methodology which includes standard calibrations at zero wind speed, an internal calibration at the field after installation to account for sensor and mounting specific issues and a turbine specific calibration to account for the different turbine type geometries. The latter is performed using a nacelle mounted LiDAR; the uncertainty of measurements from nacelle mounted LiDARs has not yet been properly quantified within the industry.

ROMO Wind is also using an alternative calibration of the spinner anemometer to calibrate the vertical flow angle (yaw angle) called, Kα calibration. By using the Kα calibration it is possible to calibrate the vertical flow angle (yaw angle) measurement without the use of a LIDAR or met mast and this facilitates the use of the spinner anemometer for correction of yaw misalignment without performing calibration of the spinner anemometer using LiDAR.

With ROMO Wind's historical focus on yaw misalignment, accuracy of the wind speed measurements is less important. Additionally, due to the calibration methodology, DNV GL considers that calibrating and using the iSpin in complex sites may be challenging. It should be noted that ROMO Wind has informed DNV GL that they have never performed turbine type specific calibration of the iSpin on complex sites.

ROMO Wind may use a relative power curve measurement based on the wind speed from the spinner anemometer before and after correction of a yaw misalignment to establish the increase in energy production obtained by the correction of the yaw misalignment, the results of such measurement will have some level of unknown uncertainty due to the uncertainty of the iSpin wind measurement not having been quantified. However, DNV GL expects that it should be possible to use a relative power curve measurement to estimate the energy increase obtained with a uncertainty of less than ± 10% provided:

- The requirements in the IEC61400-12-1 standard for power performance measurements of wind turbines with respect to data collection and data handling including meeting the requirements for number of data samples in;
- The site is flat without significant obstacles or the influence of such obstacles is considered in the data processing.
- Weather conditions during the period of the two measurements are comparable.

The operating experience with the spinner anemometer is limited and it is therefore difficult to conclude around the expected reliability. The sonic wind speed sensors are supplied by METEK Meteorologische

Messtechnik (METEK) GmbH. The spinner anemometer shares its technology with the USA-1 ultrasonic sensor. Based on DNV GL understanding of the spinner anemometer and METEK's substantial experience with the technology of ultrasonic anemometer, DNV GL is not aware of any reason to assume a reliability level that is different from what is commonly assumed for wind turbine sensors.

ROMO Wind has used the spinner anemometer to measure and correct yaw misalignment on 152 turbines of which 93 (61 %) had yaw misalignment lager than 4°. ROMO Wind has as of end 2014 corrected the yaw misalignment on 73 of the 93 turbines where yaw misalignment has been detected. According to ROMO Wind, the average possible improvement in energy due to the correction of the yaw misalignment from the 152 turbines if corrected will be approximately 2% using the simple model ($\cos^2$) to calculate the improvement. DNV GL has also undertaken independent theoretical calculations and considers this to be achievable. Investigations on the Vedersø Kær wind farm in Denmark have also been undertaken using a reference turbine and the results from the analysis support ROMO Wind's claim.

DNV GL also notes that there is a number of opportunities to use the data from a spinner anemometer for other wind farm applications, provided the uncertainty associated with measurements from the iSpin decreases and becomes well defined.

2 INTRODUCTION

ROMO Wind A/S (ROMO or the "Client") has requested that Garrad Hassan and Partners Ltd (DNV GL) perform a technical review of their spinner anemometer called the iSpin.

The objective of the review is to provide the Client with an independent evaluation of the spinner anemometer and the benefits that installation of a spinner anemometer may offer to a wind turbine owner.

The scope of the work is described in the DNV GL proposal 113605-DKAR-P-01-01, dated 2014-10-24.

References are provided throughout this report, in square parenthesis: for example, /1/. A list of references is also provided at the end of this report.

This report presents the findings of the technical review.

3 REVIEW

3.1 Background Information

ROMO Wind is a technology and engineering company, established in 2011 by a group of people with extensive experience from the wind industry. ROMO Wind is, in general, focusing on assisting wind farm owners in optimising the energy output from their wind farms. However, during recent years the business is focused on providing services related to the iSpin spinner anemometer.

ROMO Wind offers installation of their spinner anemometer to improve the yaw accuracy of the turbine, thereby improving the energy output. The subject of this review is the spinner anemometer.

ROMO offers both permanent installation of the iSpin and short measurement campaigns for detecting and making a one-off correction of potential yaw misalignments.

The permanent installation of the iSpin is called iSpin Monitor and is offered in two versions, Basic and Advanced.

The iSpin Monitor Basic consists of three iSpin sensors mounted on the spinner and a small data collection/processing unit mounted in the hub of the turbine. The iSpin Monitor Basic will collect yaw misalignment data and send these data to a ROMO server via SMS text messages.

The iSpin Monitor Advanced consists of the three iSpin sensors mounted on the spinner, nacelle position sensor, air pressure sensor and temperature sensor. The data is collected and processed in a unit located in the nacelle of the turbine. Data for the iSpin sensors is transferred via WIFI to the unit in the nacelle.

ROMO Wind is based in Switzerland and the ROMO Wind technical team is located in Denmark.

3.2 The Spinner anemometer technique

The technology behind the spinner anemometer was originally invented and developed at the Department of Wind Energy (formerly RISØ) of the Technical University of Denmark (DTU).

A spinner anemometer is an anemometer that uses the aerodynamics of the spinner of a wind turbine for measurement of the wind conditions experienced by the wind turbine. The spinner anemometer is able to measure wind speed, yaw error and the wind inclination angle. The spinner anemometer used by ROMO Wind consists of three sonic wind speed sensors, mounted on the spinner, as shown in Figure 3-1 .

Figure 3-1 Sonic wind speed sensors

The ROMO spinner anemometer also has a built-in rotor azimuth sensor. Each sonic wind speed sensor has a built-in accelerometer in the sensor foot which is used to determine the azimuth angle of the wind turbine rotor.

The basic principles and theory of the spinner anemometer technology are described in the Risø DTU report “Spinner anemometry - basic principles for application of the technology” /1/. According to DNV GL understanding, ROMO uses the method described in this report to calculate the wind speed and yaw error from the signals provided by the three sonic wind speed sensors with the built-in accelerometers.

3.3 Calibration routines

The calibration of a spinner anemometer involves three different calibration routines:

- Calibration of the sonic wind speed sensor instruments; this calibration routine has to be performed for every sonic wind speed sensor.
- Internal spinner anemometer calibration; this calibration routine has to be performed on every installation of the spinner anemometer.
- Calibration of spinner anemometer turbine type specific constants; this calibration routine has to be performed for every turbine type.

These calibrations are described further in the following sub-sections.

3.3.1 Calibration of the sonic wind speed sensor

Calibration of the sonic wind speed sensor can be performed in two ways:

- A simple calibration at zero wind speed or
- Wind tunnel calibration

The ROMO standard solution requires that a calibration at zero wind speed is performed by the supplier of the sonic wind speed sensor.

The zero wind speed calibration provides the required parameter input for the sonic wind speed sensor algorithm ensuring the required accuracy for the measurement.

For a traceable accredited calibration the sonic sensors on the spinner anemometer system should be calibrated in an accredited wind tunnel (MEASNET or similar tunnel). For the purpose for which ROMO is using the spinner anemometer such calibration is, in the view of DNV GL, not needed. However, if the spinner anemometer were to be used for power curve verification, a traceable accredited calibration of the sonic sensors would be required.

The calibration of the sonic wind speed sensor is described in the Risø DTU report "Spinner anemometry - basic principles for application of the technology" /1/, section 7.1 and 7.2.

3.3.2 Internal spinner anemometer calibration

The general assumption of the spinner anemometer algorithm is that the spinner has a perfect geometry, the sensors are perfect, and that they are mounted perfectly. However, as this is not normally the case, Risø DTU has developed an internal spinner anemometer calibration routine. This routine assumes that the three sonic wind speed sensors experience the same measured average values over time during rotation. This is a consequence of the spinner anemometer measurement principle.

This calibration routine will result in two constants per sonic wind speed sensor slope and offset.

The internal spinner anemometer calibration routine is performed in the field after the spinner anemometer has been installed on the turbine. The routine involves operating the turbine for at least 30 minutes sampling data from the three sensors of the spinner anemometer when the wind speed is in the range between 6 to 10 m/s. The processing of the data is done automatically providing the two calibration constants for each sensor.

For further information on the Internal spinner anemometer calibration see the Risø DTU report Spinner anemometry - basic principles for application of the technology /1/ section 7.3.

3.3.3 Calibration of spinner anemometer - turbine type specific constants

As the wind speed and direction measured by the three sonic wind speed sensors is affected by the geometries of the spinner, nacelle and blade roots, a calibration of the spinner anemometer is needed for every turbine type to convert the wind measured by the sonic wind speed sensor to the free wind affecting the turbine. This calibration can be performed by CFD calculation and by comparing a measurement of the free wind affecting the turbine. Risø DTU recommends that a measurement of the free wind is always used to verify the CFD calculations.

The result of the spinner anemometer turbine type specific calibration is two constants; one for the wind speed component parallel to the turbine nacelle direction (K1) and one for the wind speed component perpendicular to the turbine nacelle direction (K2).

ROMO Wind is currently not using CFD calculation as part of their routine for calibration of spinner anemometer turbine type specific constants and is not expecting to do so in the future.

The ROMO Wind calibration of turbine type specific constants relies on a measurement of the free wind performed by a nacelle mounted LiDAR. ROMO Wind uses Zephir, Natural Power LiDAR or Avent LiDAR. It is also possible to use free wind measurement from a met mast if installed upwind of the turbine.

Wind measurements using LiDAR technology is well understood for measurements where the LiDAR is located on the ground at simple sites. However, the use of nacelle mounted LiDAR measurements is currently a technology under development to the extent where the uncertainty of the measurement has not yet been properly quantified. The method of using a met mast provides the most accurate measurement of the free wind speed. However, ROMO Wind is using LiDAR, as this method is less time consuming and with ROMO's historical focus on yaw misalignment, accuracy of the wind speed measurement has been less important.

It should be noted that the current calibration procedure does not provide calibration of the horizontal inflow angle and therefore the horizontal inflow angle is un-calibrated.

3.3.3.1 Calibration the vertical flow angle

ROMO Wind is also using an alternative calibration of the spinner anemometer to calibrate the vertical flow angle (yaw angle) called, Kα calibration where the relation between K1 and K2, Kα , is established:

$$K\alpha = \frac{K2}{K1}$$

The Kα constant is determined by yawing the stopped turbine 60° clockwise and counter clockwise five times from a position with the turbine pointing into the wind during which time the yaw position of the turbine is recorded. The yaw position of the turbine is used to analyse the output form the spinner anemometer and by this determine Kα.

The calibration should be made in flat terrain while the wind turbine is stopped with one blade pointing upwards or downwards. The wind should be in the range of 6-10 m/s and should not change average direction during the calibration.

Due to the calibration methodology, DNV GL considers that calibrating and using the iSpin in complex sites may be challenging.

The full procedure for calibration of the vertical flow angle is described in the DTU Wind Energy (Risø) report Guide for the calibration of a Spinner anemometer for flow angle measurements /5/.

By using the Kα calibration it is possible to calibrate the vertical flow angle (yaw angle) measurement without the use of a LiDAR or met mast.

3.3.4 Calibration – conclusions

DNV GL finds that ROMO Wind is following the calibration process as described by the DTU guidelines. DNV GL considers that the calibration performed by ROMO Wind should provide the basis for measurements where the uncertainty is limited to the extent possible. Although the uncertainty of the wind speed has not been quantified, it should be noted that with ROMO Wind's focus on yaw misalignment, and as measurement of the free wind speed is not used, the accuracy of the wind speed measurements is less important.

3.4 Reliability of the spinner anemometer

3.4.1 Workshop testing

The sonic wind speed sensors are supplied by METEK Meteorologische Messtechnik (METEK) GmbH. METEK was founded in 1988 in Hamburg (Germany) by members of the Meteorological Institute of the University of Hamburg. METEK is well known in the wind industry as a provider of sonic sensors for wind speed measurements in wind energy applications.

METEK supplies the sonic wind speed sensors including the built-in accelerometer and the hardware that processes the data from the three sensors providing the wind speed and yaw error. ROMO Wind provides the equipment which transmits this data from the hub to the nacelle where it is stored and can be accessed via various types of data connections.

The sensor is heated to provide protection against ice. The spinner anemometer shares its technology (including de-icing) with the USA-1 ultrasonic sensor, for which METEK has experience in heavy icing conditions.

METEK has undertaken the following testing of the sensor supplied to ROMO Wind:

- Test of temperature influence on the measured wind speed;
- De-icing tests;

METEK is also planning to undertake vibration testing of the spinner anemometer sensor.

Many of the parts used in the USA-1 anemometer are also used in the spinner anemometer sensor. Therefore, DNV GL agrees with METEK that the testing performed in relation with the USA-1 anemometer provides confidence in the reliability of the sensor used in the spinner anemometer. The following tests have been performed on the METEK product USA-1.

- Electromagnetic (EMC) testing of all of the electronic components used in the spinner anemometer. The complete spinner anemometer has not been EMC tested. However, METEK does not view this as critical as they have never had any issues around EMC interference with their products.
- Temperature tests of the complete USA-1 anemometer were performed four years ago through field tests for low temperature, -30 °C believed to be at Greenland installation by NCAR, and high temperature, +70 °C at Kuwait airport (TELVENT).

Further testing of the sonic wind speed sensors was conducted in a climate wind tunnel at WindGuard in Germany; the test and the results of the test is described in the DTU Wind Energy report Improvement of Wind Farm Performance by Means of Spinner Anemometry /6/. Based on this test DNV GL concludes that it is likely that the sonic wind speed sensors will be operating during icing conditions. However, ROMO Wind does not have any operating experience during heavy ice conditions to prove that the heating provided is sufficient.

3.4.2 Installation of the spinner anemometer

DNV GL has reviewed an installation instruction manual prepared by ROMO Wind for installation of the spinner anemometer on a Siemens SWT-2.3 MW wind turbine /2/. The instruction is a very detailed step by step instruction and DNV GL do find that ROMO Wind has attended to the details need to ensure a reliable installation of the spinner anemometer. It has to be noted that DNV GL has not inspected an installation of the spinner anemometer.

3.4.3 Track record "Reliability"

To date ROMO Wind has installed the spinner anemometer on 152 turbines over the years. According to ROMO Wind, the operating hours of the spinner anemometer amount to approximately 117 years and to date there has been a need exchange any part of the spinner anemometer installed. Although there have been some technical issue with the spinner anemometer during installation, ROMO Wind does not have any statistics on the failures during the installations phase.

It should be noted that the operating experience obtained by ROMO Wind of the spinner anemometer is limited. Therefore, the data available cannot support assumptions on the long term reliability of the spinner anemometer. However, based on DNV GL understanding of the spinner anemometer and METEK's substantial experience with the technology of ultrasonic anemometer, DNV GL is not aware of any reason to assume a reliability level that is different from what is commonly assumed for wind turbine sensors.

3.5 Yaw misalignment correction

ROMO Wind's main service is installation of the spinner anemometer and monitoring of the yaw misalignment of the turbines, adjustment of the yaw misalignment, thereby improving the energy production of the turbine.

ROMO Wind expectations for increased energy production are based on the ability to reduce the yaw error with which the turbines may be operating. This assumes that there are turbines which are operating with a substantial yaw error (see section 3.6 for DNV GL's experience around yaw error and relation to the turbine energy production).

The correction of yaw misalignment includes the following elements:

- Detection of yaw misalignment
- Correction of yaw misalignment

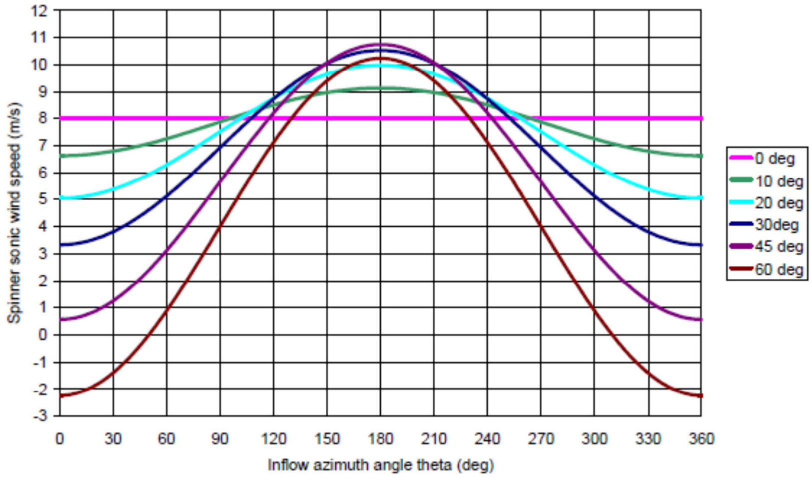
3.5.1 Detection of yaw misalignment

As a consequence of the spinner anemometer measurement principle the spinner anemometer will always be able to provide a clear indication on when the yaw error is close to zero. This is because the wind speed measured by the individual sonic sensors should be constant during one rotation of the rotor (if the wind speed is constant) when the yaw error is zero as opposed to when there is a yaw error present, see Figure 3-2. Therefore, DNV GL expects that ROMO Wind always will have the possibility to adjust the yaw error of the turbine down to a level where the effect on the energy production will be very limited by means of trial and error. The uncertainty of the spinner anemometer will however affect the number of attempts ROMO will need to get the yaw angle within acceptable limits.

It should be noted that the above procedure for correcting a yaw error assumes that the yaw error is constant as a function of both wind speed and wind direction. ROMO Wind has presented measurements which indicate that a yaw error is constant as a function of the wind speed and DNV GL also expects this generally to be the case.

Whether yaw error will be a function of the wind direction may depend on the site conditions (topography). For a reasonably flat and uniform site DNV GL would not expect the yaw error to be a function of the wind direction. However, for a site with complex site topography, DNV GL proposes that this is evaluated.

Figure 3-2 Sonic sensor wind speed of sensor 1 for inflow angles to rotor axis α from 0° to 60° as function of inflow azimuth angle θ /1/



ROMO Wind uses a simple model to provide an indication of the expected increase of the energy production when a yaw misalignment is corrected, which is referred to by ROMO Wind as Cos^2. The formula for this simple model is:

$$P = 100\% * (1 - \cos(\theta)^2)$$

Where:

P: is the expected energy increase in %

θ : is the yaw misalignment

As far as DNV GL has been able to establish, this simple model provides a good indication of the increase in energy production when a yaw misalignment is corrected; see section 3.6.1 for this report for a detailed analysis.

3.5.2 Correction of yaw misalignment

ROMO Wind uses the spinner anemometer measurement to determine the yaw misalignment of the turbine and when a yaw misalignment above 2° is found, it is corrected either by entering a yaw offset in the turbine controller, if such functionality is available, or by adjustment of the turbine wind vane . ROMO Wind's preferable solution is use of the turbine controller.

After adjusting the yaw misalignment, this is checked and in cases where the yaw misalignment is still above 2°, a new adjustment is performed.

3.5.3 Relative power curve measurement

In exceptional cases and, as additional service, ROMO Wind offers quantification of the improvement of the energy production after the yaw misalignment correction based on a relative measurement of the turbine power curve using the spinner anemometer.

Relative power curve measurements are commonly used in the industry to detect changes in the performance of turbines using the nacelle anemometer to establish the wind speed. However, such relative power using the nacelle anemometer is subject to significant uncertainty.

ROMO has informed DNV GL that they will perform the relative power curve measurement meeting the requirements in the IEC61400-12-1 standard for power performance measurement of wind turbines with respect to data collection and data handling including meeting the requirements for a number of data samples. DNV GL finds this to be a suitable approach.

As discussed in Section 3.3.3 the uncertainty of the free wind speed measured by the ROMO spinner anemometer is, to some extent, unknown. However, as the measurement of the power curve is only used to establish the changes in energy production, the uncertainty in the wind speed measurement is of less significance compared to standard power verification measurements.

When evaluating the effect of uncertainty in a relative power curve measurement, there are two components of the measurement uncertainty, one which is assumed to be constant between the two power curve measurements (before and after correction of the yaw error) and a component which may change between the two measurements.

The part of the uncertainty which one can expect to be constant includes much of the uncertainty which relates to establishing the free wind speed using the spinner anemometer. DNV GL has assessed the effect of a constant uncertainty (error) in the free wind speed on the obtained changes in energy production by assuming a conservative estimate of this uncertainty (error). This shows that the uncertainty of the individual power curve (before and after correction of the yaw error) can be very high. However, the percentage-wise increase in production between the two power curves (before and after correction of yaw error) is not affected by this.

The part of the uncertainty which may change between the two measurements is related to changes in the conditions under which the two measurements are performed and, therefore, is very dependent on the site conditions. Assuming a relatively homogeneous site and relatively comparable weather conductions during the period of the two measurements, DNV GL would expect this to add an uncertainty on the estimated energy increase of less than ± 10 %.

In the document "Spinner anemometer for relative power curve measurements (Test site Overgaard, wtg #21)" /3/ ROMO Wind has assessed the uncertainty of the relative power curve measurement assessing the following error sources.

- Power measurement.
- Statistical variation of power measurements in each measurement bin.
- Uncertainty in the determination of the correction factors for the spinner anemometer K1 and K2. (The uncertainty on the wind speed measured by the spinner anemometer).

The assessment made by ROMO indicates that it should be possible to estimate/measure the obtained energy increase as a result of correction of a yaw error larger than 10° with an uncertainty of ± 8%. However, DNV GL considers that ROMO in their assessment has assumed that the uncertainty in the LiDAR wind measurement is cancelled out for the relative power curve measurement. DNV GL assesses that when taking LiDAR wind measurement uncertainty into account, the total uncertainty should be slightly increased.

All in all, DNV GL finds that it should be possible to use a relative power curve measurement to estimate the obtained energy increase with an uncertainty of less than ± 10% if:

- The requirements in the IEC61400-12-1 standard for power performance measurements of wind turbines with respect to data collection and data handling including meeting the requirements for number of data samples;
- The percentage-wise increased production between the two power curves (before and after correction of yaw error) is multiplied by the actual energy production of the turbine to get to the value of the increased production.
- The site is flat without significant obstacles or the influence of such obstacles is considered in the data processing;
- Weather conditions during the period of the two measurements comparable.

3.5.4 Track record

By 23rd December 2014, ROMO Wind had used the spinner anemometer to measure and, where necessary, correct yaw misalignment on 152 turbines on 23 different turbine models from seven different turbine manufacturers. Some of the turbine models are very closely related models so that the 23 turbine models are from 15 different turbine platforms.

The results of the measurement of yaw misalignment are shown in Table 3-1.

Table 3-1 Persistent yaw misalignment

No. Measured	Persistent yaw misalignment										
	<2°	2-4°	4-6°	6-8°	8-10°	10-12°	12-14°	14-16°	16-18°	18-20°	Over 20°
152	25	34	22	22	17	12	10	7	2	0	1
	16%	22%	14%	14%	11%	8%	7%	2%	1%	0%	1%

ROMO Wind has completed the correction of the yaw misalignment on a total of 73 turbines. In 62 % of the cases the yaw misalignment was corrected to a yaw misalignment below 2° with the first attempt, 30 % needed two adjustments to get the yaw misalignment below 2° and for the remaining 8 % three adjustments were needed.

According to ROMO Wind, the average possible improvement in energy due to the correction of the yaw misalignment from the 152 turbines if corrected will be approximately 2% using the simple model of $\cos^2$.

3.5.5 Results from the Vedersø Kær wind farm

On the Vedersø Kær wind farm in Denmark, both DTU and ROMO Wind have analysed the data from the mounted spinner anemometers. The Vedersø Kær wind farm consists of 10 NM64C/1500 wind turbines and the spinner anemometer was installed on 9 out of the 10 turbines as the last turbine is owned by a different entity.

The results of the DTU Wind Energy analyses are documented in the Improvement of Wind Farm Performance by Means of Spinner Anemometry report /6/.

The calibration of spinner anemometer turbine type specific constants K1 and K2 was conducted on turbine no. 3 using a Windlris LiDAR.

After installation of the spinner anemometers, ROMO Wind and DTU analysed the yaw misalignment of the individual turbines; ROMO wind adjusted the yaw misalignment by adjusting the wind vanes on the turbines and measured the power curve with the spinner anemometer before and after adjustments of the yaw errors.

Table 3-3 Vedersø Kær wind farm yaw misalignment

Turbine	yaw misalignment before adjustment [°] By ROMO Wind	yaw misalignment before adjustment [°] By DTU	yaw misalignment after adjustment [°] By ROMO Wind	Energy increase by ROMO Wind [2] Relative measured power curve [%]	Energy increase by ROMO Wind simple model Cos^2 [%]
Vedersø Kær #1	4.8	4.6	0	2.6	0.7
Vedersø Kær #2	1.6	1.4	0.8	0.5	0.1
Vedersø Kær #3	7.2	6.4	2.2	2.2	1.5
Vedersø Kær #4	8.2	7.7	0.6	3.7	2.1
Vedersø Kær #6[1]	(30.5) 9.7	(28.9) 9.7	-0.2	3.9	2.9 [1]
Vedersø Kær #7	9.2	8.7	-0.4	3.0	2.6
Vedersø Kær #8	7.5	7.2	0.3	3.7	1.7
Vedersø Kær #9	6.8	6.7	-0.6	3.8	1.4
Vedersø Kær #10	1.8	1.8	1	-0.8	0.7
Average				2.5	1.5

1. At turbine number 6 the yaw misalignment was corrected to 9.7° before the energy increase was measured.
2. Energy increase by ROMO Wind based on the measured power curve with the spinner anemometer before and after adjustments of the yaw errors

The table above shows that there are deviations between the yaw misalignment found by ROMO Wind and DTU are alike. This provides some confidence in ROMO Wind's ability to analyse the data from the spinner anemometer.

Vattenfall, the owner of the 9 Vedersø Kær turbines, also made a separate measurement with their SCADA system. They measured the energy of the wind farm in a period before wind vane adjustment and in another period after wind vane adjustment. They normalized the energy production with turbine number 2, which only had a yaw error of 1.6° or 1.4° and limited adjustment of the wind vane. They found an average increase of AEP (annual energy production) of 2.6% for the wind farm. It should be noted that DNV GL have not had the opportunity to review the method used by Vattenfall to compare the energy production before and after the wind vane adjustments. However, the use of normalizing energy production to a reference turbine is a known method in the industry.

Comparing the increase in energy production due to the correction of yaw misalignment estimated using the three different methods, the simple model (cos^2), the relative power curve measurement and the normalized energy production indicates that the simple model ($\cos^2$) underestimated the increase in energy production.

3.6 DNV GL reflection on the effect of yaw error correction on energy production

3.6.1 Correction of a yaw error and increase in energy production

ROMO Wind claims that one should expect an increase in energy production from 1% to 5% by using the spinner anemometer to correct any yaw error.

DNV GL has performed calculations of the expected increase in energy production using a generic model of a 2.0 MW pitch regulated variable speed wind turbine and the Bladed turbine simulation software. The results are shown in Table 3-4.

Table 3-4 Energy production increase in %

Mean wind speed at site[1] (m/s)	Yaw error corrected to 0°										
	-20°	-16°	-12°	-8°	-4°	0°	4°	8°	12°	16°	20°
6	13	8	5	2	0.4	0	0.4	2	5	8	13
7	11	7	4	2	0.4	0	0.4	2	4	7	11
8	10	6	3	1	0.3	0	0.3	1	3	6	10

1. The site wind distribution used is a Weibull distribution with a shape factor of 2.

To perform such a calculation, a number of assumptions on the site conditions need to be made. For this calculation, DNV GL has made the following assumptions which should reflect a wind farm located on a relative flat site in northern Europe.

- Turbulence class between IEC class A and B;
- Turbulence model Kaimal;
- Air density 1.225 kg/m^3 ;
- Wind inflow angle 0°;
- Wind shear 0.2.

As can be seen from Table 3-4 the simulation performed by DNV GL shows that one should expect to improve the energy production by around 5% but that

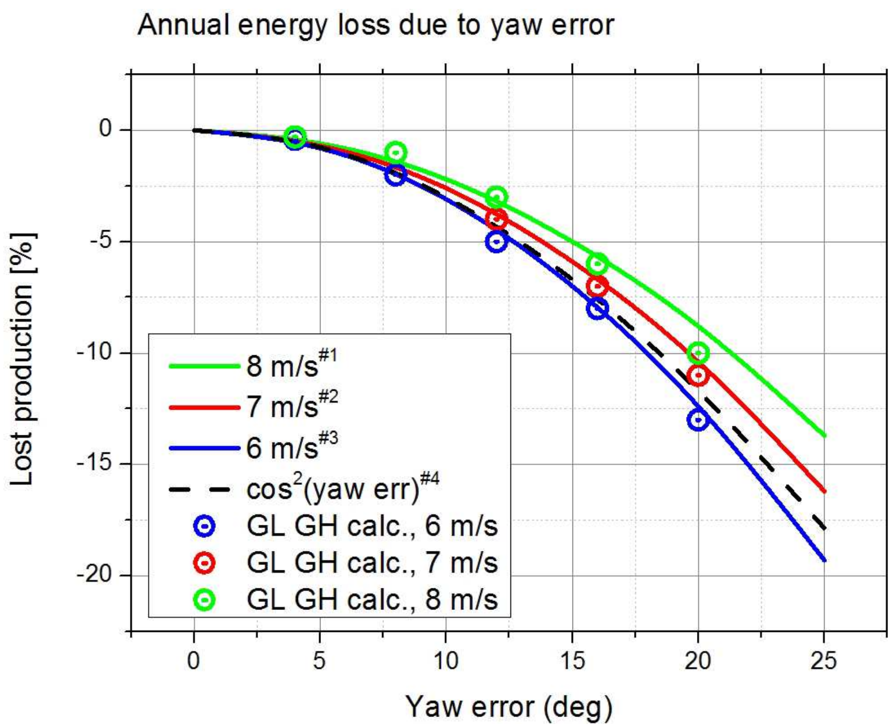
- yaw errors of less than 4° have very limited influence the energy production of a wind turbine;
- correction of a yaw errors of from 8° to 12° to less than 4° will increase the energy production by up to 5%;
- correction of a yaw error of 16° or more to less than 4° will increase the energy production by more than 7%.

It should be noted that the data presented above are based on a theoretical calculation using a generic turbine model and any theoretical calculation should be supported by field experience. There may also be differences depending on the turbine type in question.

The simulation performed by DNV GL support the expectation of a production increase from 1 to 5% by correction of a significant yaw error of more than 8° to a level below 4° and for extreme yaw errors the increase in energy production may be higher.

The calculations by DNV GL shown in Table 3-4 are consistent with the calculations done by ROMO Wind using a much simpler model (Cos^2) /3/, except for extreme yaw errors, where the DNV GL calculations show a higher loss of energy than the simple model; see Figure 3-3.

Figure 3-3 Energy loss as function of the yaw error



1. Calculation performed by ROMO based on the reduction of the projected rotor area using power curves from three different turbine types for a site with a mean wind speed of 8 m/s /3/.
2. Calculation performed by ROMO based on the reduction of the projected rotor area using power curves from three different turbine types for a site with a mean wind speed of 7 m/s /3/.
3. Calculation performed by ROMO based on the reduction of the projected rotor area using power curves from three different turbine types for a site with a mean wind speed of 6 m/s /3/.
4. Calculation performed by ROMO simple model /3/

3.6.2 DNV GL Experience of energy losses resulting from yaw error

The objective of this section is to present DNV GL's experience of the magnitude and probability of energy loss resulting from persistent yaw error on a wind farm project. The following topics will be discussed:

- Definition of types of yaw error;
- Case study of persistent yaw error from wind sensor misalignment;
- Probability of persistent yaw error and resulting energy loss.

3.6.2.1 Definition of yaw error

There are two main types of yaw error:

1. Normal operational yaw error;
2. Persistent yaw error.

These types of error are described below:

Normal operational yaw error

A turbine operating under normal wind conditions will produce power for a large proportion of the time with a certain degree of yaw error. This yaw error is due to the natural turbulence in the wind and hysteresis programmed into the controller. The turbine cannot practically operate all the time with the rotor directly perpendicular to the wind direction as this would quickly wear out mechanical components. This can be considered 'normal operational yaw error' and will occur regardless of the accuracy of alignment of the wind sensor.

Energy losses resulting from this 'normal operational yaw error' can be considered inherent in the turbine manufacturer's sales power curve which is backed up by field measurements and is suitable for a given site turbulence intensity.

Persistent yaw error

Persistent yaw error is where the turbine is consistently operating with a yaw error bias in orientation. In DNV GL's experience this is most often caused by a misaligned wind direction sensor. The wind direction sensor is in a fixed position that is misaligned with the centre-line of the drive-train of the turbine. This can occur at the commissioning stage of operation or can happen when the fastening mechanism is broken. DNV GL will typically identify large yaw error through analysis of SCADA data. The following section describes a case study where persistent yaw error was identified and energy losses quantified.

Case Study: Wind Farm revenue losses due to persistent yaw error resulting from wind sensor misalignment

The following is a case study on a multi-MW UK wind farm.

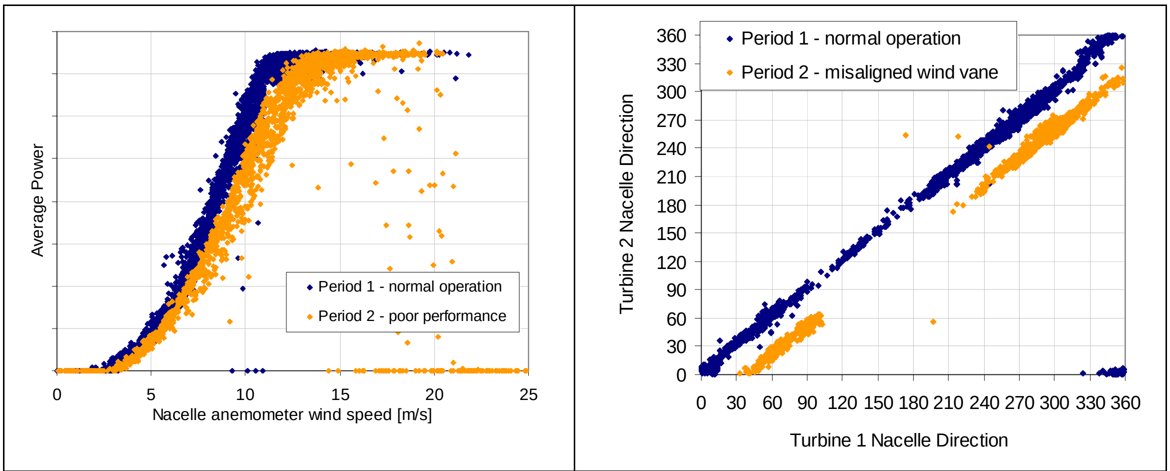
Initial SCADA analysis identified a degraded power curve at several turbines as shown by the plot in Figure 3-4 (a). The turbine initially operated with the power curve shown in blue, but after a period of time the power curve quality took a rapid downward step to the trend shown in orange.

Further investigation showed a change in turbine orientation relative to its neighbour as shown in Figure 3-4 (b). The time periods highlighted in the figure are the same as those highlighted in Figure 3-4 (a).

The root cause was identified as a simple misalignment of the wind vane that controls the orientation of the turbine. Whilst the operating technicians had successfully identified the wind vane misalignment, existing maintenance procedures were neither regular nor accurate enough to prevent this issue from recurring.

This off-axis operation persisted for many months, resulting in production losses as high as 20 % at some turbines. An additional concern is associated with the loads experienced by the structure whilst operating off-axis.

Figure 3-4 Rotor misalignment; effect and diagnosis



(a)	(b)

In this case DNV GL estimated that over £150k of annual revenue that would have otherwise been lost is now received as a direct result of the improved wind vane monitoring and maintenance procedures. An additional benefit is the prevention of excessive loading caused by persistent off-axis operation.

3.6.2.2 Probability of persistent yaw error and resulting energy loss

The case study described in the Section above is considered non-typical in terms of magnitude of energy losses. DNV GL observes measurable persistent yaw error on a minority of projects. However, DNV GL also acknowledges that the analyses of yaw misalignment based on SCADA data analyses as described in the case study above have the following limitations:

- It is not suitable for detection of minor yaw misalignment (less than 8°);
- The approach assumes that the turbines are installed without significant yaw misalignment;
- There needs to be sufficient time (months) where the turbine has been operating both with and without yaw misalignment before yaw misalignment can be detected.

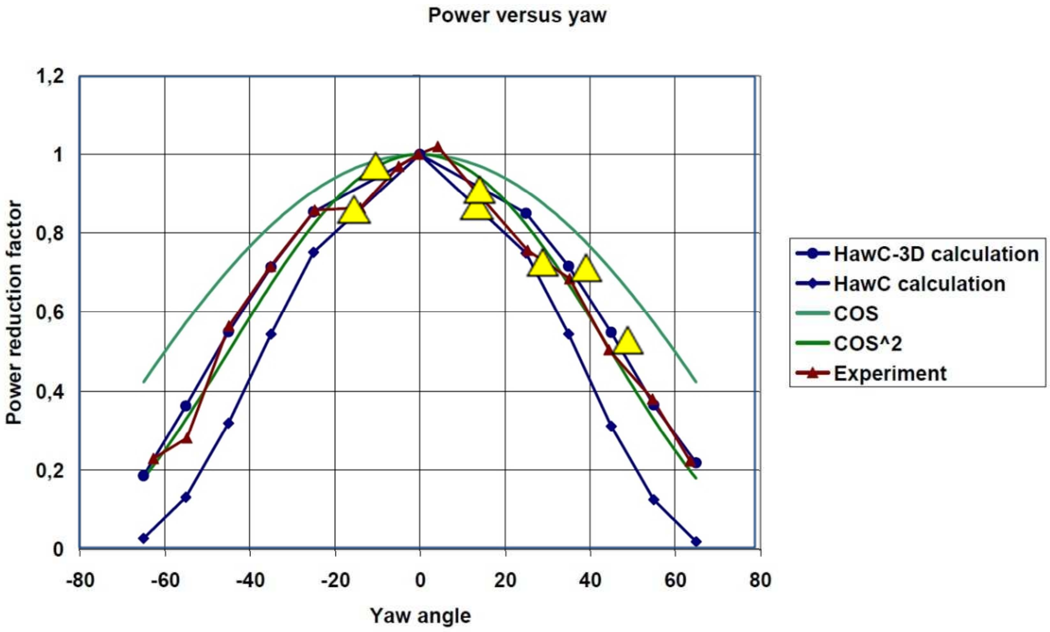
It should be noted that ROMO has advised DNV GL that according to their experience persistent yaw error is common. DNV GL finds that the difference in the experience between ROMO and DNV GL on the frequency of persistent yaw error may be caused by a difference in the attention and focus to both installation and operation of the turbines between the DNV GL clients and the ROMO clients and the difference in methods used by DNV GL to assess yaw misalignment.

Figure 3-5 illustrates the impact of persistent yaw error on power production. The plot shows research carried out by Risø Laboratory. The plot shows theoretical and measured power losses resulting from yawing a turbine persistently out of the wind flow. The yellow triangles illustrate observations made by

DNV GL for MW-scale turbines. These observations have been made during the monitoring and analysis of wind farm projects in Europe. The observations largely validate the earlier research, in particular the 'Experiment' shown by the red series, which is where a 75 kW turbine was actively run with a known yaw error and the resulting power loss observed for a constant wind speed range of 8-9 m/s.

It should be noted that this chart shows power losses for a single wind speed range; when the whole wind speed range is considered, along with the distribution of frequency of occurrence, the actual losses estimated will be smaller.

Figure 3-5 Research results showing the measured and theoretical power losses from persistent yaw error /4/. Yellow triangles show yaw error observations for MW-scale turbines by DNV GL.



3.7 Other applications of the iSpin

The data from a spinner anemometer measurement provide information on a number of parameters which DNV GL expects can be used to optimise the operation of the turbine and provide verification of the individual turbine performances. However, the value of this is very dependent on the accuracy of the spinner anemometer measurement.

ROMO Wind is currently in the process of validating the spinner anemometer measurement on a wind farm in Demark where a number of turbines are equipped with a spinner anemometer and the calibration is performed using a LiDAR technology. A meteorological mast with mounting arrangements according to IEC 61200-12-1, located upwind of one of the turbines is to be used to verify the spinner anemometer measurement.

DNV GL expects that this test will provide information which would allow for an evaluation of to what extent spinner anemometer measurement can be used for purposes other than correcting yaw misalignment and it should also provide a significant improvement in the verification of ROMO Wind's method of correcting yaw misalignment.

DNV GL finds that the spinner anemometer measurement may be of interest for the following areas.

Dynamic yaw misalignment

The spinner anemometer measurement provide information on the dynamic yaw misalignment (Normal operational yaw error) and DNV GL finds that such information can be used to indicate whether the yaw operating strategy implemented in the turbine control system is optimal for the operating conditions for the given turbine. Such information would be valuable in the process of optimising the energy production. However, changing the yaw operating strategy implemented in the turbine control system will require the cooperation of the turbine manufacture.

Overview of the site conditions

The spinner anemometer measurement should be capable of providing the following information on the wind conditions which the turbine is subject to:

- Wind speed distribution
- Wind direction distribution
- Inflow angle
- Turbulence Intensity
- Air density

Then one would only need to estimate the wind shear to have all the parameters defining the site conditions according to IEC 64100-1 and having the information on what wind conditions a turbine has been subject to would allow for an estimation of the remaining life of the turbine.

Power curve verification

If the uncertainty of spinner anemometer measurement can be sufficiently low the spinner anemometer can be used for power curve verification. This is yet to be demonstrated.

4 CONCLUSIONS

The technology of the spinner anemometer was originally invented and developed at the Department of Wind Energy (formerly Risø) of the Technical University of Denmark (DTU) and the spinner anemometer marketed by ROMO is, to a very large extent, based on the work performed Risø DTU. DNV GL has reviewed some of the work performed by Risø DTU and as expected finds that the technology of the spinner anemometer is based on sound theoretical analyses and practical testing.

DNV GL finds that by installation of the spinner anemometer it should be possible to correct a significant yaw misalignment to a level where it can be considered as acceptable, leading to an increase in the energy production. It should be noted that DNV GL has not compared the correction of a yaw misalignment by use of the spinner anemometer with other technique to correct yaw errors.

The operating experience with the spinner anemometer is limited and it is therefore difficult to conclude around the expected reliability. However, DNV GL finds that ROMO is doing what it can to ensure high reliability and DNV GL has no indication of issues which may lead to technical problems with the spinner anemometer.

ROMO Wind has used the spinner anemometer to measure and correct yaw misalignment on 152 turbines of which 93 (61%) needed correction of the yaw misalignment. According to ROMO Wind, the average possible improvement in energy due to the correction of the yaw misalignment from the 152 turbines if corrected will be approximately 2% using the simple model of $\cos^2$.

DNV GL observes measurable persistent yaw misalignment on a minority of projects. DNV GL finds that the difference in the experience between ROMO Wind and DNV GL may be due to a difference in the type of clients serviced by ROMO Wind and DNV GL. However, DNV GL also acknowledges that the analysis of yaw misalignment based on SCADA data analyses used by DNV GL has limitations.

ROMO uses a relative power curve measurement based on the wind speed from the spinner anemometer before and after correction of a yaw misalignment to establish the associated increase in energy production. However, the uncertainty of the free wind speed measured by the ROMO spinner anemometer is to some extent unknown. Therefore, the results of a relative power curve measurement will also have some level of unknown uncertainty. An estimation of the increase in energy production obtained by the correction of the yaw misalignment based on the relative power curve measurement may also have an unknown uncertainty depending on how this calculation is performed. However, DNV GL expects that it should be possible to use a relative power curve measurement to estimate the energy increase obtained with a uncertainty of less than ± 10% if the following are implemented:

- The requirements in the IEC61400-12-1 standard for power performance measurements of wind turbines with respect to data collection and data handling including meeting the requirements for number of data samples in;
- The site is flat without significant obstacles or the influence of such obstacles is considered in the data processing.
- Weather conditions during the period of the two measurements are comparable.

DNV GL has pefomed theoretical calculations of the energy lost due to yaw error and therefore the potential energy increase due to the correction of the yaw error. The calculations are generally consistent with the calculations done by ROMO Wind using a much simpler model $\cos^2$, except for extreme yaw misalignment, where the DNV GL calculations show a higher loss of energy than the simple model. Results from the Vedersø Kær wind farm, following evaluation of the relative power curve measurement and a normalized energy production comparison with a reference turbine, show that the average energy increase is larger than the one cacaluted using the simple model $\cos^2$.

DNV GL also notes that there is a number of opportunities to use the data from a spinner anemometer for other wind farm applications, provided the uncertainty associated with measurements from the iSpin decreases and becomes well defined.

5 REFERENCES

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/4/ Pedersen, Risø National Laboratory, Research Article on Wind Turbine Power Performance Measurements at Inclined Flow, Wind Energy. 2004; 7:163–176

/5/ DTU Wind Energy, Guide for the calibration of a Spinner anemometer for flow angle measurements, date June 2014.

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About DNV GL

Driven by our purpose of safeguarding life, property and the environment, DNV GL enables organizations to advance the safety and sustainability of their business. We provide classification and technical assurance along with software and independent expert advisory services to the maritime, oil and gas, and energy industries. We also provide certification services to customers across a wide range of industries. Operating in more than 100 countries, our 16,000 professionals are dedicated to helping our customers make the world safer, smarter and greener.