In: 2023 IEEE International Conference on Environment and Electrical Engineering and 2023 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), 6-9 June 2023, Madrid, Spain
DOI: 10.1109/EEEIC/ICPSEurope57605.2023.10194644

Experimental Analysis Of The Effect Of Static Yaw Error On Wind Turbine Nacelle Anemometer Measurements

Davide Astolfi
Department of Engineering
University of Perugia
Perugia, Italy
davide.astolfi.green@gmail.com

Linyue Gao
Department of Mechanical Engineering
University of Colorado
Denver, U.S.
linyue.gao@ucdenver.edu

Ravi Pandit
Centre for Life-Cycle Engineering and Management
Cranfield University
Bedford, U.K.
ravi.pandit@cranfield.ac.uk

Jiarong Hong
Mechanical Engineering & Saint Anthony Falls Laboratory
University of Minnesota
Minneapolis, U.S.
jhong@umn.edu

***Abstract*—The operation of wind turbines in real-world environments can be affected by the presence of systematic errors, which might diminish the Annual Energy Production up to 3-4%. Therefore, it is fundamental to leverage the availability of SCADA-collected measurements in order to formulate reliable diagnosis methods. The static yaw error of a wind turbine occurs when, due to wind vane or installation defects, the rotor plane is systematically not perpendicular to the wind flow. The present work is devoted to the experimental analysis of how the presence of a static yaw error affects the wind turbine nacelle anemometer measurements. Measurements collected at the Eolos Wind Research Station at the University of Minnesota are analyzed. The qualifying aspect is that a utility-scale wind turbine has been fully controlled and imposed to set to a non-vanishing yaw error. Furthermore, approximately two rotor diameters south of the turbine there is a meteorological tower which provides unbiased measurements of the environmental conditions. The main result of this work is that, for given wind speed measured by the meteorological mast anemometers, the measurements of the nacelle wind speed changes systematically in presence of the static yaw error. This aspect has up to now been overlooked in the literature. Therefore, the results of this work might stimulate a critical revision of the existing methods for static yaw error diagnosis and the formulation of new ones.**

***Index Terms*—Wind Energy, Wind Turbines, Measurement, Yaw Error, Anemometer, Instrumentation**

I. Introduction

Wind turbines are considered a leading technology for power generation from renewable sources [1], such that the European Commission has set a target that half of the electricity produced in Europe by 2050 should be produced from wind. Therefore, there is ever-growing attention towards the formulation of intelligent wind farm Operation & Maintenance strategies, in order to diminish energy losses and maximize the lifetime of the wind turbines. In this context, there is as well an ever-growing interest towards the optimization of the efficiency of real-world wind turbines in operation. This objective requires reliable methods for the individuation and the solution of systematic errors affecting wind turbine operation, such as blade pitch misalignment [2] and systematic yaw error [3].

The control system of a wind turbine operates to minimize the static yaw error, which means that the plane of the rotor should be perpendicular to the incoming wind. Therefore, in general, the yaw error is a dynamic quantity which could be conceived as a Gaussian variable which should have a vanishing mean. Mainly due to wind vane defects, it might happen that the yaw error has also a non-vanishing static component. This means that, when the control system indicates a correct alignment of the rotor, the rotor is not exactly perpendicular to the wind flow. If the static component of the yaw error is remarkable (in the order of more than $5°$), the effect on the energy production is non-negligible [4]. Actually, if the static yaw error is indicated with γ, the component of the wind intensity v which is really perpendicular to the rotor is $v \cos \gamma$. Since in a first approximation the extracted power P scales with the cube of the longitudinal wind intensity, a static yaw error γ affects the extracted power by a factor of $\cos \gamma^3$.

Based on the above considerations, there is attention in the scientific literature about the methods for individuating the static yaw error of wind turbines operating in field [5], [6]. The widespread diffusion of Supervisory Control And Data Acquisition (SCADA) measurements comes at hand because vast sets of data are available to the end user. Yet, the individuation of the static yaw error based on SCADA data analysis is cumbersome due to the fact that, according to the collected direction data mediated by the nacelle transfer function, the wind turbine is oriented correctly, while it is not. Therefore, the literature is devoted to the formulation of methods which are based on somehow indirect consequences of the static yaw error, as for example under-performance. For completeness, it should be cited that there are studies based on the use of upwind sensor systems like LiDAR or Spinner anemometers. The use of such sensors allows for circumventing the drawbacks of the SCADA-collected data, but their exploitation is costly against an uncertain outcome (the selected wind turbine might not have yaw error problems).

The motivation of this study is that important aspects of the influence of the static yaw error on the measurements collected by the affected wind turbine have been up to now overlooked. Furthermore, as argued in [7], for real-world test cases, there is a lack of labeled data, which means an established ground truth about the presence of a static yaw error. The aim of this work if filling the above gaps. The related work and the innovative contributions of this study are outlined in detail in the following Subsection I-A.

A. Related Work and Innovative Contribution

As argued above, most static yaw error diagnosis methods in the literature are based on the individuation of an under-performance. This substantially means analyzing the power curve [8], which is the relation between the incoming wind speed and the extracted power. In principle, the presence of the static yaw error should be detected from a slightly diminished extracted power for a given wind speed. In practice, detecting such effects is a complicated task due to the fact that the power extracted by wind turbines has a multivariate dependence on working parameters and environmental conditions. Therefore, non-trivial data analysis methods are required.

In [9], the power curve is analyzed through the binning method upon grouping the data per yaw error intervals of 2°. In [10], the employed power curve model is Least-Square B-spline Approximation upon (similarly to [9]) grouping the data per yaw error intervals. In [11], a more complex model is employed which takes as input also operation variables like rotor speed and blade pitch and the yaw error is detected from the residuals between measurements and model estimates. The work in [12] is particularly inspiring for the purposes of the present study. First of all, it is based on ground truth evidence provided by LiDAR measurements. Secondarily, critical results related to the use of SCADA data are obtained but not fully interpreted. Two methods for power curve analysis are employed. The former is the binning method and the latter is based on the rejection of outliers with respect to the nominal power curve. The former method is therefore based merely on the observed power curve (without processing) before and after the correction of the static yaw error. The comparison between those curves provides implausible results, i.e. a large overestimation of the impact of the yaw error on the power output. The work in [13] constitutes the premise of the present study. Actually, the authors of [13] had the possibility of fully controlling a wind turbine (Eolos Wind Research Station at the University of Minnesota), which is a 2.5 MW Clipper C96. The authors have forced the operation of the wind turbine subjected to several values of static yaw error, thus obtaining labeled data from which they could investigate phenomena highlighting the presence of the static yaw error. In particular, the employed method is a data-driven fit to a physical model of the power curve, inspired by the cosine cube law cited in Section I.

The present study is as well based on measurements collected at the Eolos Wind Research Station at the University of Minnesota, which therefore means labeled data. Actually, three data sets, with 0° and $\pm 10^\circ$ of static yaw error, are analyzed. The objective of this work is to analyze if the presence of the static yaw error has an influence on nacelle anemometer measurements. If the answer to this question is positive, as is supported by the results collected in this work and hinted in the work [14], this means that the detection methods based on the power curve analysis should be revised critically. Actually, when analyzing the power curve of a wind turbine, the implicit assumption is that the x-axis (i.e. the wind speed) is a fixed reference. Yet, it rather is a measurement and in particular, it is a measurement that might be influenced by the presence of the static yaw error, since it is collected behind the rotor span. The results collected in this work, therefore, stimulate a critical revision of the methods employed up to now and suggest a more in deep exploitation of the nacelle anemometer measurements for static yaw error detection. It should be noticed that this work has been made possible by the experimental setup (described in detail in Section II-A) which is unique in the literature, due to two matters of fact:

- The fact that the wind turbine can be fully controlled for research purposes leads to collected labeled data, about which the presence of a certain yaw error is ascertained;
- The presence of a meteorological tower, sited approximately two rotor diameters south of the wind turbines, guarantees that there are measurements of environmental conditions, which are not affected by the presence of the static yaw error on the target wind turbine.

The structure of the work is therefore the following. The experimental setup and the data analysis methods are described in Section II. The results are outlined in Section III and the conclusions are drawn in Section IV.

II. Materials And Methods

A. The Eolos Wind Research Station

The experimental facility is described in [15] and we refer to that study for further details. The station consists of a 2.5 MW upwind, 3-bladed, horizontal-axis wind turbine (Clipper Liberty C96) and a 130 meters meteorological tower, sited 170 meters south of the wind turbine. Four high-resolution sonic anemometers (Campbell Scientific, CSAT3) are sited on the tower at meaningful heights: rotor top tip (129 m), hub height (80 m), rotor bottom tip (30 m), and standard 10 m. Cup anemometers (Met One, 014-A) are installed 3 m below each sonic anemometer. The Eolos turbine is variable-speed, variable-pitch regulated, with a rotor diameter 96 m and a hub height of 80 m. The cut-in, rated and cut-out wind speeds are 4, 11 and 25 m/s. For the purposes of this work, Supervisory Control and Data Acquisition (SCADA) data collected with a sampling rate of 1 Hz have been analyzed. The scheme of the sensors arrangement is reported in Figure 1.

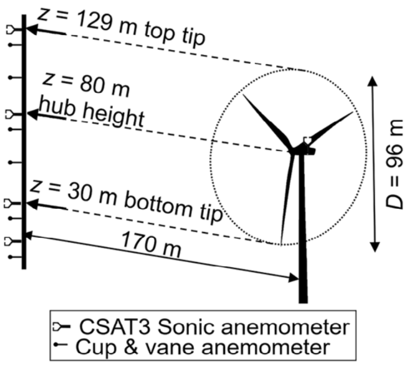

Fig. 1. The scheme of the sensors, adapted from [15].

The employed meteorological mast measurements are the following:

- v_s (m/s), wind speed measured by a sonic anemometer at the same height of the wind turbine hub (80 meters);
- v_c (m/s), wind speed measured by a cup anemometer placed three meters below the sonic one (i.e. 77 meters);
- $\theta_{up}(°)$ is the wind direction measured at the top tip of the blade (129 meters);
- $\theta(°)$ is wind direction measured at hub height;
- $\theta_{down}(°)$ is the wind direction measured at the rotor bottom tip (30 meters);

The employed SCADA-collected measurements are:

- v_n (m/s), wind speed measured by the nacelle anemometer;
- P (kW), which is the power output;
- ρ (kg/m^3), air density;
- turbine state.

The representation of the presence of a static yaw error is given in Figure 2.

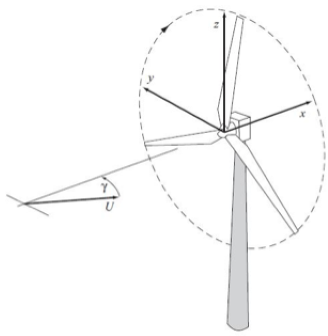

Fig. 2. Representation of a wind turbine operating subject to a static yaw error γ, adapted from [4].

B. Data sets and processing

The employed data sets are indicated in Table I. The sampling time is 1 second and the SCADA-collected data and the meteorological data are synchronized.

TABLE I
THE ANALYZED DATA SETS

Data Set	Yaw Error	Number of samples
D_0	0°	428127
D_{10}	10°	431972
D_{-10}	−10°	518328

The following pre-processing steps are applied:

- Data have been averaged with 10 seconds of averaging time (10 records);
- Request that the turbine state corresponds to turbine ok and running;
- Request that $90° \leq \theta \leq 270°$, in order to avoid the meteorological mast being under the wake of the wind turbine;
- Renormalize all the measurements of wind speed according to
$$v_r = v\left(\frac{\rho}{\rho_{ref}}\right)^{\frac{1}{3}}, \quad (1)$$
where $\rho_{ref} = 1.225$ kg/m^3.
- Request that
$$\Gamma = \frac{|\theta_1 - \theta_3|}{R} < 0.2°/\text{m}. \quad (2)$$

Equation 1 is a common practice in order to renormalize the wind speed, referring to standard air density conditions. The rationale of the filtering in Equation 2 is selecting data with a comparable amount of wind veer [16], which is requested to be low enough to neglect the influence of such factor on rotor rotation and turbine behavior.

C. Methods

The first wind speed analysis method is based on visualizing the relation between v_n (target) and v_s and v_c (references) and inquiring how this changes for the three data sets. In order to make the comparison quantitative, a linear relation is posed in Equations 3 and 4:

$$v_n = k_1 v_s; \quad (3)$$

$$v_n = k_2 v_c. \quad (4)$$

The behavior of k_1 and k_2 as a function of the static yaw error is analyzed.

Furthermore, the power curve is analyzed using the binning method. Power data are averaged per wind speed intervals of 0.5 m/s. The nacelle wind speed v_n and the meteorological tower v_s are respectively put in the x-axis, in order to compare how the observed power curves change. The performance difference between a target data set (D_{10} or D_{-10}) and D_0 is quantified as follows.

- First, weight the observed frequency w_i per wind speed bin of the D_0 data set against the observed average power for that bin P_i. The Equation is:
$$P_{tot} = \sum_i P_i \cdot w_i, \quad (5)$$

- Compute the indicator of the performance which would be achieved if, with the frequencies, w_i of the D_0 data set, the wind turbine had behaved as in the $D_{\pm 10}$ data set. This means substituting P_i in Equation 5 with the average power for the corresponding bin in the $D_{\pm 10}$ data set ($P_{i,\pm 10}$), as in Equation 6:

$$P_{tot,\pm 10} = \sum_i P_{i,\pm 10} \cdot w_i, \tag{6}$$

- The average percentage performance difference between the target and reference case is estimated as:

$$\Delta_{\pm 10} = 100 \left(\frac{P_{tot}}{P_{tot,\pm 10}} - 1 \right). \tag{7}$$

III. Results

The results of the wind speed analysis are visualized in Figures 3 and 4. When the yaw error is $+10°$, the wind speed measured by the nacelle anemometer is systematically higher than that measured by the meteorological mast sonic anemometer. The effect is less pronounced for the case $-10°$. The difference between the $+10°$ and $-10°$ indicates that the results depend on the relation between the yaw error and the rotor sense of rotation. In general, the takeaway message from Figures 3 and 4 is that the nacelle wind speed measurements are influenced by the presence of the yaw error. With the type of data at disposal, it is impossible to argue within what limit this is a matter of unreliable nacelle transfer function in yawed conditions or of flow acceleration in the proximity of the nacelle anemometer, which is induced by the rotor rotation. In general, this aspect has up to now been overlooked in the literature about the static yaw error.

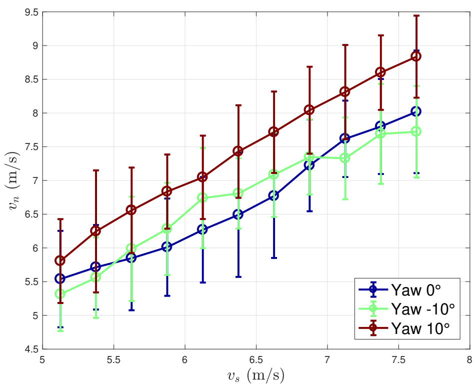

Fig. 3. The average nacelle anemometer wind speed (v_n) per meteorological tower sonic anemometer wind speed (v_s) intervals of 0.25 m/s. Bins with more than 50 measurements are kept.

In Tables II and III, the results for the linear regression between v_s (respectively v_c) and v_n are reported for the various cases. It results that the coefficients largely increase in the $+10°$ case with respect to the $0°$, while they decrease very slightly in the opposite case $-10°$. Although basic aerodynamic principles suggest that symmetrical static yaw errors ($\pm 10°$) should have an equal effect on wind turbine performance, in reality, this is not the case. The rotation of the rotor exacerbates (or reduces) the impact of flow acceleration in the vicinity of the nacelle anemometer, resulting in asymmetrical effects.

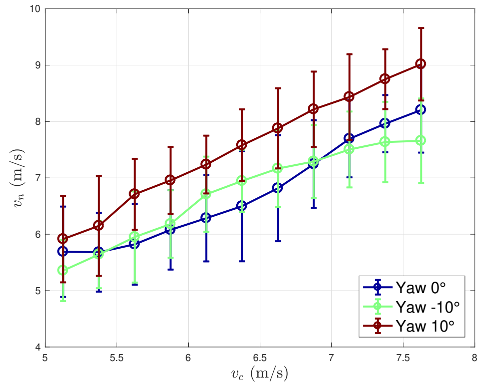

Fig. 4. The average nacelle anemometer wind speed (v_n) per meteorological tower cup anemometer wind speed (v_c) intervals of 0.25 m/s. Bins with more than 50 measurements are kept.

TABLE II
The results for k_1

Data Set	k_1
D_0	1.06
D_{10}	1.14
D_{-10}	1.02

TABLE III
The results for k_2

Data Set	k_2
D_0	1.05
D_{10}	1.15
D_{-10}	1.02

The power curves obtained using the nacelle anemometer are reported in Figure 5. A situation similar to the study in [12] arises. In the case with $10°$ of static yaw error, the power curve appears largely under-performing, while in the case $-10°$ the power curve is comparable with the $0°$ case and this is not consistent. This means that the results of [12] about the power curve analysis, as well as those here collected for the $10°$ case, might be explained by the hypothesis that the nacelle wind speed measurement is biased (overestimated) in presence of the static yaw error and this leads to exaggerating the apparent effect of the yaw error on the power curve. When comparing the performance of a wind turbine in the presence or absence of static yaw error, it is important to use a reference that is not influenced by the error. For example, meteorological mast measurements can provide an unbiased reference of the environmental conditions, enabling a more accurate comparison of wind turbine performance. Nevertheless, the power curve reported in Figure 6 shows that it is any case complicated to use as a reference for wind turbine performance analysis a wind speed measured around two rotor diameters far from the rotor.

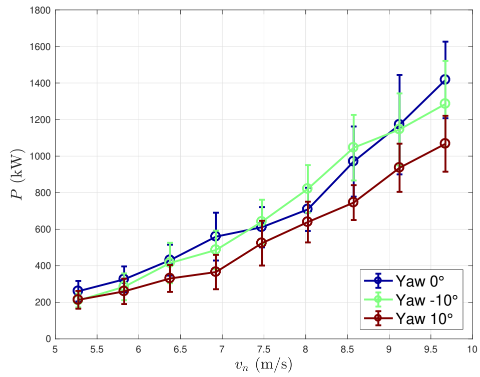

Fig. 5. The average power curve for D_0, D_{10} and D_{-10}. The nacelle wind speed v_n is used as a reference in the x-axis. Bins with more than 50 measurements are kept.

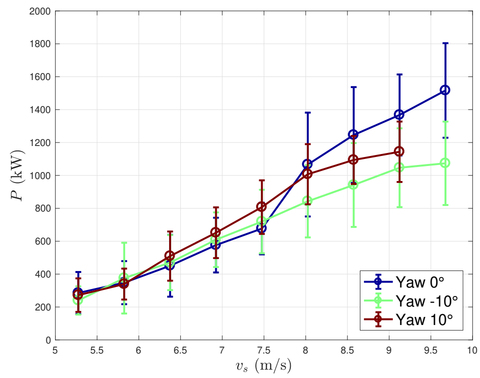

Fig. 6. The average power curve for D_0, D_{10} and D_{-10}. The meteorological mast sonic anemometer wind speed v_s is used as a reference in the x-axis. Bins with more than 50 measurements are kept.

The results in Table IV indicate that the assumption that v_n is unbiased by the presence of static yaw error is implausible. For example, a static yaw error of $10°$ is estimated to cause an average performance improvement of +1.7% compared to the 0 degree case, which is unlikely. Similarly, the estimated average performance decrease of -20.2% for the $-10°$ degree case is also unrealistic. While there are some critical points in our analysis due to the distance between the meteorological tower and the turbine, the results obtained with v_s are more consistent. Specifically, both positive and negative static yaw errors result in a significant decrease in turbine performance. However, additional data sets are needed to obtain more accurate performance analyses using v_s.

IV. Conclusions

The main focus of our work is to investigate how the presence of a static yaw error affects the measurements of the nacelle anemometer of a wind turbine. As we highlighted in Section I, a comprehensive analysis of this aspect is essential for gaining a deeper understanding of the effects of the yaw

TABLE IV
THE RESULTS FOR Δ

Wind Speed	Δ_{10}	Δ_{-10}
v_n	-20.2%	+1.7%
v_s	-13.4%	-7.2%

error, and for identifying its presence. This aspect has largely been overlooked in the literature to date, underscoring the importance of our research in shedding new light on the effects of the static yaw error on wind turbine performance.

Our experimental setup is unique in the literature, as we have access to a fully controlled, utility-scale wind turbine located at the Eolos Wind Research Station at the University of Minnesota. Furthermore, a meteorological mast situated approximately two rotor diameters south of the turbine provides accurate and unbiased measurements of the environmental conditions. This configuration allows us to have the two critical ingredients that have been lacking in previous studies:

- labeled data, for which the presence of the static yaw error is ascertained;
- a measurement chain for environmental conditions that is entirely immune to the effects of the static yaw error.

The results of our study, presented in Section III, clearly demonstrate that the presence of static yaw error, specifically $\pm 10°$, impacts the relationship between wind speed measured at the meteorological mast and that measured by the nacelle anemometer. The extent of the effect is likely influenced by the interaction between the yaw error and rotor rotation. In light of these findings, it is inappropriate to use the wind turbine power curve alone to diagnose the static yaw error without considering the potential influence on nacelle wind speed measurements. Our analysis shows that the power curve inferred from the nacelle wind speed measurements for both $\pm 10°$ cases is inconsistent. Specifically, the $10°$ case shows an unrealistic average performance degradation of -20%, likely due to an overestimate of nacelle wind speed. These findings are discussed in detail in Section III

The limitations of nacelle wind speed measurements due to their collection behind the rotor span are well documented in the literature. [17]. Nevertheless, the results of this paper shed light that the fact that the wind turbine nacelle anemometer is sited behind the rotor can be leveraged in order to detect the static yaw error. The phenomenon to be addressed would be a change in how the wind turbine measures the wind speed, relative to a reference, which can be more conveniently be a meteorological mast but in principle can be also a nearby wind turbine. If two nacelle anemometers are installed, flow equilibrium considerations might be employed, as is done in [14]. Furthermore, the results of this work not only highlight the importance of considering the impact of the static yaw error on wind turbine performance, but also provide a starting point for further research into other effects of the error, such as increased tower vibrations or uneven blade loading. In general, the results of this work should be taken into account for future developments in data-driven wind turbine condition monitoring [18], [19].

References

[1] Q. Wang, Z. Dong, R. Li, and L. Wang, "Renewable energy and economic growth: New insight from country risks," *Energy*, vol. 238, p. 122018, 2022.

[2] U. Elosegui, I. Egana, A. Ulazia, and G. Ibarra-Berastegi, "Pitch angle misalignment correction based on benchmarking and laser scanner measurement in wind farms," *Energies*, vol. 11, no. 12, p. 3357, 2018.

[3] D. Astolfi, R. Pandit, A. Lombardi, and L. Terzi, "Diagnosis of wind turbine systematic yaw error through nacelle anemometer measurement analysis," *Sustainable Energy, Grids and Networks*, vol. 34, p. 101071, 2023.

[4] D. Astolfi, F. Castellani, M. Becchetti, A. Lombardi, and L. Terzi, "Wind turbine systematic yaw error: Operation data analysis techniques for detecting it and assessing its performance impact," *Energies*, vol. 13, no. 9, p. 2351, 2020.

[5] Y. Pei, Z. Qian, B. Jing, D. Kang, and L. Zhang, "Data-driven method for wind turbine yaw angle sensor zero-point shifting fault detection," *Energies*, vol. 11, no. 3, p. 553, 2018.

[6] J. Yang, L. Wang, D. Song, C. Huang, L. Huang, and J. Wang, "Incorporating environmental impacts into zero-point shifting diagnosis of wind turbines yaw angle," *Energy*, vol. 238, p. 121762, 2022.

[7] D. Astolfi, R. Pandit, L. Gao, and J. Hong, "Individuation of wind turbine systematic yaw error through scada data," *Energies*, vol. 15, no. 21, p. 8165, 2022.

[8] Y. Wang, Q. Hu, L. Li, A. M. Foley, and D. Srinivasan, "Approaches to wind power curve modeling: A review and discussion," *Renewable and Sustainable Energy Reviews*, vol. 116, p. 109422, 2019.

[9] B. Jing, Z. Qian, Y. Pei, L. Zhang, and T. Yang, "Improving wind turbine efficiency through detection and calibration of yaw misalignment," *Renewable Energy*, vol. 160, pp. 1217–1227, 2020.

[10] Y. Bao and Q. Yang, "A data-mining compensation approach for yaw misalignment on wind turbine," *IEEE Transactions on Industrial Informatics*, vol. 17, no. 12, pp. 8154–8164, 2021.

[11] R. Pandit, D. Infield, and T. Dodwell, "Operational variables for improving industrial wind turbine yaw misalignment early fault detection capabilities using data-driven techniques," *IEEE Transactions on Instrumentation and Measurement*, vol. 70, pp. 1–8, 2021.

[12] C. Qu, Z. Lin, P. Chen, J. Liu, Z. Chen, and Z. Xie, "An improved data-driven methodology and field-test verification of yaw misalignment calibration on wind turbines," *Energy Conversion and Management*, vol. 266, p. 115786, 2022.

[13] L. Gao and J. Hong, "Data-driven yaw misalignment correction for utility-scale wind turbines," *Journal of Renewable and Sustainable Energy*, vol. 13, no. 6, p. 063302, 2021.

[14] N. Mittelmeier and M. Kühn, "Determination of optimal wind turbine alignment into the wind and detection of alignment changes with scada data," *Wind Energy Science*, vol. 3, no. 1, pp. 395–408, 2018.

[15] L. Gao, S. Yang, A. Abraham, and J. Hong, "Effects of inflow turbulence on structural response of wind turbine blades," *Journal of wind engineering and industrial aerodynamics*, vol. 199, p. 104137, 2020.

[16] L. Gao, B. Li, and J. Hong, "Effect of wind veer on wind turbine power generation," *Physics of Fluids*, vol. 33, no. 1, p. 015101, 2021.

[17] D. Astolfi, G. Malgaroli, F. Spertino, A. Amato, A. Lombardi, and L. Terzi, "Long term wind turbine performance analysis through scada data: A case study," in *2021 IEEE 6th International Forum on Research and Technology for Society and Industry (RTSI)*. IEEE, 2021, pp. 7–12.

[18] D. Astolfi, F. De Caro, and A. Vaccaro, "Condition monitoring of wind turbine systems by explainable artificial intelligence techniques," *Sensors*, vol. 23, no. 12, p. 5376, 2023.

[19] X. Chesterman, T. Verstraeten, P.-J. Daems, A. Nowé, and J. Helsen, "Overview of normal behavior modeling approaches for scada-based wind turbine condition monitoring demonstrated on data from operational wind farms," *Wind Energy Science*, vol. 8, no. 6, pp. 893–924, 2023.

2023-08-03

Experimental analysis of the effect of static yaw error on wind turbine nacelle anemometer measurements

Astolfi, Davide

IEEE

Astolfi D, Gao L, Pandit Ravi, Hong J. (2023) Experimental analysis of the effect of static yaw error on wind turbine nacelle anemometer measurements. In: 2023 IEEE International Conference on Environment and Electrical Engineering and 2023 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), 6-9 June 2023, Madrid, Spain

https://doi.org/10.1109/EEEIC/ICPSEurope57605.2023.10194644