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A Comprehensive Methodology Based on SCADA Data Analysis for Diagnosing Static Errors Affecting Wind Turbine Performance

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Abstract – **One of the most important root causes of non-optimal efficiency in the conversion of wind kinetic energy into electricity is represented by static errors affecting wind turbines. These can simply involve sensors (like the anemometers) or might deal with the set up of the rotor (as when the three blades do not have the same pitch reference). Based on such premise, in this work, a comprehensive framework is proposed for diagnosing static errors affecting wind turbine performance, based on SCADA data analysis. The three types of considered static errors are: static yaw error; absolute or relative blade pitch misalignment; anemometer bias. It is desirable to exploit as much as possible the SCADA-collected data for diagnosing such types of static errors. Yet, given the mediation of the control system, the SCADA data might even be misleading and, for example, might indicate a correct alignment of the rotor to the wind flow, while it is not correct. Hence, the objective of the work is identifying phenomena observable through SCADA data which can be related to such static errors. Acknowledged that some manifestations can be similar for the various errors, a work flow is set up for distinguishing between them. The selected phenomena are: under-performance, which is associated to all the errors; increased vibrations; shift in the nacelle anemometer measurements. Real-world test cases, namely wind farms operated by the ENGIE Italia company, are discussed. A combination of single wind turbine and fleet-wide methods is proposed. The latter involve dividing the fleet in potentially anomalous and normal wind turbines and modeling quantities of interest (like the power) as a function of the corresponding quantities of the healthy wind turbines. The collected case studies indicate that the proposed method is effective and allows distinguishing between the various types of errors related to the anemometer, the yaw and the pitch systems.**

I. INTRODUCTION

In the near-future scenarios [1, 2, 3], wind turbines will likely represent the most important technology for the production of electricity. Hence, it is fundamental that wind farms operate at their maximum possible efficiency but, unfortunately, this is typically not the case in real-world environments.

In particular, an overlooked cause of wind turbine efficiency loss is the presence of static errors. At least three main examples of such errors can be identified:

- The static yaw error [4, 5], meaning that, when the control system records that the rotor plane and the wind flow are perpendicular, indeed there is a constant angular shift γ;
- The blade pitch misalignment β [6, 7, 8], which can be absolute or relative;
- The anemometer bias [9], meaning that, at a certain point in the lifetime of the turbine, a constant shift δ occurs in the measurements collected by the nacelle anemometer.

The first two types of static error cause a loss of producible energy up to some percents of the Annual Energy Production [10, 11], while the anemometer bias might or might not be associated to a performance worsening, depending on the logic of the control system. Typically, for wind turbines with less than 2 MW of rated power, the wind speed measured by the nacelle anemometer is used as input for setting the rotational speed and blade pitch set points and, thus, a measurement bias leads to a non-optimal operation point [9].

It is desirable to exploit as much as possible the SCADA-collected data [12, 13] for diagnosing such types of static errors. Yet, given the mediation of the control system [14, 15], the SCADA-collected data might even be misleading. Furthermore, in the literature it has not been systematically elaborated what manifestations (observable through SCADA data) are associated to the various types of static errors.

Hence, the contribution of this study is a comprehensive framework for employing SCADA data to diagnose static errors and distinguish between them. Namely, the main innovation of the present work is in the following aspects:

- Application of multivariate SCADA data analysis for wind turbine performance monitoring;
- Identification of the observable phenomena associated to the most common static errors;
- Formulation of guidelines for fixing the static errors and improving the power production of a fleet.

Real-world test cases, namely wind farms operated by the ENGIE Italia company, are discussed.

II. METHODOLOGY

In this work, a comprehensive analysis is carried out regarding the following phenomena, which can possibly be associated to the various static errors:

- Under-performance;
- Shift in the nacelle anemometer measurements;
- Increased level of vibrations.

Single wind turbine (Section A.) and fleet-wide (Section B.) can be employed. A brief explanation is provided here on and the flowchart of the method is reported in Figure 1, which is discussed as well in the related paper [16].

A. Single Wind Turbine Methods

The single wind turbine methods can be employed on their own for characterizing the behavior of wind turbines affected by static errors, and hence for diagnosing, but can as well be employed as preliminary steps for dividing a fleet in potentially anomalous and likely healthy wind turbines.

A..1 Nacelle Anemometer Measurement Analysis

A devoted analysis has to be dedicated to the nacelle anemometer measurements, as they are evidently associated to the anemometer bias and, less evidently, to the static yaw error [17]. If there are two sensors sited at the opposite lateral ends of the nacelle, it is possible to analyze the relation between the so collected wind speed measurements v_1 and v_2. By posing a linear relation, as in Equation 1:

$$v_2 = kv_1, \tag{1}$$

it has been observed in [17] that the Least Squares estimate of k changes as the static yaw error changes and, in particular, if the two anemometers are of the same type, the expected baseline if $k \simeq 1$ if $\gamma \simeq 0$.

A..2 Operation Curve Analysis

Based on the above observations, it is more reliable to analyze the power and vibration measurements without putting them in relation with the nacelle anemometer measurements, because those are altered by the presence of the errors. Hence, the method of bins can be applied for characterizing various operation curves. Consider for example to group the measurements in rotor speed intervals of 0.5 rpm from cut-in rotor speed to rated. For each interval, average the corresponding set of power or absolute value of vibration measurements. The following might occur:

- Decreased power extracted for a certain rotational speed means under-performance (which can be associated to all the considered static errors);
- Increased level of vibrations for a certain rotational speed should be associated to blade pitch misalignment and static yaw error.

B. Fleet-Wide Approaches

The fleet-wide approach can be implemented as follows:

- Based on the single wind turbine methods, divide the fleet in anomalous and normal wind turbines;
- Set up a data-driven regression for, respectively, the power, the wind speed and the vibrations of the target wind turbines as a function of the corresponding quantities of the normal wind turbines;
- Analyze how the behavior of the residuals between measurements and model estimates changes in time.

III. RESULTS

A. Case Studies

Due to space constraints, it is prohibitive to comprehensively discuss all the cases indicated in Figure 1. Hence, two meaningful test cases have been selected, noticeably with the same wind turbine model (Senvion MM92). The former is a case of relative blade pitch misalignment, ascertained through laser measurements, and the latter is a static yaw error case, ascertained by upwind spinner anemometer measurements. For the former test case, the label "No PM" refers to laser measurements indicating a pitch misalignment below a threshold (0.3°). For the latter test case, data are available for the anomalous wind turbine and for three normal wind turbines belonging to the same fleet.

The measurements at disposal for both test cases are:

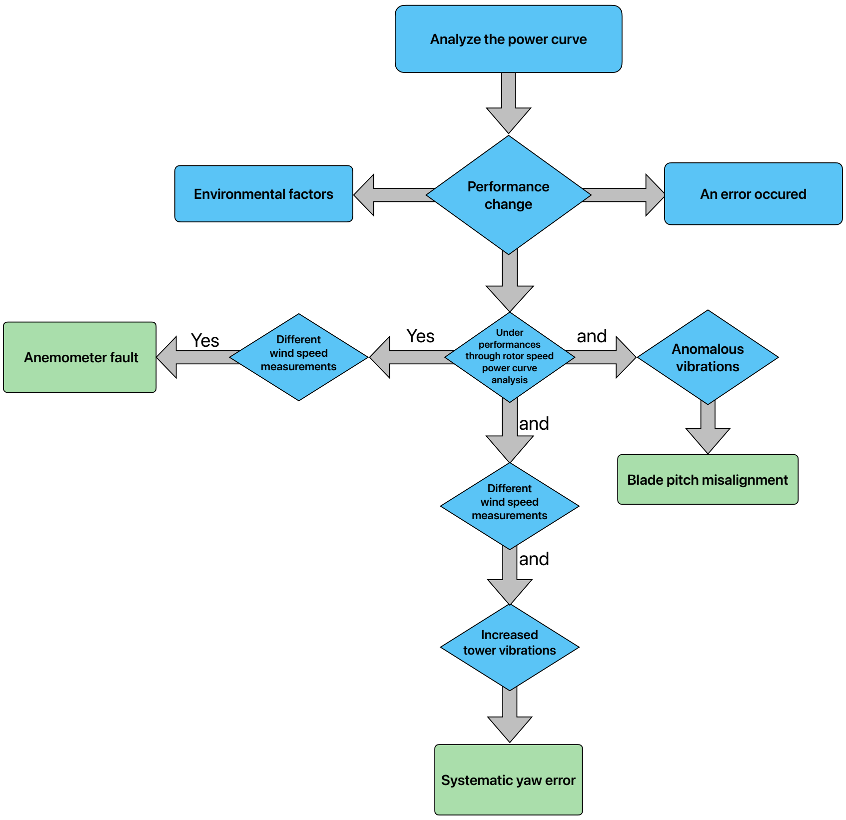

Fig. 1. Flow chart of the approach

- Wind speed sensor 1 (m/s);
- Wind speed sensor 2 (m/s);
- Grid Power (kW);
- Blade Pitch (°).

The measurement channel indicated as wind speed in the SCADA-collected data is the average of the measurements from the two physical sensors (cup anemometers mounted at the opposite lateral ends of the nacelle). For the former case study, the tower vibration measurements (mg) are available, while for the latter, there are the drivetrain vibrations (mg) which presumably are collected at a meaningful component of the drivetrain (unknown to the authors).

B. Pitch Misalignment Analysis Through Single Wind Turbine Methods

In Figure 2, the power curve is reported for the wind turbine of interest for various portions of the data set, associated to the presence of various values of relative pitch misalignment. Referring to the flowchart in Figure 1, Figure 2 provides a qualitative evidence of performance change, from which the further analyses follow for identifying what type of static error possibly affects the wind turbine.

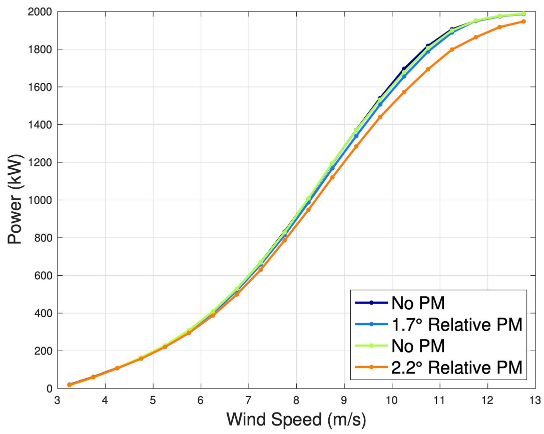

Fig. 2. The average power curve, for various values of relative pitch misalignment, ascertained through laser measurements.

Hence, from Figures 3 and 4, it arises that, for a certain rotational speed, the average absolute tower vibrations remarkably increase with the blade pitch misalignment and the extracted power decreases.

In Table 1, the Least Squares estimates of k (Equation 1) are reported. The variation as the blade pitch misalignment varies is much more limited with respect to the static yaw error case [17]. Hence, it can be argued that such type

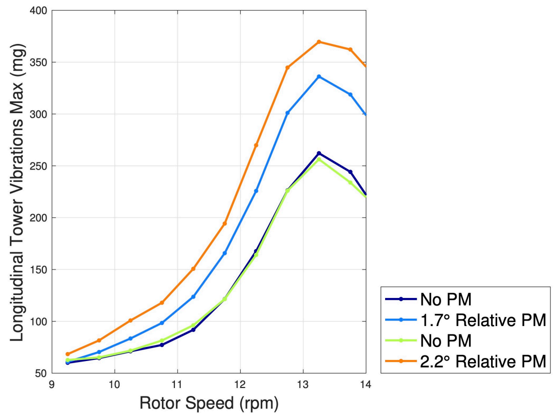

Fig. 3. The average curve of the tower vibrations as a function of the rotational speed, for various values of relative pitch misalignment, ascertained through laser measurements.

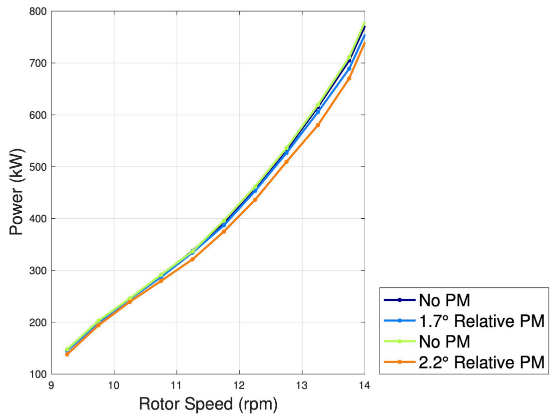

Fig. 4. The average curve of the extracted power as a function of the rotational speed, for various values of relative pitch misalignment, ascertained through laser measurements.

of error does not impact the nacelle anemometer measurements, thus confirming the hypothesis summarized in the flowchart in Figure 1.

Pitch Misalignment	Estimated k
No pitch misalignment (1)	0.971
1.7° pitch misalignment	0.977
No pitch misalignment (2)	0.975
2.2° pitch misalignment	0.976

Table 1. Estimates of k (Equation 1), for various values of relative pitch misalignment, ascertained through laser measurements.

C. Static Yaw Error Through Fleet-Wide Approaches

The data set at disposal regards one wind turbine (analyzed in [17]), for which the static yaw error passes from order of $-14°$ to less than $1°$ in correspondence of the vertical line in Figures 6, 7 and 8. Correspondingly, the power curve changes, as observable from Figure 5, which represents the starting point of the flow diagram in Figure 1.

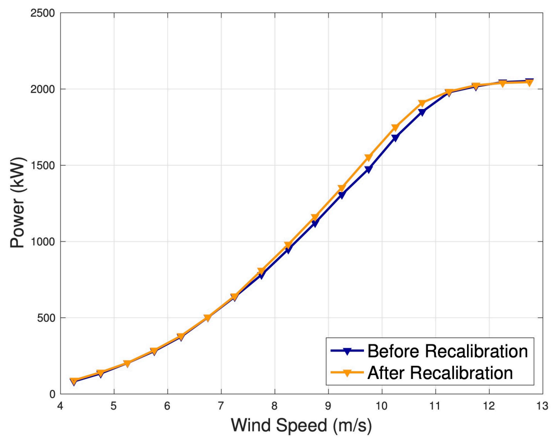

Fig. 5. The average power curve of wind turbine of interest, before and after the correction of $-14°$ of static yaw error.

According to the line of reasoning of Section B., the wind speed, the power and the drivetrain vibrations at the target wind turbine are modeled through a data-driven multivariate regression as a function of the corresponding quantities of the three normal wind turbines. It arises that, as the static yaw error decreases, the wind speed measurements change in relation to those of the nearby wind turbines, the power increases (error fixing, hence performance improvement) and the vibrations decrease as well (although drivetrain vibrations are less responsive than tower vibrations). Hence, the hypothesis formulated in Figure 1 about the manifestations of the various static errors is confirmed.

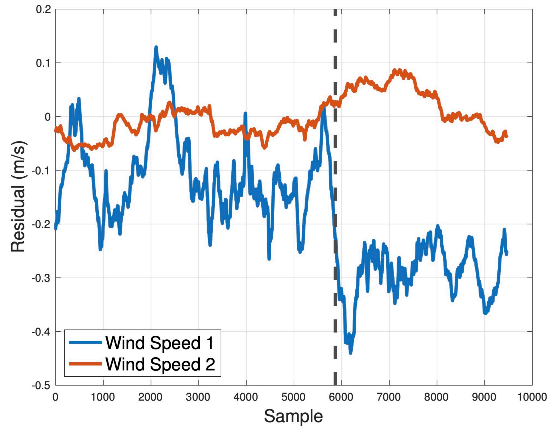

Fig. 6. The moving average of the residuals between measurements and model estimates for the two wind speed sensors. The vertical line indicates the date of correction of the yaw offsets.

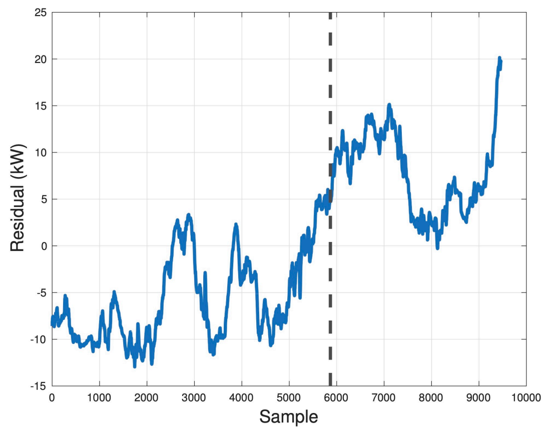

Fig. 7. The moving average of the residuals between measurements and model estimates for the power. The vertical line indicates the date of correction of the yaw offsets.

IV. CONCLUSIONS

A novel comprehensive framework for diagnosing static wind turbine errors through SCADA data analysis has been proposed. The collected case studies indicate that the proposed method is effective and allows distinguishing between the various types of errors related to the anemometer, the yaw and the pitch systems, by targeting appropriate phenomena like nacelle anemometer measurement shifts,

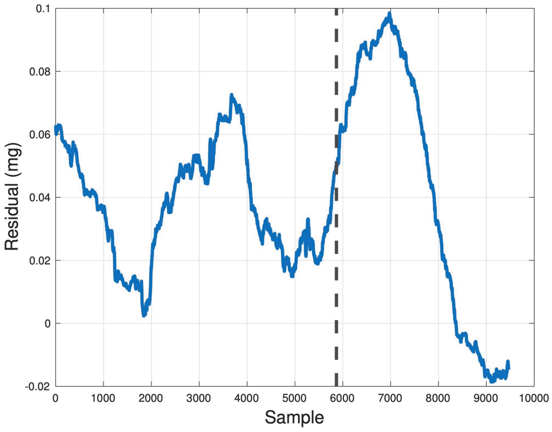

Fig. 8. The moving average of the residuals between measurements and model estimates for the drivetrain vibrations.

reduced power production and increased vibrations. Future developments of the present work regard incorporating further types of anomaly (like, for example, blade cracks) in the framework, especially for taking into account what happens in harsh environments [18].

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