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Development of a novel method for the correction of the nacelle wind speed in stall-controlled wind turbines

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Abstract. Accurate estimation of the oncoming wind is key to ensure an accurate control of any wind turbine. The wind speed is commonly measured with an anemometer located on the nacelle; hence, the measurement is influenced by the rotor and the nacelle itself and needs to be corrected so as not to incur inaccurate energy yield assessments. This study introduces an innovative method for correcting the nacelle wind speed in stall-controlled wind turbines. The development of the method has benefitted from the unique possibility of exploiting two datasets containing 10-minute averaged wind data from two identical EUNICE EW16 wind turbines and a meteorological mast located at the same site. The innovative method is systematically compared with the Nacelle Transfer Function outlined in the IEC 61400-12-2, serving as a benchmark for evaluation. The high accuracy and simplicity of the proposed method make it particularly suitable for the optimization of wind turbine performance in industrial applications. Moreover, an accurate estimation of the incoming wind speed can enable innovative control techniques, such as those based on Tip-Speed-Ratio (TSR) tracking. This is addressed in the study through simulations by comparing a TSR-Tracking strategy with the most common k-ω^2 strategy. The study demonstrated that the TSR-Tracking strategy could be adopted in stall-controlled wind turbines if an accurate estimation of the free-stream wind speed is available.

1. Introduction and objectives

During 2022, 77.6 GW of new wind power capacity was connected to grids, bringing the total global installed capacity to 906 GW [1], with a growth of 9% compared with 2021. While most of the new installed capacity is in the form of large utility-scale wind farms, Small Wind Turbines (SWTs) can play an important role [3], since they contribute to powering remote or rural areas of the world. Moreover, with the diffusion of smart energy systems, their application has shown notable growth, and they are used daily for powering remote communities, single households, and a variety of off-grid equipment.

However, the widespread adoption of small wind turbines continues to be hindered by high costs due to inadequate system optimization and underdeveloped design [3]. In contrast to utility-scale turbines, where pitch regulation has emerged as the primary method for power regulation, SWTs have been less inclined to adopt this approach due to cost implications and space constraints within the nacelles [4]. Nevertheless, stall regulation often causes lower Annual Energy Production (AEP), jeopardizing peak performance above rated wind speed due to the aerodynamics of the blades, which need to be designed with some compromises [4]. Furthermore, the monitoring of the performance of SWTs usually relies on hub-height wind speed observations, which are assessed using affordable measurement systems, i.e., cup anemometers installed on the nacelle. These sensors are affected by the shape of the nacelle, which can result in either a slowdown or an acceleration of the flow, and the reduced flow speed due to the momentum extracted by the turbine [5]. Therefore, measurements from these devices often yield imprecise power curves and energy yield assessments compared to the more sophisticated sonic or ultrasonic sensors utilized in larger turbine models [6].

To address this issue and obtain a more accurate estimate of the energy produced by small turbines, it is essential to implement a method for correcting the wind speed measured by the nacelle-mounted anemometer. This corrective method should be easy to implement and fast-running, to ensure an effective regulation of the turbine. Various methods proposed in the literature, such as the "Straight Line Method", the "No Wakes Method", and the "Statistical Method" proposed in [7], as well as the 5th order polynomial function method described in [5], aim to meet these criteria. However, among the correcting strategies, the Nacelle Transfer Function (NTF) described in the IEC 61400-12-2 [8] is probably the most used one. To apply the NTF, a reliable measurement of the free stream wind speed is needed. The mathematical function is derived through linear interpolation between the free stream measurement and the nacelle wind speed. The validation of the NTF involves passing the Self-Consistency Check, which states that the established transfer function must be used to correct the nacelle wind speed, which is then used to compute both a power curve and AEP and compare them with the one obtained by applying the methodology described in IEC 61400-12-1 [9]. However, according to industry findings, there have been occasions where the transfer function established by using the standard method has failed to meet the requirements for the Self-Consistency Check [10].

The objective of this study was first to examine the applicability of the NTF on stall-controlled small wind turbines, where the complex flow patterns induced by blade aerodynamics in stall conditions and the typically low Reynolds number are known to induce disturbances that are detrimental to the control. An alternative approach is then proposed to calculate the wind speed in front of the rotor based on a Linear Regression Method (LR). The LR method, relying on linear regression for corrective function determination, stands out for its simplicity in implementation. While the NTF solely considers the wind speed measured by the nacelle as the variable, the LR Method introduces innovation by incorporating the rotational speed of the rotor as an additional variable. This inclusion enables to consider and thus to correct, the effects caused by the rotation of the rotor on the nacelle measurement. If precise enough, the novel method could enable innovative control techniques such as tip-speed-ratio (TSR) tracking, potentially improving the AEP of small wind turbines. A common strategy to regulate torque below rated wind speed in small wind turbines makes use of the k-ω^2 law, where the generator torque is equal to the square of the rotor speed (ω^2) multiplied by a constant (k), which depends on the design TSR and power coefficient, as explained in [12]. This strategy is easy to implement and ensures stable torque regulation. Moreover, it does not require real-time wind speed measurement sensors [13]. However, since the maximum power coefficient depends on the aerodynamic characteristics of the turbine, small manufacturing defects or blade deterioration, such as dirt accretion or erosion, may affect its value. Furthermore, changes in wind speed, especially in turbulent winds, cannot be handled promptly because the wind speed is not measured directly, resulting in a reduction in the tracking accuracy. In the cases where it is possible to have a reliable measurement or estimation of free-stream wind speed, the TSR-tracking strategy can instead be used, where a proportional-integrative (PI) feedback control loop is used to track the design TSR. This approach has the advantage of being less sensitive to external disturbances, such as changes in air density, which are critical for small turbines.

For this purpose, the wind turbine has been simulated with OpenFAST making use of two different control strategies: standard k-ω^2 torque control, and TSR-tracking.

The latter strategy has been examined using the wind speed corrected with the NTF and the LR method as estimations of the free-stream wind speed. The comparative performance analysis of the turbine under both control strategies is presented.

2. Case Study

The development of the method has been carried out by exploiting two datasets containing 10-minute averaged wind data from two identical wind turbines and a meteorological mast (MET-Mast) installed at the "Asprovouni-Ano Splitharia" wind farm, which is located in the Peloponnese region of Greece.

The turbines under study are two EUNICE EW16 wind turbines. With a rated power of 50 kW and a rotor diameter of 16 m, they are considered small wind turbines according to IEC61400-12-1 [9]. These turbines have a synchronous generator, and they are connected to the local low-voltage grid through a full-inverter interface, and they are regulated by stall control. The hub height is 22 m, and cut-in, rated and cut-out wind speeds are 3, 12, and 20 m/s respectively. The turbine nacelle is retrofitted with a cup anemometer and a wind vane for wind speed and direction measurements. The mast is installed at the same altitude as the EUNICE wind turbine at 1051 asl at a distance smaller than 2.5 diameters, which is within the distance limits given by the standards [9]. The mast is retrofitted with a cup anemometer to measure the wind speed at hub height, two side-mounted vanes to measure the wind direction, and other sensors to define the meteorological conditions. Pictures of the EUNICE EW16 and the mast are shown in Fig.1.

Figure 1: Picture of the Eunice EW16 wind turbine (left) and the meteorological mast (right).

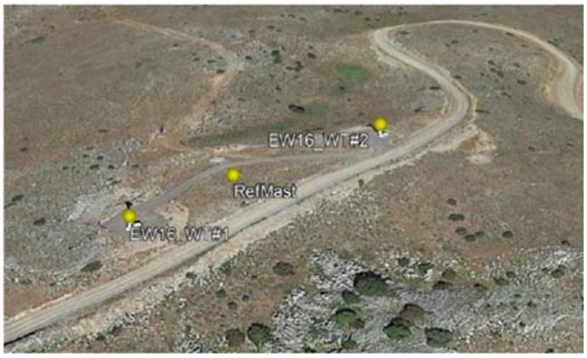


Figure 2: Picture of the test site with the tested wind turbine (EW16WT#1), the second wind turbine (EW16WT#2), and the mast (RefMast).

The terrain of the installation site is complex and of type C [9]. Still, the site calibration showed that the anemometer measurement of the MET-Mast is a good estimation of the free stream wind speed in the wake-free wind direction sectors. To avoid spurious effects, only data relative to these specific wind directions have been considered while analyzing both the Nacelle Transfer Function and the Linear

Regression Model. The wind turbine designated as WT1, utilized for site calibration, was employed to train and test the correction methods (reference wind turbine). Subsequently, these methods were validated on the second wind turbine, denoted as WT2. A visual representation of the installation site, depicting the turbine positions and the mast, is presented in Fig.2.

3. Methodology

3.1. Nacelle Transfer Function method

The method presented in Clause D.4 of [8] has been followed to establish the NTF. The MET-mast wind speed is binned against the nacelle wind speed employing the Method of Bins with the nacelle wind speed on the X-axis [8], as shown in Fig.3. The Method of Bins is described in [9], and it consists of in dividing the wind speed range in 0.5 m/s bins containing the average wind speed values.

Subsequently, a linear interpolation between bins is made, and the estimation of the free stream wind speed is obtained with the following formula:

$$v_{free} = \frac{v_{free,i+1} - v_{free,i}}{v_{nac,i+1} - v_{nac,i}} (v_{nac} - v_{nac,i}) + v_{free,i} \tag{1}$$

where the velocities, all in [m/s] are defined as:

- $v_{nac,i}$ and $v_{nac,i+1}$ are bin averages of the nacelle wind speed in bin i and i+1;
- $v_{free,i}$ and $v_{free,i+1}$ are bin averages of the met-mast wind speed in bin i and i+1;
- v_{nac} is the measured value of the nacelle anemometer for which we want to estimate the free stream wind speed;
- v_{free} is the free-stream wind speed estimated using the measured nacelle and met mast speeds.

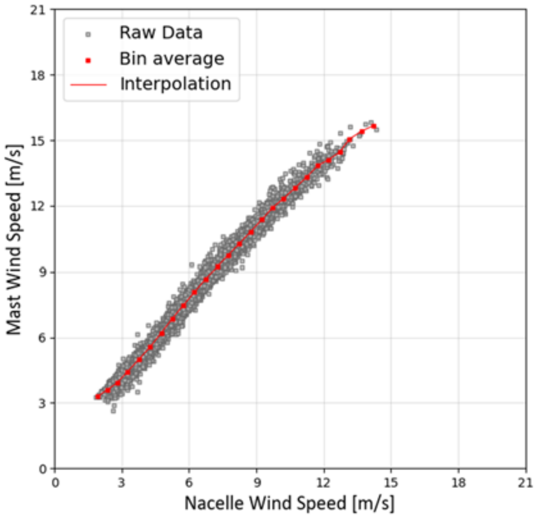


Figure 3: Nacelle Transfer Function representing Wind Turbine 1.

3.2. Linear Regression method

The Wake-Free database is split into a Training Period, containing 75% of the data that is used to develop the transfer function, and a Test Period, with 25% of the data to test the accuracy of the function. The regression is created by setting the nacelle wind speed and the square of the rotational speed as input and the REF-mast wind speed as output, resulting in the following function:

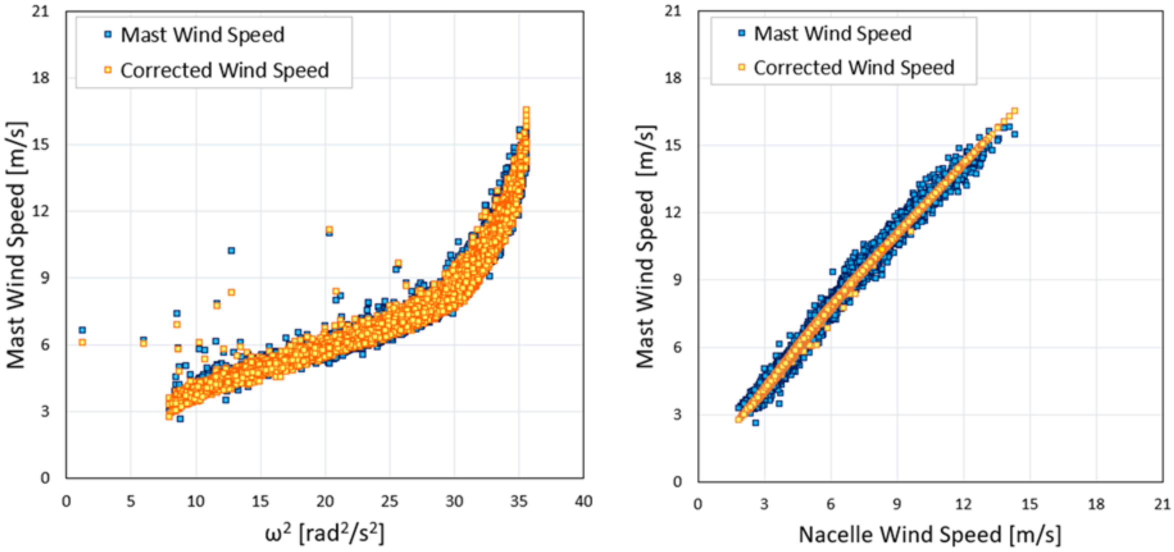
$$v_{free} = \alpha + \beta_1 \, v_{nac} + \beta_2 \omega^2 \tag{2}$$

where:

- v_{nac} [m/s] is the measured nacelle wind speed;

- ω^2 [rad^2/s^2] is the rotational speed of the rotor;
- α, β_1, β_2 are the regression coefficients.

The values of the coefficients are obtained by applying the regression to training data, as shown in Fig. 4. The function is then used to calculate the corrected wind speed in the test period and, if the comparison with the reference wind speed leads to a relatively high (>90%) square of the correlation coefficient (R^2), the corrected wind speed is considered a reliable fit for the free stream wind speed.



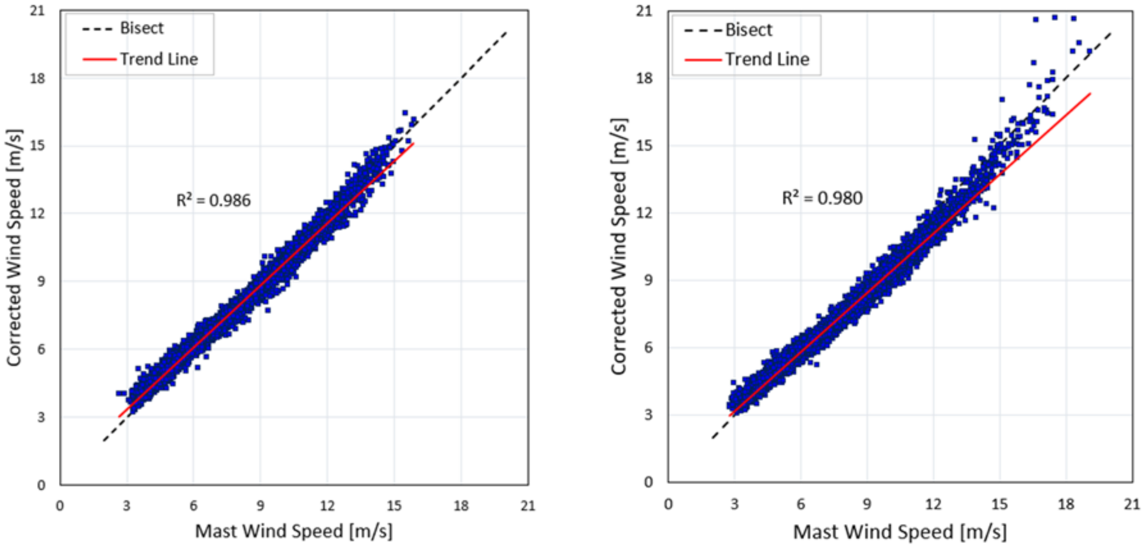
(a) Mast Wind Speed vs ω²
(b) Mast Wind Speed vs Nacelle Wind Speed

Figure 4: Linear Regression representing the Training Period: (a) Mast Wind Speed vs ω², (b) Mast Wind Speed vs Nacelle Wind Speed.

4. Results

4.1 Nacelle Transfer Function

The corrected nacelle wind speed from Eq. (1) is compared to the reference wind speed measured by



(a) Reference Wind Turbine
(b) Second Wind Turbine

Figure 5: Mast Wind Speed vs Corrected Wind Speed with the NTF for (a) Reference Wind Turbine, (b) Second Wind Turbine.

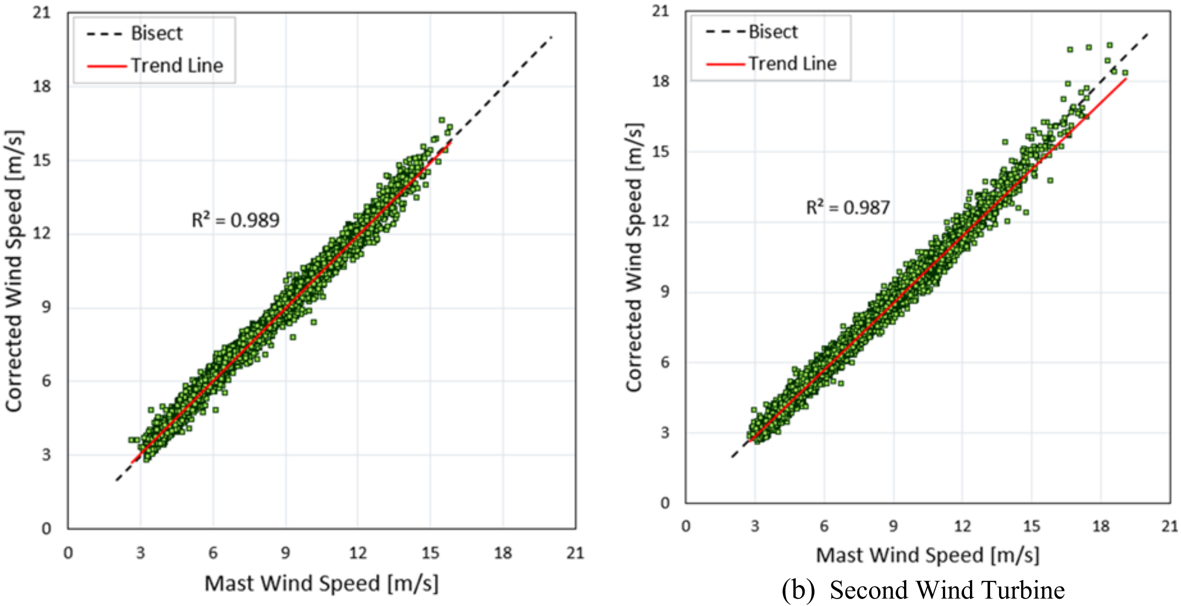
the mast. The regression between the two values results in an R^2=0.986 for WT1, which is accurate enough to consider the transfer function reliable for the correction of the wind speed. When the same NTF is applied to the WT2, it results in R^2=0.980, which confirms the effectiveness of the function in terms of regression. The scatter plot between the Mast Wind Speed measured and the Corrected Wind Speed in both cases is depicted in Fig. 5, with the trend line of the data shown in red.

4.2 Linear Regression method

The regression coefficients have been inserted in Eq. (2), resulting in the following correcting formula:

$$v_{free} = 0.580 + 1.022 v_{nac} + 0.037\omega^2 \tag{3}$$

The corrected wind speed was then compared to the reference wind speed resulting in a R^2=0.989. When the same LR Function is applied to the second wind turbine, it results in a R^2=0.987, which is very close to the value obtained for the Reference Wind Turbine, thus very accurate. The scatter plot between the Reference Wind Speed measured and the Corrected Wind Speed in both cases is shown in Fig. 6, along with the trend line shown in red.



(a) Reference Wind Turbine

(b) Second Wind Turbine

Figure 6: Mast Wind Speed vs Corrected Wind Speed with LR Method for (a) Reference Wind Turbine, (b) Second Wind Turbine.

4.3 Comparative analysis and discussion

The Regression Coefficients of the described methods are compared in Tab. 1, along with the Root Mean Square Error (RMSE), used to assess their accuracy. Although the results are closely aligned, both indicators consistently reveal a higher accuracy of the Linear Regression method compared to the Nacelle Transfer Function method. Moreover, the proposed method proved to work equivalently well (or even slightly better in this case) on a turbine different from the one it has been developed on. From an industrial perspective, this last aspect is very interesting since, in theory, the manufacturer could develop a regression for its specific turbine only once (or multiple times, depending on different factors) and then embed that expression in the control logic of each turbine. As apparent upon examination of Fig. 5 and Fig. 6, it is evident that the trend line of the results from the innovative method closely aligns with the ideal one, represented by the bisect. The discussed increase in accuracy is mainly obtained at high wind speeds, where the stall control induces more alterations on the measured nacelle speed. In particular, a more scattered area for the second wind turbine is noticeable for data exceeding 15 m/s. This variance is attributed to the wider range of wind speed values and increased data volume in the database of WT2 compared to the reference dataset. This underscores a limitation of the Nacelle Transfer Function procedure, as it cannot be reliably extrapolated for values outside the bins obtained with the reference data.

Table 1. Accuracy of the NTF and LR methods on the Reference and Second wind turbines.

	R^2	RMSE
NTF applied to the reference wind turbine	0.986	0.350
LR applied to the reference wind turbine	0.989	0.267
NTF applied to the second wind turbine	0.980	0.600
LR applied to the second wind turbine	0.987	0.490

The amount of data in the high-wind regions was scarce for the test site used in the study, therefore the methods could be analyzed and studied more thoroughly in a larger database. Nevertheless, the new correcting method still demonstrates notable advantages, including its simplicity of application and its efficacy in a different wind turbine. Therefore, the Linear Regression method demonstrated to have potential application in the industrial sector to correct the nacelle wind speed, enabling a more precise estimation of the power production.

5. Effects of the wind speed correction on wind turbine control

Based on the promising results obtained with the LR method in section 4, its effectiveness if used to control a stall-regulated wind turbine using TSR-tracking is preliminary evaluated in this section.

5.1 Control Strategies Overview

This work does not aim to provide a detailed explanation of the control strategies used for wind turbines, which can be found in [11]. However, a brief overview is provided to facilitate a better understanding of the subsequent analysis. A common regulation strategy in small wind turbines is variable-speed stall regulation, where the rotor speed is allowed to vary below rated wind speed to maximize efficiency and aerodynamic stall is exploited to limit power output. In these machines, the control system acts on the generator torque to control rotor speed, keeping the turbine operating near its maximum efficiency below rated and bringing the rotor to stall above rated wind speed. If the k-ω^2 strategy is used to regulate power between cut-in and rated wind speed (Control-Region 2), the torque that the generator needs to extract is equal to the square of the rotor speed (ω^2) multiplied by a constant $k = (0.5\rho\pi R^5 Cp_{max})/(TSR_{opt})^3$, which, if tuned properly, ensures the turbine operates at its optimal TSR (TSR_{opt}), thus maximising efficiency (Cp_{max}). . This strategy is easy to implement and ensures stable torque regulation. Moreover, it does not require real-time wind speed measurement sensors [13]. However, since the maximum power coefficient depends on the aerodynamic characteristics of the machine, small manufacturing defects or blade deterioration, such as dirt accretion or erosion, may affect its value. In the cases where it is possible to have a reliable measurement or estimation of free-stream wind speed, the TSR-tracking strategy can be used, where a proportional-integrative (PI) feedback control loop is used to track the design TSR This approach has the advantage of being less sensitive to external disturbances, such as changes in air density. Moreover, it is a relatively simple concept, an adaptable controller design [13]. In fact, when the power curve changes due to external factors, in many cases the optimal TSR does not change significantly, hence this control strategy can potentially lead to improved power output.

5.2 Simulation approach and main outcomes

To assess the potential of the new wind speed correction method, in particular, if this method is accurate enough to enable TSR-tracking control on small wind turbines, simulations were conducted using OpenFAST, which is an open-source tool developed by the National Renewable Energy Laboratory (NREL) for modelling the dynamic response of wind turbines [14]. In this preliminary assessment, no inflow turbulence is considered, and a constant horizontal wind speed is used instead. Wind shear is included using a power-law vertical wind profile with exponent 0.2. A subset of inflow conditions was sourced from the database of the EUNICE wind turbines by sampling the scatter data shown in Figs. 3-6. We focus on wind speeds smaller than rated wind speed, as the improvements in efficiency are irrelevant above this threshold, as the blades progressively stall to regulate power. The run time has been set to 200 s, with a time step of 0.0025 s, removing the first 100 s of the simulation to remove start-up effects. The mean, maximum and minimum power coefficients recorded during the simulations are shown as a function of the mast-measured wind speed in Fig. 7. Startup and initial transients have been effectively removed and the difference between maximum and minimum Cp is approximately 5% for all simulation and is a result of wind shear and tower shadow. The use of the EUNICE EW16 OpenFAST model was approved by EUNICE, however, in adherence to the industrial non-disclosure agreement with the industrial partner, all the results will be shown only qualitatively.

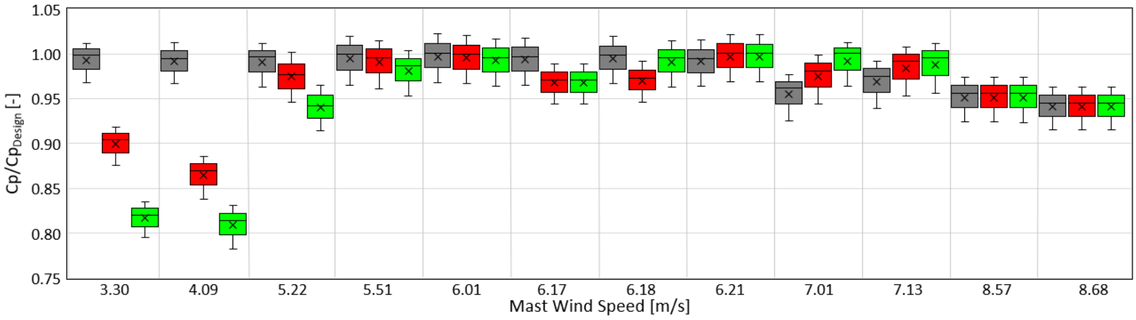


Figure 7: Mean, maximum and minimum Cp: Grey (k-ω^2 strategy), Red (TSR-tracking with LR), Green (TSR-tracking with NTF)

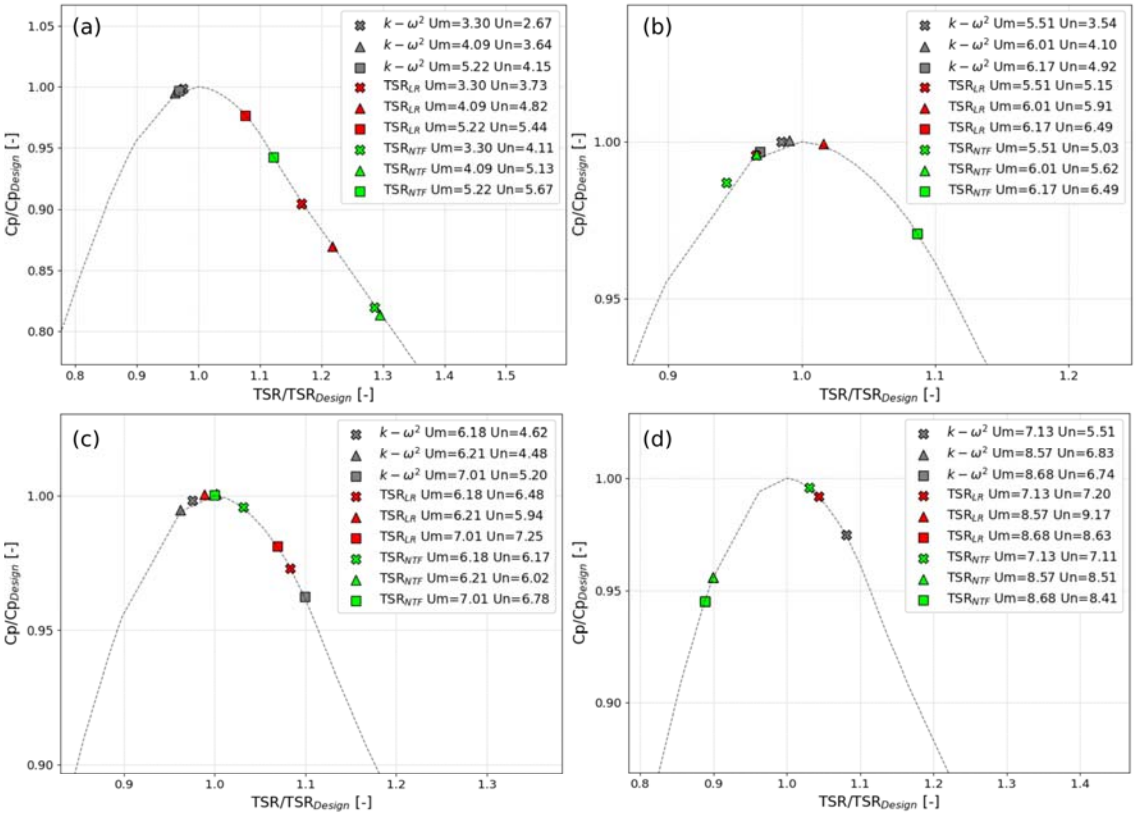


Figure 8: Cp-TSR of the EUNICE EW16 wind turbine for a selection of operating points. Um = actual, mast-measured wind speed used in the simulations | Un = wind speed estimate at nacelle used in control routines | Un in k-ω^2 method = uncorrected nacelle-measured wind speed (included for reference only).

The UNICO controller, an open-source research controller designed for stall-regulated wind turbines and developed by the University of Florence is used [15] in this study. The controller offers the flexibility to choose between TSR-tracking or the k-ω^2 law for torque control within Region 2. Performance characteristics obtained using this controller are representative of the turbine's actual operation but are different from those obtained with EUNICE's industrial controller, which is fine-tuned to the EUNICE EW16 characteristics. The mast-measured wind speed is used as the undisturbed input wind speed in OpenFAST, while the nacelle-measured wind speed is used as input to the controller, after being corrected with the two correction functions. Therefore, simulations employing the TSR-tracking method were conducted in two instances: 1) using the wind speed corrected with the Nacelle Transfer Function, and 2) employing the Linear Regression method. This approach was adopted to evaluate and compare the performance of the TSR-tracking method under the influence of the two correction methodologies studied herein. A significant subset of the results is shown in Fig. 8, where twelve operating points are reported, characterized by different mast-measured (actual) wind speeds (Um – marked by a different symbol). The selected points also differ in the quality with which the wind speed is estimated in the NTF and LR methods. As shown in the legend of Fig. 8, indeed the points feature varying levels of agreement between the mast wind speed (Um) and the nacelle-estimated wind speed (Un). The results are analyzed by observing the Cp-TSR curves of each operating point. Graphs are scaled with respect to the maximum values of the power coefficient and tip-speed ratio.

As apparent from Fig. 8, the k-ω^2 law enables better control of the wind turbine at lower wind speeds, although the turbine operates slightly below the optimal TSR. In fact, the k constant is tuned using the reference design density of 1.225 kg/m, which is higher than the mean air density at the installation site. As shown in Fig. 8 (a, b), when the estimated wind speed Un is greater than the actual wind speed Um, the TSR in the TSR-tracking methods is higher than the optimal design value, and vice-versa when Un is lower than Um. In contrast, for higher wind speed values, both TSR-tracking strategies, corrected using either the Nacelle Transfer Function (NTF) or the Linear Regression (LR) method, yield better results, if compared to the k-ω^2 law, slightly edging ahead in certain cases. Moreover, both TSR-tracking strategies lead to quite similar power coefficients at higher wind speeds (Fig. 8 (c,d)). This can be explained by two factors; the first being the lower relative prediction error of the LR and NTF methods as wind speed increases. In fact, as shown in Fig 5 (a) and 6 (a), in both methods, as the wind speed increases, the spread of the raw data around the first quadrant bisect stays qualitatively the same, decreasing the relative error with respect to the mast-measured wind speed. The second reason for the improved predictions of the TSR-tracking methods with respect to the k-ω^2 law can be found in the fact that the latter control strategy transitions from k-ω^2 to TSR-tracking of the nominal rotor speed for wind speeds between 7 and 8m/s, causing the TSR to increase past the nominal value in some instances in Figs 8 (c) and 8 (d). Overall, the same trend that was noted for lower wind speeds is true also for higher speeds: the TSR at which the TSR-tracking strategies operate the turbine depends on the quality of the wind speed estimate. If the Un overestimates Um, the turbine is operated at a TSR higher than optimal, and vice-versa if Un is lower than Um. Finally, past 8 m/s (Fig 8 (d)) the controller transitions to Region 3, where the nominal rotor speed is tracked, and thus the same control logic is used in all three cases.

It is important to clarify that the presented results do not fully capture the realistic conditions of the installation site, given the limitation of conducting solely steady-state simulations. Moreover, the volume of data examined in this study precludes a detailed analysis of the dynamic response of the turbine. However, it was interesting to see that the performance of TSR-tracking is in fact influenced by the choice of the correction method. The NTF method, in certain instances, proves to be more effective, while in other scenarios, the LR method demonstrates better results.

Nevertheless, these results highlight that improvements to the proposed transfer function are required before it can be reliably adopted in the field for TSR-tracking control, even in the simplified conditions evaluated herein. In fact, if the estimated wind speed is inaccurate, performance using TSR-tracking control is worse than that produced with the k-ω^2 strategy. Some additional parameters that could be considered are yaw misalignment and air density. In fact, both parameters influence the momentum extracted from the turbine, and thus the nacelle-measured wind speed.

6. Conclusions

In the study, a novel method for the correction of the nacelle wind speed in stall-controlled wind turbines has been introduced, the Linear Regression method (LR). The development of the method was carried out by exploiting datasets from two identical small wind turbines and a meteorological mast. Comparative analysis with the method proposed by the IEC Standards, the Nacelle Transfer Function (NTF), revealed that the LR method achieves higher accuracy, particularly at high wind speeds where stall control induces significant alterations in the measured nacelle speed. This improvement was also evident for another wind turbine, which was however different from the one the method was originally developed for, thus highlighting an interesting robustness of the proposed method. The results obtained from both correction methods were then employed to simulate the wind turbine in OpenFAST, using the TSR-Tracking strategy to control the turbine. A comparison with the k-ω^2 strategy demonstrated that, with an accurate wind speed estimation, the TSR-Tracking strategy showed benefits in the steady-state conditions evaluated herein. However, even in these simplified conditions, inaccuracies in the estimated wind speed caused TSR-tracking to perform worse than the simpler k-ω^2 strategy. From this point of view, the logical evolution of this work is to investigate the performance of NTF and LR method when coupled to TSR-tracking control in a turbulent-wind simulation, where additional challenges, more in line with real-world operation, such as wind veer, gusts and partial wake shadowing, can be introduced. If not accurate enough to enable TSR-tracking, the method could nonetheless enable advanced control strategies, such as tuning the k constant in the k-ω^2 strategy based on the turbine's actual performance. In conclusion, the LR method emerges as a valuable tool for industrial applications, providing a reliable fit for free-stream wind speed and thereby enabling more precise energy yield assessments. These findings aim to contribute to the ongoing efforts to optimize small wind turbine control strategies and encourage further exploration of advanced correction methodologies to enhance their performance.

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