Comparison of correction methods of wind speed for performance evaluation of wind turbines

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Comparison of Correction Methods of Wind Speed for Performance Evaluation of Wind Turbines

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***Abstract* – The performance of horizontal axis wind turbines strongly depends on the speed of the wind that enters in the rotor of the turbine. Unfortunately, this quantity is rarely available since the wind speed is measured on the back of the turbine, where a lower value is present. For this reason, two correction methods are usually employed that require two input quantities: the wind speed on the back of the turbine nacelle and the wind speed detected by a meteorological station close to the investigated turbine. Since an anemometric station is not always available, a third method is here proposed that does not require this input quantity. The proposed method relies on the wind speed on the back of the turbine and the manufacturer power curve. The effectiveness of such a method is shown by comparison to the results obtained with the standard methods implemented on a wind power plant in Southern Italy.**

I. INTRODUCTION

In recent years, the Renewable Energy Sources (RES) are rapidly spreading due to the increasing energy demand and the requirements of minimal environmental impact. The main drawback of RES is their intermittency, which can be mitigated by the integration of storage units, e.g. electrochemical batteries [1]-[3]. Among the RES, Wind Turbines (WTs) represent a reliable and clean source of electricity with low marginal costs [3]. In 2020, new wind power plants with a cumulative rated power of about 7 GW will be installed in Europe, while in 2021 the rated power of new installations will increase up to about 10 GW, reaching a cumulative capacity of about 250 GW [4]. In this context, offshore applications will represent about 20% of new installations in the time frame 2020-2023, especially in the Netherlands, Ireland, Norway and France.

Generally, WTs can be of two types: fixed and variable speed. Contrarily to the fixed speed turbines, variable speed turbines are able to adjust the rotor speed, thus following the maximum aerodynamic power of the wind [5]. However, their control requires a measurement of the wind speed that is performed by an anemometer, which increases the overall cost and the size of the system. The anemometer is generally located on the back of the turbine, where a wind speed that is lower than the wind speed entering in the rotor is measured. For this reason, the experimental performance of a WT could seem better than its nameplate specification, since the power curve stated by the manufacturer refers to the wind speed at the entrance of the rotor. In addition, manufacturer-stated performance of WTs refers to ideal conditions of minimum turbulence, flat terrain and absence of wakes due to obstacles [6]. With the aim of obtaining reliable estimation of WT performance, two correction methods have been defined in technical specifications and International Standards. The first method does not take into account the effects due to the wakes of other turbines and obstacles, while the second method filters the considered direction of the wind, thus also removing the wake effects of other turbines and obstacles. Both the methods require two experimental inputs: the wind speed v_{WT} measured by the anemometer and the wind speed v_{stat} detected by a meteorology mast that is close to the turbine under investigation. However, this latter information is generally missing in wind power plants, thus preventing the implementation of these correction methods. In the present work an alternative method is proposed that is based on the manufacturer power curve and requires only an input quantity, which is the wind speed detected by the turbine anemometer.

The paper is organized as follows: in the Section II, a review of the two standard methods is presented and the new correction method is described; Section III defines a yearly average efficiency taking into account the energy generated by a WT; in section IV, the case study is described that refers to a wind power plant in Southern Italy; in Section V preliminary results are presented; eventually, Section VI summarizes the main outcomes of the work.

II. CORRECTION METHODS

Before the application of one of the proposed correction methods, a preliminary normalization to the reference air density $\rho_{\mathrm{ref}} = 1.225\ \mathrm{kg/m^3}$ is performed, since manufacturer specifications refer to this condition. In particular, for WTs with active power control, experimental results are corrected according to the following expression [6]:

$$v_{\mathrm{cor}} = v_{\mathrm{exp}} \cdot \left(\frac{\rho_{\mathrm{air}}}{\rho_{\mathrm{ref}}} \right)^{1/3} \quad (1)$$

where v_{cor} is the corrected wind speed, v_{exp} is the measured wind speed and ρ_{air} is the air density during the measurement.

A. *Method #1 - Straight Line Method (SLM)*

The first method requires the input quantities v_{WT} and v_{stat} and consists of the following steps:

- Step A - Selection of the wind-speed direction.
  The wind direction β is properly selected in order to consider valid the assumption $v_{\mathrm{stat}} \approx v_{\mathrm{entr}}$, where v_{entr} is the wind speed that enters in the turbine rotor. In particular, experimental results are filtered in order to analyze the wind contributions flowing from the station to the WT. Assuming to simplify the problem as a 2D system without the vertical coordinate, a straight line is traced between the anemometric station and the WT under test and its orientation β_{WT} with respect to the North direction is calculated. However, if the set of experimental data is limited, a low number of experimental points is available. In this case, it is generally convenient to extend the analysis to wind speeds with orientations $\beta = \beta_{\mathrm{WT}} \pm \Delta\beta$, where $2 \cdot \Delta\beta$ is the top angle of a triangle whose base is the rotor diameter D of the WT ($D = 2 \cdot r_{\mathrm{d}}$, by assumption, where r_{d} is the length of a blade, neglecting the hub radius) and the third vertex of the triangle is the meteorology mast.

- Step B - Selection of data with $v_{\mathrm{entr}} > v_{\mathrm{WT}}$.
  As described in the step A, the wind speeds of interest flow from the anemometric station to the WT. Therefore, v_{entr} has to be larger than v_{WT} because the kinetic energy of the wind decreases when it flows through the meteorology mast.

- Step C - Removal of experimental data with turbulence larger than 10%.
  The power curve provided by the manufacturer is measured in conditions of minimum turbulence, which is generally lower than 10% [7].

- Step D - Linear regression of experimental data.
  In this step, a linear equation that describes v_{stat} as a function of v_{WT} is identified in order to estimate v_{entr} by the line of regression of v_{stat} on v_{WT}, where the measurement of v_{WT} is corrected thanks to the measurement of v_{stat}. The goodness-of-fit of the linear regression to the experimental data is measured through the parameter R^2, which ranges from 0 (no suitable model) to 1 (best model).

During the design of a wind power plant, it is recommended to investigate the optimal positioning of the turbines in order to minimize their mutual wakes and maximizing their energy production. However, due to different constraints, such as terrains and land morphology, it is not always possible to minimize these effects. Therefore, in order to remove the errors due to mutual wakes effect, the first method needs to be adjusted.

B. *Method #2 - No Wakes Method (NWM)*

This method is similar to the SLM and includes the same steps. However, since it aims to avoid that mutual wakes affect the measurements, the step A is modified. Indeed, NWM does not focus the correction on the direction joining the meteorology mast and the WT, but it investigates all the directions in which the anemometric station and the WT are not affected by the wakes of other turbines. The procedure used to determine the wind directions disengaged from any obstacles is based on the document [6]. In particular, for each obstacle in the neighborhood of the WT, such as other operating WTs or a meteorology station, the wind direction angles α that must be excluded from the analysis are calculated according to this expression:

$$\alpha = 1.3 \cdot \arctan \left(\frac{2.5 \cdot \mathrm{D}}{\mathrm{L}} + 0.15 \right) + 10 \quad (2)$$

where D is the rotor diameter and L is the mutual distance between the obstacle and the WT under test.

After the selection of the proper wind direction, it is possible to verify the validity of the results thanks to a more sophisticated analytical model, which is named the “Jensen Model” or “Park Model” [8]. It permits to estimate the wind speed $v*$ perturbed by the wake of a turbine using the following expression:

$$v* = v_0 \cdot \left[1 - \frac{1 - \sqrt{1 - C_{\mathrm{T}}}}{\left(1 + \frac{k \cdot x}{r_{\mathrm{d}}} \right)^2} \right] \quad (3)$$

where v_0 is the wind speed not affected by wakes, C_{T} is the thrust coefficient of a WT that depends on the wind intensity, r_{d} is the radius of the turbine rotor and x is the downwind distance. The parameter k is the decay constant of the wake that is estimated according to the following equation:

$$k = \frac{0.5}{\ln \left(\frac{h}{z_0} \right)} \quad (4)$$

where h is the hub height of the WT and z_0 is the roughness of the ground. According to Jensen model, the wake increases linearly with x and its diffusion radius r_{x} can be estimated as:

$$r_{\mathrm{x}} = r_{\mathrm{d}} + k \cdot x \tag{5}$$

It should be noted that the model considers the perturbation of the flow profile along the direction of the wind, while its perpendicular component is assumed constant (1-D model). Finally, this model assumes that k is a constant parameter that depends only on h and z_0.

C. Method #3 - Statistical Method (SM)

The alternative method does not require experimental data provided by a meteorology station [9]: the input quantities are the wind speed measured by the WT anemometer and the power curve provided by the manufacturer. The assumption behind this methodology is that the power curve of the WT manufacturer is the locus of the points where the generator operates with the best performance. Therefore, the analytic relation between v_{WT} and the wind speed provided by the WT manufacturer (for the same output electric power P_{k}) is derived. More in detail, the methodology is described by the following steps:

- Step A - Removal of experimental data with turbulence larger than 10% [7].

- Step B - Selection of the experimental set S_{k}.
One of the available working point $P_{\mathrm{k}} = P(v_{\mathrm{k}})$ is selected on the power curve provided by the WT manufacturer. Then, a set S_{k} of experimental data is identified such that the electric output power lies in the neighbourhood of P_{k}, i.e. in the interval between $P_{\mathrm{k}} \cdot (1-\epsilon)$ and $P_{\mathrm{k}} \cdot (1+\epsilon)$. In this work, the value of ϵ has been set to 0.01 based on the consideration that output powers within a $\pm 1\%$ interval are not distinguishable due to the common measurement uncertainty of this quantity. The set S_{k} is described as:

$$\begin{gathered} S_{\mathrm{k}} = \{[v_{\mathrm{WT,i}}, P(v_{\mathrm{WT,i}})] : \\ P(v_{\mathrm{WT,i}}) \in [P_{\mathrm{k}} \cdot (1-\epsilon) \div P_{\mathrm{k}} \cdot (1+\epsilon)]\} \end{gathered} \tag{6}$$

- Step C - Calculation of the Empiric Cumulative Distribution Function (ECDF) of the wind speed.
The ECDF of the wind speed corresponding to the selected value of v_{k} is calculated, as shown in the Fig. 1 (blue dots) that refers to the value $v_{\mathrm{k}} = 12$ m/s. The same figure also highlights as the calculated ECDF is well approximated by the CDF $F(v_{\mathrm{WT}})$ (red line) corresponding to the Probability Density Function (PDF) $f(v_{\mathrm{WT}})$ of the known factorial function Γ [10]:

$$f(v_{\mathrm{WT}}) = \frac{v_{\mathrm{WT}}^{\mathrm{a}-1}}{b^{\mathrm{a}} \cdot \Gamma(a)} \cdot \mathrm{e}^{-\frac{v_{\mathrm{WT}}}{b}} \quad (v_{\mathrm{WT}} \geq 0) \tag{7}$$

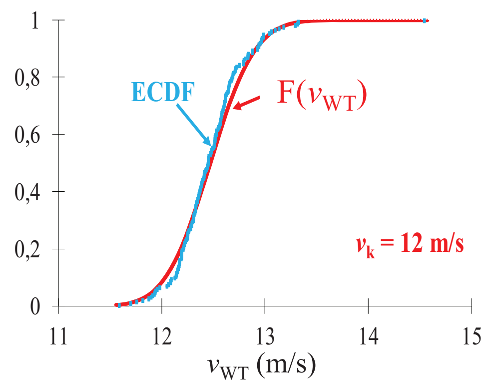

Fig. 1. Example of calculated ECDF for $v_{\mathrm{k}} = 12$ m/s.

where the parameter a is estimated as the square ratio between the mean value and the standard deviation of S_{k} and the parameter b is derived as the ratio between the mean value of S_{k} and a.

- Step D - Estimation of the wind-speed fifth percentile. Starting from the PDF $f(v_{\mathrm{WT}})$, the fifth percentile $v_{\mathrm{WT}}^{5\%}$ of the wind speed, i.e. the value that has the 5% of probability to not be exceeded in S_{k}, is selected.

  Steps form B to D are repeated for each available working point $P(v_{\mathrm{k}})$ in the power curve provided by the manufacturer.

- Step E - Linear regression of experimental data.
This step is similar to step D of the other methods, but in this case a linear equation is obtained between $v_{\mathrm{WT}}^{5\%}$ and the the corresponding v_{k}.

One should note that when the WT reaches its nominal power, the correspondence between the wind speed and the output power is not unique. The output power is indeed limited to the rated value and it can be obtained with several values of the wind speed. This represents a limit of the proposed method, which is not applicable in the range of high wind speeds due to its strong dependence on the power curve of the WT manufacturer.

III. ESTIMATION OF WT EFFICIENCY

The efficiency of a WT is the ratio between the electrical power it produces and the aerodynamic power of the wind at the entrance of the rotor. The aerodynamic power P_{aer} of the wind can be calculated as [11]:

$$P_{\mathrm{aer}} = \frac{1}{2} \cdot \rho_{\mathrm{air}} \cdot \frac{\pi}{4} \cdot D^2 \cdot v_{\mathrm{entr}}^3 \tag{8}$$

The efficiency can be also estimated as the ratio between electrical and wind energies in a certain time interval Δt. Indicating the measured WT output power as P_{out}, the efficiency can be obtained as [12]-[13]:

$$\eta = \frac{P_{\text{out}}}{P_{\text{aer}}} = \frac{P_{\text{out}} \cdot \Delta t}{P_{\text{aer}} \cdot \Delta t} = \frac{E_{\text{el}}}{E_{\text{aer}}} \tag{9}$$

where E_{el} and E_{aer} are electrical and aerodynamic energies, respectively.

With the aim of comparing the three proposed correction methods, the results will be expressed in terms of weighted yearly efficiency η^*:

$$\eta^* = \frac{\sum_{\text{year}}(\eta_{\text{k}} \cdot E_{\text{k}})}{\sum_{\text{year}}(E_{\text{k}})} = \frac{\sum_{\text{year}}(\eta_{\text{k}} \cdot E_{\text{k}})}{E_{\text{y,exp}}} \tag{10}$$

where η_{k} is the WT efficiency, E_{k} is the output energy in the $k-th$ time interval ($\Delta t = 10$ min) and $E_{\text{y,exp}}$ is the experimental yearly energy generated by the WT.

Thanks to the availability of an anemometric station and the accurate selection of the wind direction, NWM is considered as the reference method. The other two methods will be then compared to NWM by means of the efficiency deviation $\Delta\eta^*$, which is defined as:

$$\Delta\eta^* = 100 \cdot \frac{\eta^* - \eta^*_{\text{NWM}}}{\eta^*_{\text{NWM}}} \tag{11}$$

where η^*_{NWM} is the average efficiency estimated with NWM.

IV. CASE STUDY

The three methods previously described have been applied to a WT of a wind farm in Southern Italy (altitude between 1100 m and 1200 m) using data collected during a measurement campaign in 2017. The WT has a nominal power of 2.5 MW, a hub height of 80 m and a three-bladed rotor. The wind speed range is the following: cut-in speed $v_{\text{c-in}} = 3.5$ m/s, cut-out speed $v_{\text{c-out}} = 25$ m/s. In the wind farm, a meteorology mast (height of about 80 m) is present that allows the quantities of interest to be measured. In particular, it is equipped with:

- a First Class cup anemometer, which acquires the horizontal component of the wind speed according to the requirements provided in [6];
- First Class sensors that detect the wind direction according to [7];
- pressure, humidity and temperature sensors, which measure the environmental quantities that are used to estimate the air density at the height of meteorology mast and turbine.

The anemometer provides a resolution of 0.05 m/s and its stated uncertainty is $\pm1\%$ of the measured value in the range $(0.3 \div 50)$ m/s with a minimum uncertainty of ±0.2 m/s. The environmental quantities are measured with uncertainties of ±2 C for the temperature, $\pm5\%$RH for the relative humidity and ±1 kPa for the pressure.

Regarding the WT, it is equipped with an ultrasonic anemometer that measures the direction of the wind speed and its absolute value, providing a resolution of 0.01 m/s and an uncertainty of $\pm2\%$ of the measured value in the range $(0.5 \div 60)$ m/s (minimum uncertainty ±0.25 m/s). The electrical output power of the WT is measured with a standard relative uncertainty of 1%.

V. PRELIMINARY RESULTS

The electrical power measurements P_{out} obtained at the output of the WT (average values in 10 min time intervals) are shown in Fig. 2 (blue dots) with respect to the measured wind speed, which has been corrected according to equation (1). In the same figure, which refers to results that have been collected during a time interval of about one year, the manufacturer power curve (red line) is also reported. One should note that none correction methods have been applied to these experimental results: for this reason, a high number of observations are on the left of the manufacturer power curve. This behavior is not realistic, because the experimental performance of the WT could not be higher than the manufacturer's specifications. Furthermore, the cut-in and cut-out wind speeds are about 3 m/s and 24 m/s, respectively, which are lower than the corresponding nominal values ($v_{\text{c-in}} = 3.5$ m/s, $v_{\text{c-out}} = 25$ m/s).

According to the correction methods described in the section II, experimental results that show turbulence larger than 10% have been removed. In addition, also results that show null output power for wind speed in the range $(v_{\text{c-in}} \div v_{\text{c-out}})$ have been removed, since they refer to failure conditions of the investigated plant.

Before applying the described correction methods, a preliminary uncertainty estimation has been performed,

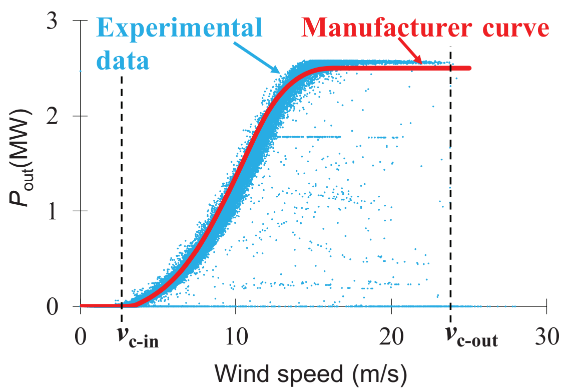

Fig. 2. Uncorrected raw experimental data (blue dots) and manufacturer power curve (red line).

taking into account the instrumental uncertainty of wattmeter and anemometer of the WT and the contribution related to the repeatability of the measured output power. As a first step, the method of bins [14] has been applied: power measurements have been grouped according to the corresponding wind speed measured by the WT anemometer. Since its uncertainty has a maximum value of $0.5\ \mathrm{m/s}$ for wind speed value of $25\ \mathrm{m/s}$, experimental results have been grouped in uniform wind-speed bins with a width of $\pm 0.5\ \mathrm{m/s}$. Then, the mean output power has been estimated for each identified group and the standard deviation of the mean, i.e. the experimental standard deviation of the single readings divided by the square root of the number of readings in each group, has been considered as the estimation of the measurement repeatability. This contribution has been combined to the instrumental standard uncertainty (1% of the measured value), thus obtaining the combined standard uncertainty $u(P)$. The obtained results are summarized in Fig. 3, where the red bars refer to the manufacturer power curve, while the gray bars represent the experimental means of each group centered around integer values of wind speed. The error bars superimposed to each gray bar are the intervals $P_{\mathrm{mean,i}} \pm u(P_{\mathrm{i}})$. Even though the anomalous data points have been removed, the uncorrected experimental results are still not fully conform to the manufacturer specifications: for wind-speed up to $6\ \mathrm{m/s}$ and at $21\ \mathrm{m/s}$, the electrical output power is higher than the manufacturer specifications and cut-in and cut-out wind speeds remain the same estimated before.

Implementing the SLM, the wind speed direction considered in the correction is $\beta = (231 \pm 13)$and the linear regression ($R^2 = 0.969$) results in the following equation:

$$v_{\mathrm{stat}} = 0.971 \cdot v_{\mathrm{WT}} + 0.758 \qquad (12)$$

The results after the correction with equation (12) are reported in Fig. 4. For wind speed lower than $21\ \mathrm{m/s}$ the corrected output power is now lower than manufacturer power curve. Regarding cut-in and cut-out wind speeds, the SLM correction brings to an estimation of $v_{\mathrm{c-in}}$ that is comparable to the nameplate specification ($\approx 3.5\ \mathrm{m/s}$), while $v_{\mathrm{c-out}}$ remains lower ($\approx 24\ \mathrm{m/s}$). Moreover, for wind speeds higher than $13\ \mathrm{m/s}$, the manufacturer power curve reaches a saturation power of about 2.5 MW, while the experimental data reach a higher saturation electrical power at high wind-speed values. This is due to the pitch regulation of the WT: in this region, the turbine is allowed to work with a maximum power of about 104% of rated data. Therefore, the WT is over performing with respect to the manufacturer data. This behavior of the WT results in a higher energy production; however, an earlier aging of the turbine due to a higher degradation of the materials may occur.

VI. CONCLUSIONS

In this work three different methods have been described that aim to estimate the wind speed at the entrance of the rotor of a wind turbine. The first two methods, which are based on technical specifications and International Standards, rely on the presence of a meteorology mast for the estimation of the wind speed. The third proposed method is able to evaluate the velocity of the wind in entrance to the rotor only using the manufacturer power curve and the measurement of the turbine anemometer.

Preliminary results have been shown that refer to a one-year experimental campaign on a wind farm in southern Italy. The effects of the first correction method, which is the Straight Line Method (SLM), have been evaluated representing the electrical output power by means of the method of bins, setting the width of the bins according to the uncertainty of the used anemometer. A preliminary uncertainty estimation has been also performed taking into account the power measurement uncertainty and the repeatability within each wind-speed bin.

The final version of the paper will include the results obtained implementing the other two correction methods, which are No Wakes Method (NWM) and Statistical Method (SM). Eventually, the three proposed methods will be compared through the efficiency deviation that has been defined in the section III.

REFERENCES

[1] F. Spertino, A. Ciocia, V. Cocina and P. Di Leo, "Renewable sources with storage for cost-effective solutions to supply commercial loads", Proc. of 2016 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), Anacapri, 2016, pp. 242-247.

[2] A. Mahesh, K.S. Sandhu "Hybrid wind/photovoltaic energy system developments: Critical review and findings", Renewable and Sustainable Energy Reviews, Vol.52, 2015, pp. 1135-1147.

[3] Z. Zhang, Y. Zhang, Q. Huang and W. Lee, "Market-oriented optimal dispatching strategy for a wind farm with a multiple stage hybrid energy storage system", CSEE Journal of Power and Energy Systems, vol.4, no.4, Dec. 2018, pp. 417-424.

[4] "Wind Energy in Europe: Outlook to 2023", available at https://windeurope.org/about-wind/reports/wind-energy-in-europe-outlook-to-2023/ (visited on 2020-03-23).

[5] P.W. Carlin, A.S. Laxson, and E.B. Muljadi, "The History and State of the Art of Variable-Speed Wind Turbine Technology", 2003, pp. 130-131.

[6] CEI EN 61400-12-1: Power performance measurement of electricity producing wind turbines.

[7] V. Cocina, P. Di Leo, M. Pastorelli, and F. Spertino, "Choice of the most suitable wind turbine in the instal-

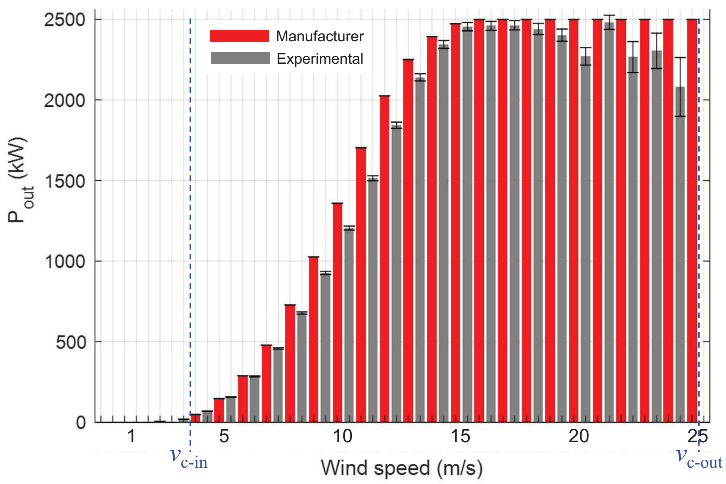

Fig. 3. Uncorrected experimental data after the preliminary data processing.

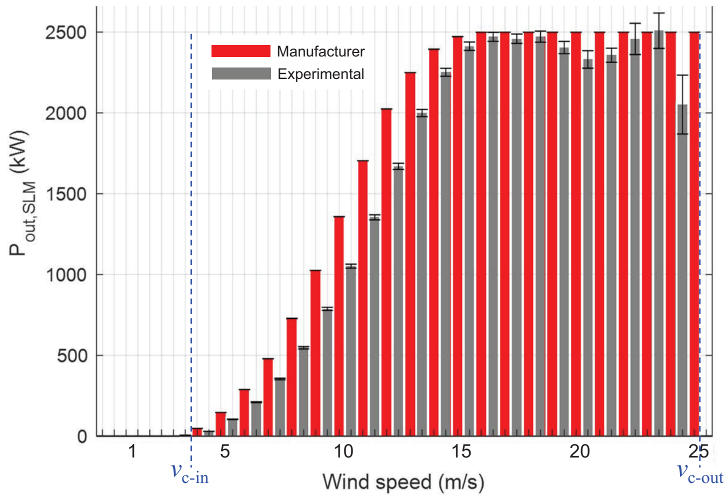

Fig. 4. SLM corrected results (gray bars) and manufacturer power curve (red bars).

lation site: A case study", Proc. of 2015 International Conference on Renewable Energy Research and Applications (ICRERA), Palermo, 2015, pp. 1631-1634.

[8] A. Peña, P.E. Rethore, and M.P. Van Der Lan, "On the application of the Jensen wake model using a turbulence-dependent wake decay coefficient: The Sexbierum case", Wind Energy, 19.10.1002/we.1863.

[9] F. Spertino, P. Di Leo, I.S. Ilie, and G. Chicco, "DFIG equivalent circuit and mismatch assessment between manufacturer and experimental power-wind speed curves", Renewable Energy, Vol.48, 2012, pp. 333-343.

[10] P.J. Davis, "Leonhard Euler's Integral: A Historical Profile of the Gamma Function", American Mathematical Monthly, 66(10), 1959, pp. 849-869.

[11] K. Grogg (2005), "Harvesting the Wind: The Physics of Wind Turbines".

[12] M.H. El-Ahmar, A.M. El-Sayed, and A.M. Hemeida, "Evaluation of factors affecting wind turbine output power", Proc. of Nineteenth International Middle East Power Systems Conference (MEPCON), Cairo, 2017, pp. 1471-1476.

[13] F. Spertino, A. Ciocia, P. Di Leo, G. Iuso, G. Malgaroli, L. Roberto, "Experimental testing of a horizontal-axis wind turbine to assess its performance", Proc. of 22nd IMEKO-TC4 International Symposium, 2017 September, pp. 411-414.

[14] J.F. Manwell, J.G. Mcgowan, and A.L. Rogers, "Wind Energy Explained", 2010, John Wiley and Sons, Ltd.