

COB-2023-0420

**METHODOLOGY FOR EVALUATING THE PERFORMANCE OF A
SMALL-SCALE HAWT IN A EEE WIND TUNNEL**

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Abstract. This paper consists in the creation of a methodology for obtaining the main characteristics of any small Horizontal Axis Wind Turbine (HAWT) for tests realized in a modified Wind Energy Unit (EEE) produced by Edibon with a circular cross section of 0.55 m and a length of 2 m. The work is divided in three main parts. The first part describes all the equipment used during the experiments and the standard EEE wind tunnel's turbine composed of 3 blades and a diameter of 0.5 m. The second part focus on the detailed procedure for the obtention of all needed data to evaluate the performance of the turbine. The last part consists of using Bahaj's blockage correction method to correct all the power coefficient curves that were obtained. This correction was made due to the wind tunnel's small cross section. The methodology showed satisfactory performance. The use of a smaller rotor to decrease the blockage ratio and sensors to obtain data with more accuracy are recommended to the upgrade of the methodology.

Keywords: small-scale HAWT, wind turbine, power coefficient, blockage effect, Bahaj's correction method

1. INTRODUCTION

The world population has achieved the historical mark of 8 billion people in 2023. The continuous growth of this number makes the development of energy sources increasingly necessary. Due to the world's environment safety, it is extremely important that those sources start to become more renewable as possible as the years pass by. Predictions made by the International Energy Agency (IEA, 2023) indicate that the total additions to renewable energy around the world during the period of 2022-2027 will be the same added during the period of 2001-2021. It shows that nations are interested in exploring these field.

In Brazil, the demand for electricity has been increasing in the last years due to the growth of the population and the energetic demand of companies in general. Figure 1 shows the generation of electric energy by source in a national context made by MME (Ministry of Mines and Energy).

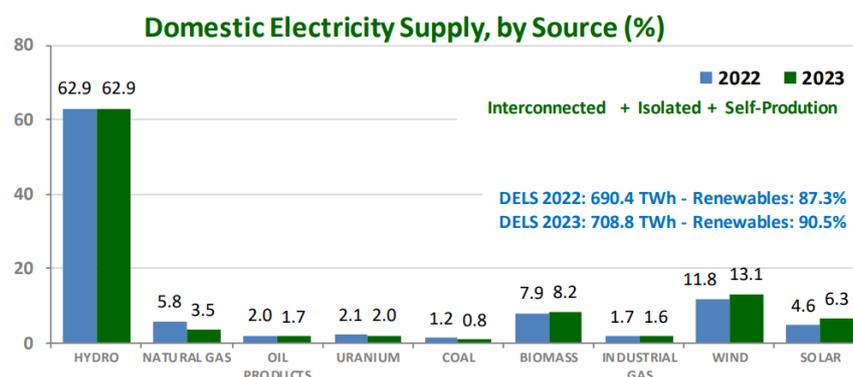


Figure 1. Generation by source (MME, 2023).

It is possible to see that renewable sources grew meanwhile nonrenewable sources decreased from 2022 to 2023. Even though the statistics show the evolution of sustainable energy process, there still a lot to be done to achieve full supply of clean energy in Brazil.

The Fluid Dynamics and Turbomachinery group (FDT – UNIFEI) has focused on the development, improvement, and experimentation of wind turbines to contribute with the necessary technology to the growth of small-scale wind energy in the Brazilian electric energy supply. In this sense, the current work was realized to develop a methodology to evaluate experimentally small-scale Horizontal Axis Wind Turbine (small-scale HAWT) in a Edibon Wind Energy Unit (EEE) of FDT’s laboratory. The results obtained with this methodology aim to provide validation for numerical methods also developed by the group.

In details, numerical methods have been utilized to enhance technology in a comprehensive manner, minimizing the need of expensive experimental methods. However, this does not exclude the fact that the final product must be experimented to validate all the data acquired through numerical solutions.

In this regard, the study conducted by Kamran Ajirlo and Pooyan Tari (2021) aimed at developing a micro wind turbine simulator. The simulator enables the testing of small-scale HAWT as if they were in free-stream conditions. To validate the results of the experimental simulator, they were compared with Blade Element Momentum (BEM) theory, Computational Fluid Dynamics (CFD) simulation as well as wind tunnel measurements results. Figure 2a illustrates the obtained results, wherein the wind tunnel curve exhibits significant divergence from the other methods. This disparity occurs due the blockage effect induced by the wind tunnel, resulting in an 18% blocking ratio (B_R). A correction to this effect was made using Maskell’s method. Figure 2b shows satisfactory results obtained after the correction.

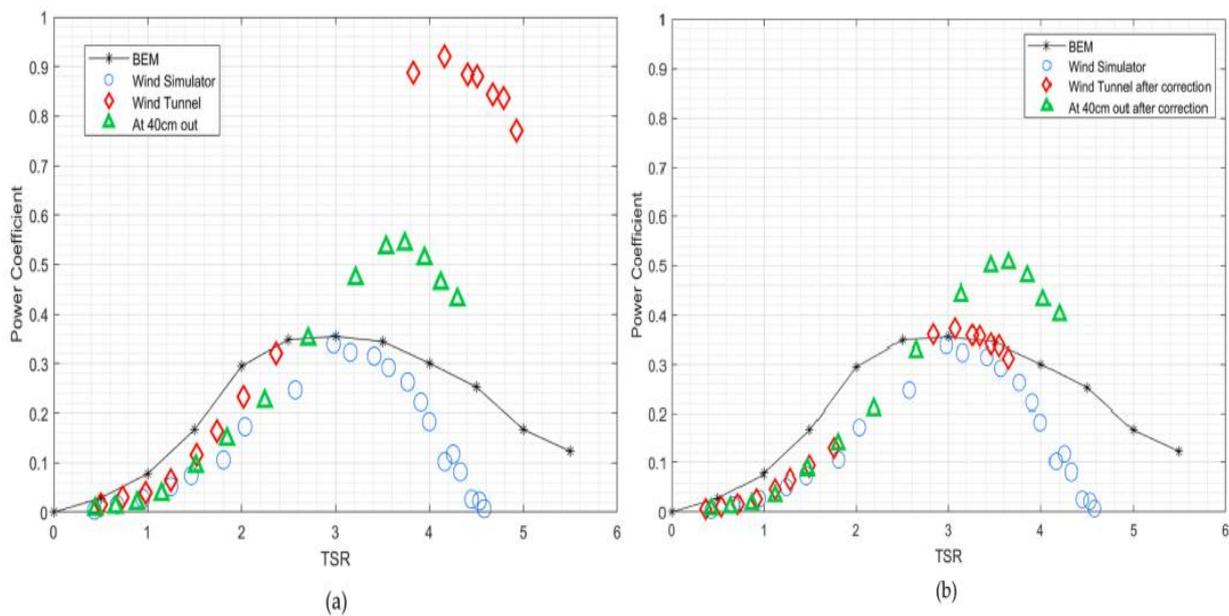


Figure 2. Experimental data from wind simulator and wind tunnel test in comparison with BEM theory for a micro HAWT. (a) Before blockage effects correction. (b) After blockage effects correction. (Ajirlo et. al., 2021).

The blockage effect is one of the main problems when the wind turbine is tested in wind tunnels. Unlike a wind turbine exposed to free air without a boundary away from the ground, the wind flows in a closed test section of a wind tunnel are different because the walls serve as boundaries. The distance from the specimen to the stream boundary of the test section of the wind tunnel is usually shorter than that in an actual operating condition in natural environments, resulting in a blockage effect (Jeong et. al., 2018). The study conducted by Houigab Jeong and Seungho Lee (2018) investigated the influence of the blockage ratio in three wind tunnel tests conducted on a small vertical-axis Darrieus wind turbine. Some correction methods such as Maskell’s method were used and compared with one another. The validation of the methods was confirmed by comparison of the corrected power coefficients obtained with all methods.

One of the methods used in the work described above is the Bahaj’s method. This method shows a good conciliation between results and difficulty of application. T.Y. Chen and L.R. Liou (2011) utilized Bahaj’s method to correct results in wind tunnel tests of small horizontal-axis wind turbines. The results obtained showed that no blockage correction is necessary if the B_R is less than 10%. Due to a B_R of 82,6 % in the present study, this method will be used to try to reduce errors due to the blockage effect. The methodology used in Chen’s study inspired the methodology developed in this work.

The current work tested a EEE's standard turbine at different wind velocities to evaluate the performance of the turbine. The wind flow profile was acquired by measuring the wind velocity with an anemometer in 10 distinct positions along the cross section and the average wind flow velocity was calculated by the average value of the wind flow profile. The power produced by the turbine was calculated by multiplying the current and voltage measured by the wind tunnel's interface. All the important parameters to evaluate the performance of the turbine were calculated and the Bahaj's correction method was used to correct the power coefficients and tip speed ratios due to the small cross section of the wind tunnel.

2. MATERIALS AND METHODS

The methodology was divided into three main sections. The first section provides a comprehensive description of the equipment utilized in the experimental setup. The second section outlines the procedure followed to acquire the data of interest. Lastly, the third section involves the application of a blockage correction method to rectify the coefficient of power curves.

2.1 Experimental setup

The Wind Energy Unit, depicted in Figure 3, was utilized for conducting the experiments. Originally, it possessed an octagonal cross-section; however, it was modified to a circular cross-section to attend mechanical experimentation standards, resulting in a diameter of 0.55 m. The axial fan of the wind tunnel has a power of 1.5 kW and a maximum flow rate of 2.96 m³/s. The average velocity offered by the equipment varies from 0 to 7 m/s.

The turbine's tower can be fixed inside the wind tunnel and in its rotor is possible to attach 6 blades at any pitch angle. The turbine's Direct Current (DC) power output was driven by a rheostat, which enables the test on different operation conditions. To account the power generated, the electric current and voltage were collected by sensors of a control unit. The accuracy of the sensors that acquired the voltage and the current was not presented by Edibon. The blade utilized during the experimentation of the turbine was the wind tunnel's default blade. Figure 4 depicts the model of the turbine and its blades.

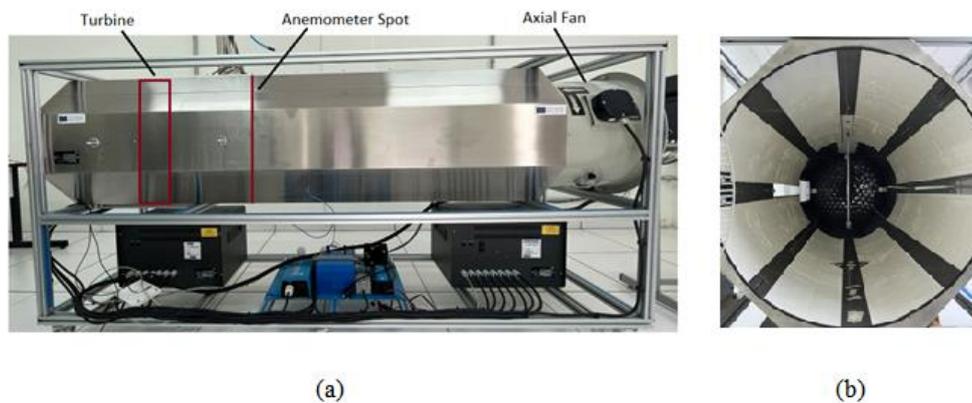


Figure 3. Wind Energy Unit (EEE) at FDT's laboratory. (a) Lateral view. (b) Frontal view.

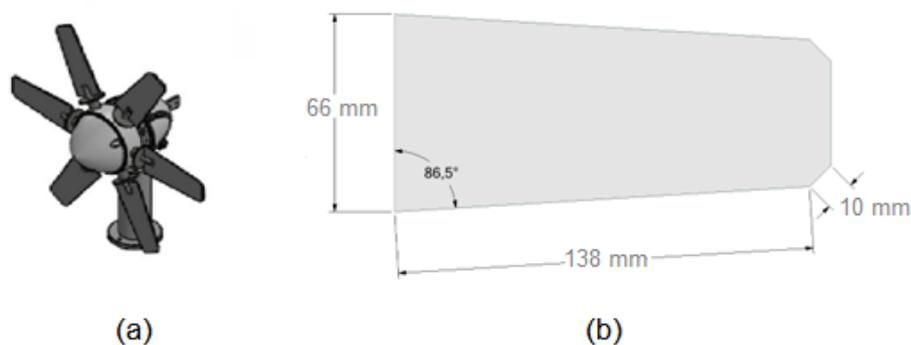


Figure 4. (a) Representative model of the turbine. (b) Representative model of the blade.

The equipment utilized for measuring the air velocity and angular velocity of the rotor consisted of a REED AM-4204 Hot Wire Anemometer and a Laser Tachometer KR98, respectively. The accuracy of the anemometer and the tachometer are 5% and 0.1%, respectively.

In the post-processing phase, Microsoft Excel® and SciLab® were the softwares utilized. All the acquired data was transferred to an Excel spreadsheet for evaluation and analysis. SciLab was used to plot all graphs present in this paper.

2.2 Experimental procedure

The pitch and yaw angles were equal to 0°. In Figure 5, γ is the yaw angle and β is the pitch angle.

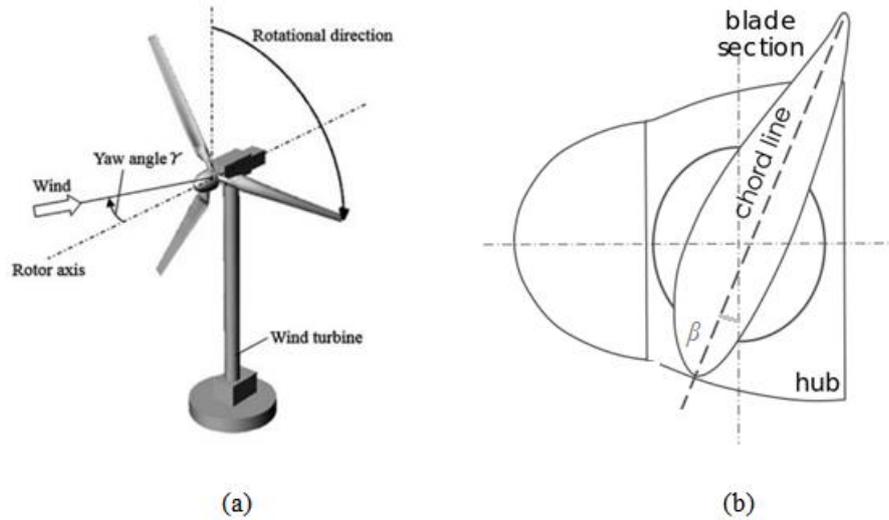


Figure 5. (a) Demonstration of the yaw angle. (b) Demonstration of the pitch angle.

The velocity profile into wind tunnel was acquired by measuring the air velocity at 10 different points across the cross-section 0.3 m upwind the turbine's rotor. An interpolation of the sixth degree with these 10 points can obtain a polynomial that mathematically represents the profile. The average wind flow velocity was obtained by the average value theorem.

$$\bar{v}(b - a) = \int_a^b f(x) dx, \quad (1)$$

where $f(x)$ is the sixth-degree polynomial, a is the initial and b is the final point of the turbine along the circular cross section and \bar{v} is the average velocity of the air's flow.

The voltage and electric current vary with the rheostat load, which was being increased from its minimum to its maximum capacity. Thus, the power was calculated as in Eq. 2.

$$P = IV, \quad (2)$$

where P is the electric power, I is the electric current and V is the voltage at each rheostat load.

The TSR (Tip Speed Ratio) was calculated as in Eq. 3.

$$\lambda = \omega R / \bar{v}, \quad (3)$$

where λ is the TSR, ω is the angular velocity of the rotor, R is the radius of the turbine and \bar{v} is the average wind flow velocity.

Equation 4 is used to obtain the C_p (Power Coefficient) of the turbine for every load of the rheostat varying from its minimum to its maximum.

$$C_p = P / 0,5\rho\bar{v}^3 A, \quad (4)$$

where P is the electric power, ρ is the density of the air, \bar{v} is the average wind flow velocity and A is the swept area of the turbine.

The swept area of the turbine can be visualized in Figure 3a. and can be calculated as shown in Eq. 5. The B_R (Blocking Ratio) it's another parameter related to the swept area; it is calculated following Eq. 6.

$$A = \pi R^2, \quad (5)$$

where A is the swept area of the turbine and R is the radius of the turbine.

$$B_R = A/A' = \pi R^2 / \pi (R')^2 = R^2 / (R')^2, \quad (6)$$

where B_R is the blocking ratio of the turbine, A is the swept area of the turbine, A' is the area of the wind tunnel, R is the radius of the turbine and R' is the radius of the wind tunnel.

2.3 Blockage effect correction

For test conducted in a wind tunnel for evaluating the performance of HAWT (Horizontal Axis Wind Turbine) it is recommended a B_R lower than 10% (Ajirilo et al., 2021). The B_R for this experiment is around 82,6%. Due to this enormous number, a blockage correction method was used to correct the TSR and the C_p . The method chosen was the Bahaj's method (Chen and Liou, 2011). This method is quite simple, the equations to correct the parameters are presented below.

$$B_F = \bar{v} / \bar{v}', \quad (7)$$

$$C_{pf} = C_{pt} B_F^3, \quad (8)$$

$$\lambda_f = \lambda_t B_F, \quad (9)$$

where B_F is the blocking factor, \bar{v} is the average wind velocity with the turbine, \bar{v}' is the average wind velocity without the turbine, C_{pf} is the power coefficient in the freestream condition, C_{pt} is the power coefficient in the wind tunnel condition, λ_f is the TSR in the freestream condition and λ_t is the TSR in the wind tunnel condition.

2.4 Uncertainly analysis

The standard deviation of the current, voltage, wind velocity and angular velocity can be calculated with Eq.10.

$$\sigma = \sqrt{\frac{\sum_{i=1}^N (x_i - \mu)^2}{N}}, \quad (10)$$

where σ is the standard deviation, N is the number of measurements, x_i is an interest parameter and μ is the average value of the chosen parameter.

2.5 Results and discussion

The shape of the air flow for 5 average velocities are shown in Figure 6. It is possible to see that the shapes are far from what is expected from wind tunnels. The short length of the tunnel implicates in a non-developed shape of the flow. That is one of the limitations of the equipment that can bring errors into the results.

The distance between the axial fan and the turbine's tower has approximately 1,2 m. It is suggested that the velocity of the air should be measured at 3,5D away from the turbine. Since the diameter of the turbine experimented in this work has 0.5 m, this recommendation could not be followed. The low velocity around the center of the tunnel occurs due to the cube of the fan.

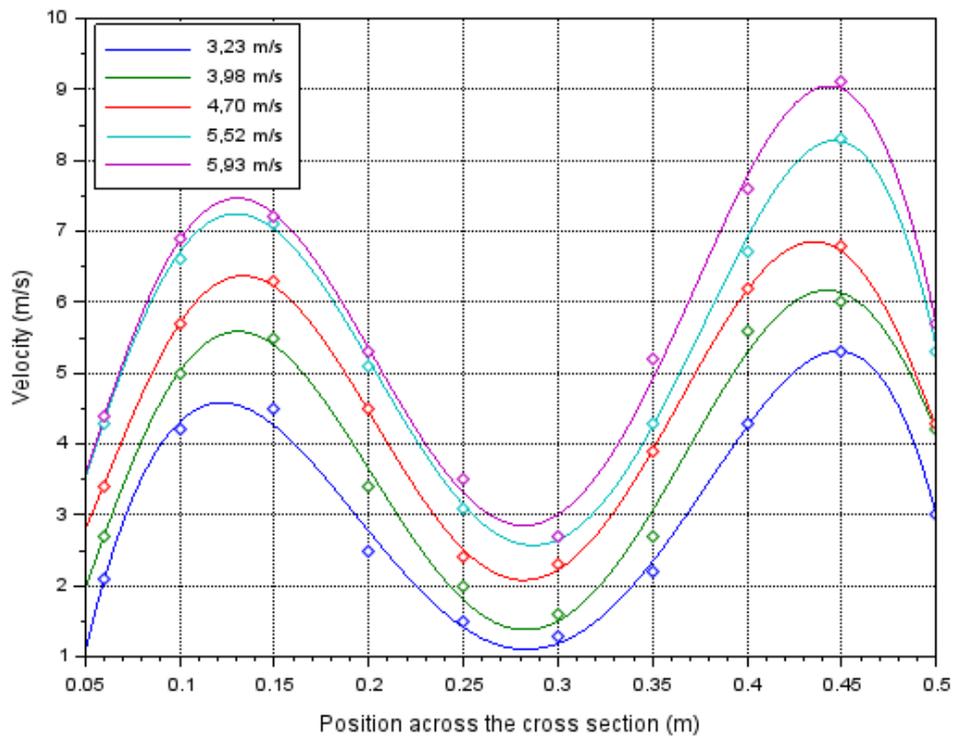


Figure 6. Average Wind Flow Profile.

Figure 7 shows the power coefficient of the turbine for all the velocities shown before.

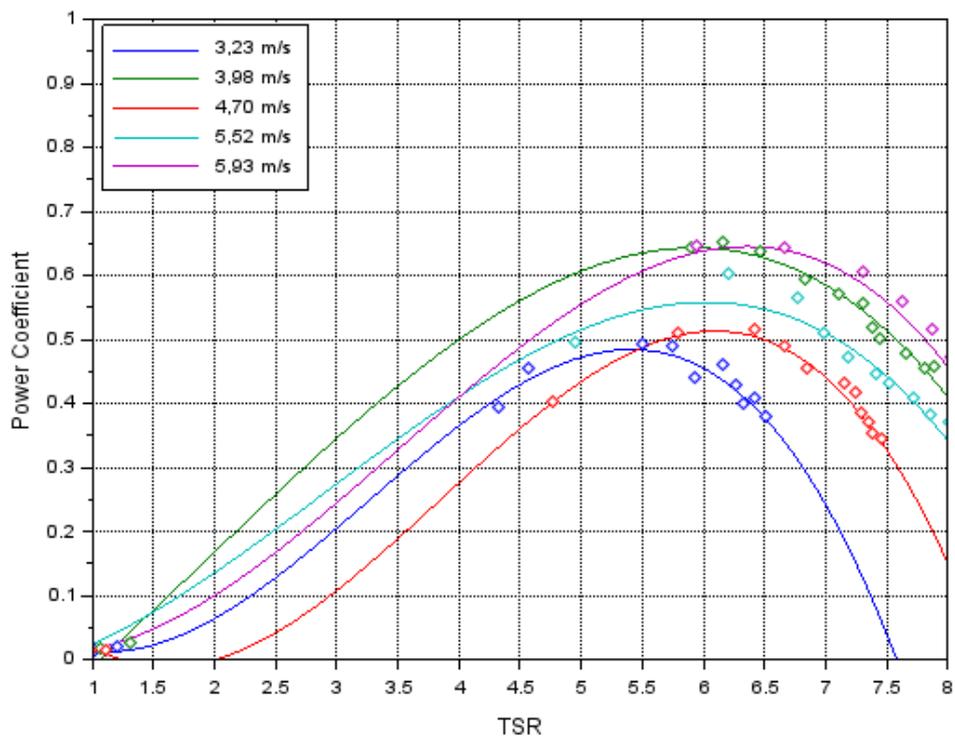


Figure 7. Power Coefficient.

It is possible to see that the curves obtained are similar from those present in the references. In the other hand, the values for some TSR's are above Betz's limit. This was expected due to the blockage effect described before. The velocity of the flow is increased when it passes through the turbine to maintain the conservation of mass. The Bahaj's correction method was applied, and the corrected curves can be seen in Figure 8.

In average the correction applied transformed the power coefficient to 75% of its measured value. After the correction, all values appeared under Betz's limit, representing that the method accomplished its objective. The graph in Figure 9 was made to compare the power coefficient curve before and after the correction.

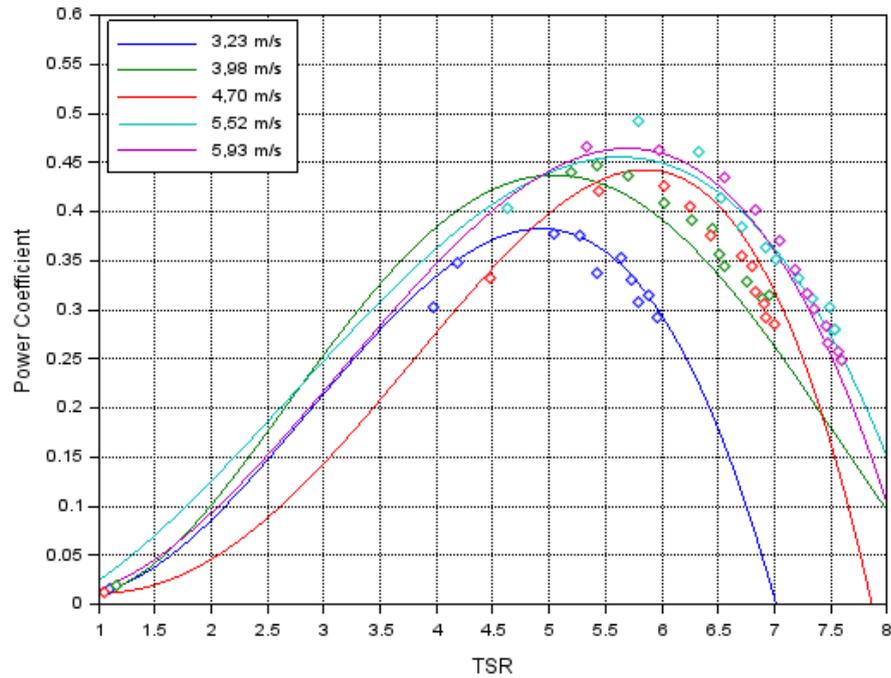


Figure 8. Corrected Power Coefficient.

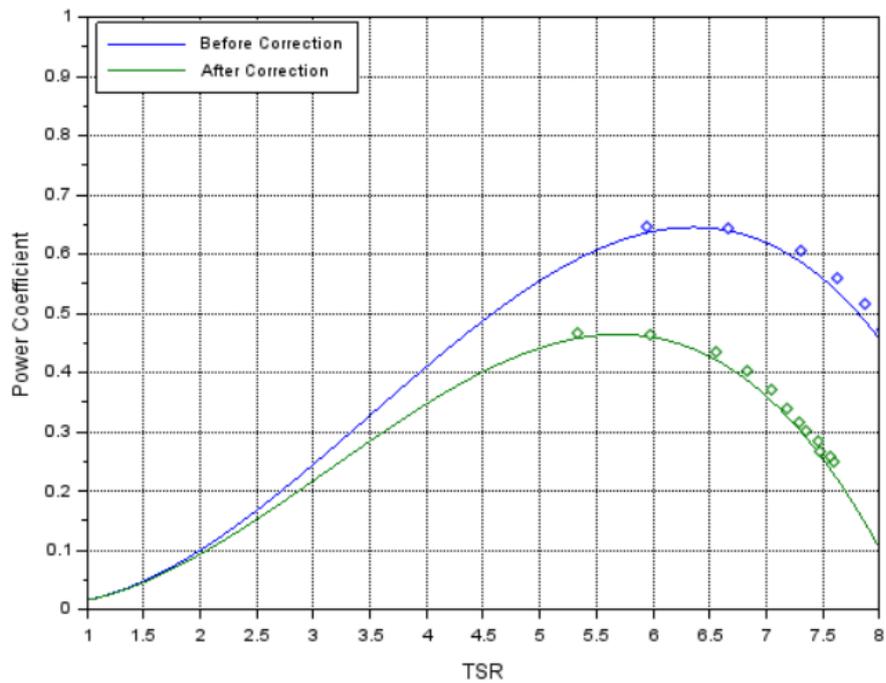


Figure 9. Comparison of the Power Coefficient curves before and after the correction at 5,92 m/s.

The methodology showed satisfactory results, the shape of the power coefficient curves obtained are like those found in the literature and they also respect Betz's limit.

Nonetheless, the results are a little bit over the expectations. The blade utilized has no extraordinary aerodynamic profile but achieved a performance even higher than the results obtained by Ajirlo and Tari (2021) in experiments realized with a NACA4412 profile, which is a consolidated profile among wind turbines.

For each test, 3 different measurements were made. The maximum standard deviation of the wind velocity, current and voltage were, respectively, 32%, 0.5% and 15%

2.6 Conclusion

The wind tunnel utilized during this work has a small cross section and length. The flow within it is also not regular. All those reasons contribute to a more difficult methodology for obtaining satisfactory results.

The continuous development of this methodology is suggested. The wind velocity profile was measured 0,3 m before the turbine, which is far away from the suggestion of 3.5D proposed by Jeong and Lee (2018). Due to the small length of the tunnel, it is impossible to follow that suggestion, but changing the distance to 0,4 or 0,5 m could show better results. The acquisition of wind velocity and angular velocity were handmade, which increase the errors. It is suggested that the acquisition of both values should be made by sensors installed within the tunnel. The power measured was electric, the change of electric power to mechanic power by installing a sensor in the turbine is highly recommended. To reduce the blockage effect, a reduction in the size of the rotor and its blades is recommended. The blockage effect corrections among literature are used for B_R varying from 10 to 30%, the B_R calculated in this work was 82,6%, making necessary the validation of this method for such high ratios.

Some suggestions above are already being followed by the FDT-UNIFEI group for further analysis.

3. ACKNOWLEDGEMENTS

We thank the Research Support Foundation of the State of Minas Gerais (FAPEMIG), process APQ-00653-22, regarding the project: “Numerical and Experimental Analysis of Wind Microgenerators for Applications in Remote Regions in Brazil” notice 001/2022, registration in DPI UNIFEI No: PVDI297-2022, for the funding of this research.

We also thank the Energy Engineering Postgraduation Program (PPGEEN) for the funding of this research.

In addition, we thank the Institutional Program of Scholarship for Scientific Initiation financed by FAPEMIG (PIBIC FAPEMIG) for the financial support to the FDT – UNIFEI (Fluid Dynamics and Turbomachinery) research group for making this work possible.

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