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Original scientific paper

SAVONIUS MICRO WIND TURBINE: A THEORETICAL ANALYSIS [*]

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Abstract. *Currently, the energy sector is the main responsible for the emission of carbon dioxide into the atmosphere. Therefore, to reverse this scenario, it is necessary to expand the use of renewable energy sources, such as wind energy. With that, the search for improving efficiency in wind turbines that work with low speed winds, make the Savonius turbine an advantageous option for presenting characteristics of low construction cost. This study aims to theoretically analyze a single model of vertical axis wind micro turbine using artificial wind. The wind power for 2 stages in this project was 0.063 W, as the power variation in relation to rotation is not linear. Another important factor to consider is that the overlap ratio of 30% collaborates a power reduction. Using the mathematical models, some results were theoretically analyzed through the Savonius turbine with central axis. The literature indicates that the most efficient turbine is a two-stage turbine with helical blades and without a central axis.*

Key words: *Wind energy, mini wind turbines, Savonius*

1. INTRODUCTION

This work is an extended version presented in [1], where the operating principles of a low-cost anemometer were presented. The world energy sector is the main responsible for the increase of carbon dioxide in the Earth's atmosphere, and in 2007, 25% of the total greenhouse gases were emitted, due to the burning of coal, natural gas and oil. Thus, in order to favor economic growth, it is necessary to invest in alternative energy sources aimed at sustainable development, as renewable energy [2].

Renewable energies are those that are replenished naturally, that is, they are inexhaustible sources such as solar, tidal, geothermal and wind energy. According to [3] the production in the

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European Union grew by 5.1% per year between 2007 and 2017, with wind being the second most produced energy source. Wind energy is the transformation of air movement into useful energy, transforming mechanical energy into electricity, especially vertical and horizontal axis wind turbines [4]. This energy has been used for many centuries, such as ocean navigation, grain milling and water pumping [4].

Persian windmills used in the transformation of wind energy into mechanical energy and their assembly was basically on vertical axes [5]. The first applications in Europe took place in the Netherlands with the same function of grinding grain, later spreading to the rest of the European continent in countries such as France, Germany, Belgium and Denmark. However, it was in Holland that they had the function of pumping water, with the change to the horizontal axis [5].

In comparison with Europe, the exploration of Brazilian wind energy began in the 1990s. This development took place through a mapping of the country's wind potential through sensors and special computers, mapping the first locations such as the states of Ceará and Pernambuco in northeastern Brazil [6], [7] and [8].

The heating up of the Brazilian market only occurred in 2004 with the creation of the Incentive Program for Alternative Sources of Electric Energy (PROINFA), with the incentive of wind farm projects. Even with the aforementioned incentive, the real growth occurred between 2009 and 2011, with the reduction of wind turbine prices and greater ease of connections to the electricity grid [9].

Brazil is among the 10 countries that most exploit wind energy, ranking sixth with 3% of the world's installed capacity [10].

Fig. 1 presents the growth of the installed capacity of wind energy in Brazil and its participation in the national energy generation until the year 2020.

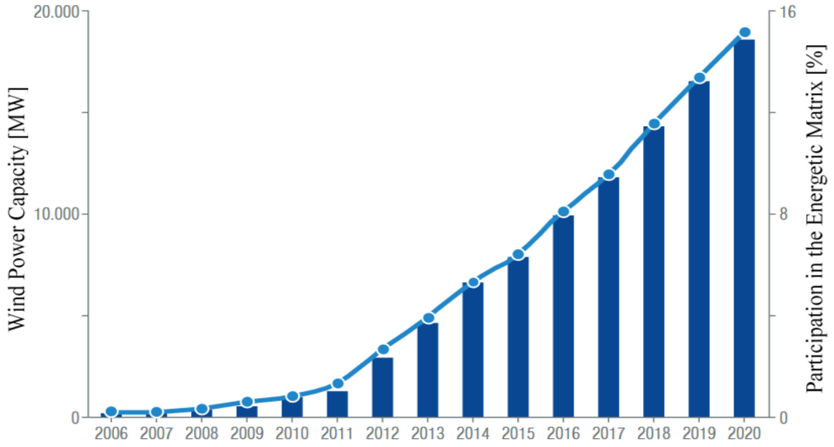

Fig. 1 Wind energy growth in Brazil [9]

1.1. Types of wind turbines

Wind turbines are divided into horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs) [11], [12] and [13].

The HAWTs are more used nowadays because they are more efficient when compared to vertical axis turbines. However, the VAWTs have proven to be viable options due to their low production cost, independence from wind direction and wide applicability. Rotary axis independence makes VAWTs work independently of wind direction [14]. The two main models of vertical axis turbines are Savonius and Darrieus [15].

In the 1930s, the Darrieus turbine was developed, operating on the principle of lift and drag from a wing. Its efficiency is similar to horizontal turbines, due to the presence of airfoils. When the moving air hits the blades, fixed to the ends of the deflector plates, a low pressure zone is generated. As the blade is fixed, the force of the wind causes the rotational movement of the set [15].

A variation of this type of turbine is the type H blades with straight and helical blades however this variation of the Darrieus turbine has a torque deficiency, requiring a starter motor. [15-16].

Mechanical systems produce constant and artificial exhaust winds, thus producing a constant rotation in the VAWTs, which provides a uniform generation of electrical energy [18].

One of the reasons VAWTs are not that expensive to build is that they do not need a yaw mechanism. This makes them ideal for small-scale applications in remote areas with electricity shortages. Their shells do not require a mechanism to change their angle, as they work with any wind direction. VAWTs are less noisy than HAWTs which facilitates application in urban environments, in addition, with their reduced size provides greater safety for wildlife in rural areas [19].

The Savonius turbine was developed and patented in 1929 in the United States of America and Finland by the Finnish Sigurd J. Savonius. Latter it became one of the most widespread and well-known radial drag turbines in the world. [18-19].

The Savonius turbine works by the aerodynamic principle of drag, having no airfoils, being formed by two opposite half channels, supported by a vertical axis [15]. Their movement is based on the difference in the drag force acting on the concave and convex parts of their shells [19]. For this equipment to have better efficiency, it is necessary to determine the aspect ratio value (α_1), which is the ratio between the height and diameter of the blades, where the most recommended value is around 4.0 [22].

According to Menet [12], the Savonius turbine, compared to other wind turbines, has greater resistance to fatigue and mechanical stress.

Aerodynamically, the Savonius is simpler to design and build, which greatly reduces its cost compared to the airfoil blade designs of other VAWTs and HAWTs [19].

Experimental studies show that the Savonius performs well at low wind speeds and that the two-blade performs better than the three-blade, due to the fact that more drag is wasted on the three-blade versions [23].

1.2. Betz's Law

Betz's Law (1926) states that "the maximum energy utilization of a wind turbine is 59.3%, and that even if a mechanical system is ideal, it is still possible to extract at most about 40% of the kinetic energy of the winds" [13] and [24].

As the maximum power coefficient, CP, is about 59% in wind turbines, according to Betz's Law, despite the efforts of HAWTs and VAWTs turbine designers to improve them, it was difficult to reach the Betz limit [24] on page 27 of that publication.

1.3. Objectives

Analyzing the characteristics of low production cost of the Savonius turbine, low noise and construction in small sizes, it makes it a suitable application in urban environments, for having low noise, and also in rural environments, for having small size [19].

Therefore, seeking to expand this approach, the aim of this work is theoretically analyze the two stages with central axis of Savonius micro turbine for future application in small equipment, in addition to producing a literature review of micro turbines.

2. SAVONIUS

The sizing of the wind micro turbines was based on a prototype developed at the Federal Institute of Science and Technology of São Paulo Campus Catanduva, Brazil, which was reduced to a 1:10 scale compared with an existing project of the Institution.

Prototypes printed on a 3D printer have two stages, each 90 mm high, as the increase in the number of these stages increases inertia and reduces dependence on the wind direction for the start of rotation. On the other hand, the excess of stages would decrease the aspect ratio and static torques [22-23].

Three “end plates” were used, or deflector plates with a diameter of 55 mm and 2 mm thick. Wind tunnel tests using 5 models of Savonius turbines found that the "end plates", which form an angle with the shells, provide improvements in efficiency [27]. Thus, the greater the number of deflector plates, the greater the number of fins, which detain the air, increasing the total drag force by up to 36% [28].

All 2-blade turbines were used, which increases the rotational speed, but also generates a reduction in efficiency [15]. Two models use conventional (straight) blades, which have an efficiency of approximately 10% if installed in a single stage. However, when the stages are overlapped the efficiency increases to 13%. Two other models used have helical-shaped blades that have an efficiency close to 18% in a single stage [29], which was no object of this work.

Savonius wind turbines are designed with the central axis completely blocking the air passage through the cavity of thickness "e" (Fig. 2). This generates better efficiency, while the turbine without the central shaft produces greater stability [30].

In the theoretical analysis of the Savonius rotor (Fig. 2), the equations of aerodynamic power (P_A) and mechanical torque (M) are used [12]. The smallest value of D_f is 10% greater than the value of D [31].

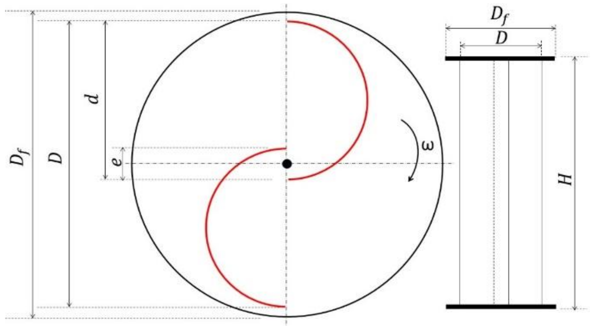

Fig. 2 Built characteristcs of the Savonius rotor $D_f = 0{,}055\ m$, $D = 0{,}04889\ m$, $d = 0{,}03\ m$, $H = 0.186014\ m$ and $e = 0{,}009\ m$

A. Aerodynamic Power (P_A)

2.1. Aerodynamic Power (P_A)

The aerodynamic power (P_A) is determined using Equation (1), derived from the Bernoulli Equation, where C_p corresponds to the aerodynamic power coefficient, ρ the air density, A_p the projected area of the rotor and V the air speed [12].

$$P_A = C_p \cdot \frac{1}{2} \cdot \rho \cdot A_p \cdot V^3 \qquad (1)$$

The projected area (A_P) refers to the product of the diameter (D) by the height of the rotor (H), that is, $A_P = D \cdot H$.

The effect of the number of blades affects the aerodynamic performance of the wind turbine, in terms of λ and C_P, as well as weight, cost, fatigue life and structural dynamics [24], [32] and [33].

The speed coefficient λ determines how fast the wind turbine will rotate. The referred coefficient depends on the specific wind turbine design with regard to the drag coefficient [34] (page 510) of the rotor and the number of shells. A high λ value can generate mechanical stress, noise and low energy absorption. Therefore, it is important that wind turbines are designed to operate in a range of λ, which considers the relationship between angular velocity and wind speed, in order to extract as much energy as possible from the airflow [35].

In Fig. 3 it can be seen that the Savonius turbine works best with lowλ.

The Savonius has a field of application similar to that of Dutch mills and multi-blade axial turbines, but the advantage of Savonius is that it has less structural material.

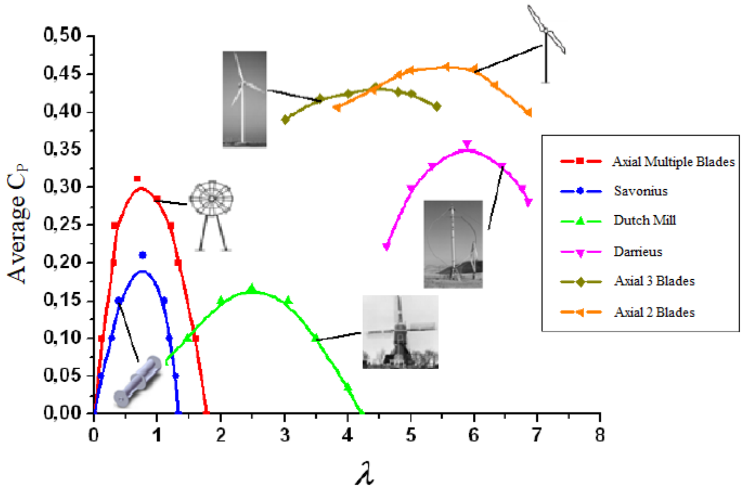

Fig. 3 Characteristic curves of Cp as a function of λ for wind turbines [20] and [36]

It can be observed in Fig. 4 that the Savonius turbine has a higher torque coefficient than the other turbines, with the exception of the Dutch mil [20].

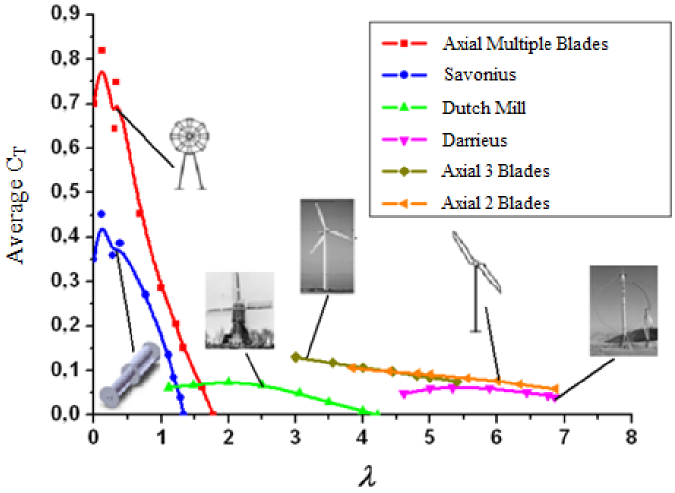

Fig. 4 C_T characteristic curves as a function of λ for wind turbines [20] and [36]

The values of the aerodynamic power coefficient C_p and the torque coefficient (C_m) are obtained graphically through Fig. 5, also studied by [37].

The value of λ is obtained through the relation $\lambda = V_{tang}/V$, where $V_{tang} = \omega \cdot D/2$. The power coefficient has its maximum value when $\lambda \approx 1$.

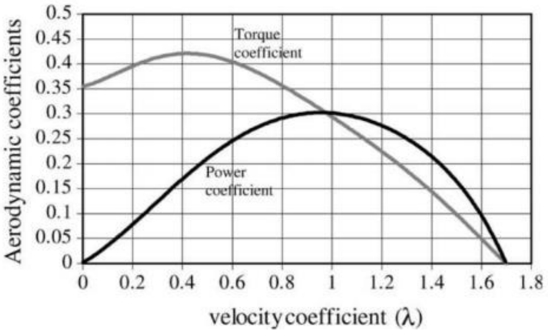

Fig. 5 Value of C_p and C_m, as a function of λ [12-13]

2.2. Torsion Torque (M)

Torsion torque is defined by the Equation (2) [12].

$$M = C_m \cdot \frac{1}{4} \cdot \rho \cdot D \cdot A_P \cdot V^2 \qquad (2)$$

Aspect ratio is an important characteristic of rotor efficiency and defined as $\alpha_1 = H/D$. The best rotor power coefficient has a value of $\alpha_1 \approx 4{,}0$ [39].

The overlap ratio[1] is calculated by $\beta = e/d$, where the best efficiency is between 20 and 30% [16], [30], [31] and [37]. The value of β used to calculate the rotor was 30%, as recommended by the authors Tahani, Kothe and Fujisawa [16], [30], [31] and [37].

The aerodynamic power coefficient relates the aerodynamic power with the power available in the wind, expressed by the expression of $C_P = P_A/P_V$ [41].

The generator's theoretical electric current (I_g), for a voltage of 12V defined by Equation (3). where ω corresponds to angular speed [31].

$$I_g = -0{,}0024 \cdot \omega^2 + 0{,}4138 \cdot \omega + 7{,}6 \tag{3}$$

3. RESULTS

The turbines were designed in Autodesk Inventor software and printed on a 400 x 400 x 400 mm 3D printer (Fig. 7 and Fig 8) with polylatic plastic (PLA) filament witch was chosen in order to a better printing and to have a less materials residues and burs. The stages were built and fitted separately with fittings to enable coupling.

The Figs. 6, 7, 8 and 9 were based on the characteristics of the Fig. 2 with dimensions, $D_f = 0{,}055\, m$, $D = 0{,}04889\, m$, $d = 0{,}03\, m$, $H = 0.186014\, m$ and $e = 0{,}009\, m$. The calculations were performed in Equations (1) and (2).

The theoretical results for the two-stage Savonius rotors applied to this work, obtained through Equation (1), (2) and (3) are presented in Table 1.

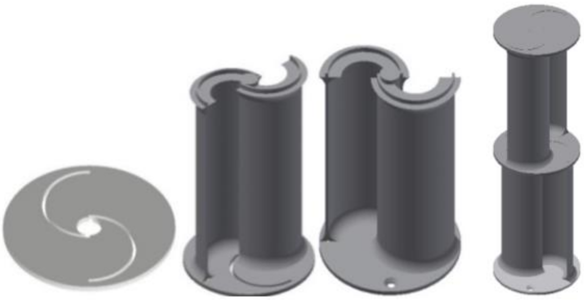

Fig. 6 Assembly of the structure of the Savonius turbine with its two stages, straight blades and shaft, developed by authors

Fig. 7 and 8 show the Savonius turbine with the central shaft dismantled and assembled, printed on 3D printer.

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[1] The overlap ratio β in Savonius turbines is the ratio between the overlap of the blades "e" and their chord length (d). Thus, this is beneficial for the wind turbine due to the increase in pressure caused in the concave region of the return blade. However, it also generates pressure reduction in the concave region of the advance blade [25].

Fig. 7 Savonius turbine printed in 3D, developed by authors

Fig. 8 Savonius turbine printed in 3D and assembled, developed by authors

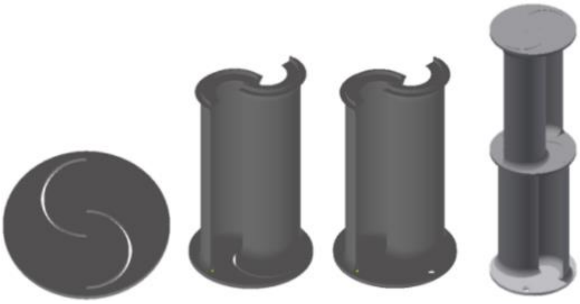

Fig. 9 Assembly of the structure of the Savonius turbine with its two stages, straight blades and no shaft, developed by authors

To generate the results of Table 1, the input data were considered as specific mass $\rho_{air} = 1.23\ kg/m^3$, dynamic air viscosity $\mu_{air} = 0.000015\ kg/m.s$, projected area $A_p = 0.009447\ m^2$, aspect ratio $\alpha_1 \approx 4{,}0$ and peripheral velocity $V_p = 5\ m/s$.

Table 1 Theoretical results for the Savonius rotor

Name	Value
R_e	20788.22
V_{air} [m/s]	5
V_{periph} [m/s]	5
ω [rad/s]	23.47
λ	0.12
C_p	0.043
C_m	0.378
P_E [W]	0.031
P_E (x2) [W]	0.063
M [N.m]	0.001
n [rpm]	224.11
β [%]	30
I_g [A]	0.79

Table 1 presents the theoretical results obtained from the equation presented by Menet [12]. The wind power for 2 stages in this project was 0.063 W, as the power variation in relation to rotation is not linear. Another important factor to consider is that the overlap ratio is very large, thus causing a reduction in power, which has already been presented as a footnote in Section 2.2.

The other results obtained in Table 1 are derived from the dimensions of the designed Savonius rotor.

4. CONCLUSION

The present work sought to expand the application of vertical rotor wind turbines with the use of artificial winds from the development and analysis of computer-assisted design of micro aero generator turbine Savonius two blades with axial shaft.

Using the literature review and theoretical results, the mechanical torque and aerodynamic power were obtained and analyzed in the proposed Savonius turbine configuration.

The analysis carried out in this work is fundamentally theoretical, and to determine the viability of these types of turbines, other analyzes are needed, such as the recovery wind energy obtained from experimental models.

Several research fields need further deeply study. A proposal to install a Savonius micro turbine printed on a 3D printer coupled to a micro electric generator may have satisfactory results through future studies. In this way, it will be possible to compare theoretical results with experimental data through electronic measurements using a Datalogger system.

Another alternative for future work would be to apply the turbine in bus routes to large centers in order to capture wind energy from the passage of buses and transform it into electrical energy. It is also possible to monitor the capture of this energy through an intelligent mobile system, as an example, the one developed for monitoring microclimatic parameters [42].

The literature review is an important tool in the study of this work. Thus, we concluded that the Savonius model with greater efficiency is the one with two stages without a central axis.

Through the experimental further analysis, it will be possible too to certify the more efficiency in two blades with no axis when compared with no shaft as searched in the current literature review.

Acknowledgmenent: *To the Federal Institute of Education, Science and Technology of São Paulo for the constant encouragement*.

NOMENCLATURE

Symbol	Name	Units
A_P	*Rotor projected area*	$[m^2]$
C_P	*Aerodynamic power coefficient*	$[adimensional]$
C_m	*Torque coefficient*	$[adimensional]$
D_f	*End plate diameter*	$[m]$
I_g	*Generator current*	$[A]$
P_A	*Aerodynamic power*	$[W]$
P_V	*Wind power*	$[W]$
V_{air}	*Air speed*	$[m/s]$
V_{perif}	*Peripheral speed*	$[m/s]$
V_{tang}	*Tangential speed*	$[m/s]$
α_1	*Aspect ratio*	$[adimensional]$
D	*Rotor diameter*	$[m]$
H	*Rotor height*	$[m]$
M	*Torsion moment*	$[N.m]$
Re	*Reynolds number*	$[adimensional]$
V	*Air speed*	$[m/s]$
d	*Diameter of rotor half cylinder*	$[m]$
e	*Spacing between the two half cylinders*	$[m]$
n	*Rotation*	$[rpm]$
β	*Overlap ratio*	$[adimensional]$
λ	*Speed coefficient*	$[adimensional]$
ρ	*Air density*	$[kg/m^3]$
$\boldsymbol{\omega}$	*Angular speed*	$[rad/s]$

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