Tests upon Savonius turbine and its usage in street lighting pole

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Abstract. The tendency nowadays is to reduce the consumption of conventional energy and to efficiently use renewable energy resources. Thus, the energy independence of the different consumers is tried, along which is the street lighting. There are many applications where street lighting is powered by renewable energy, using photovoltaic panels. This article presents a different solution for powering street lighting, with the help of wind energy, through Savonius turbines. A Savonius wind turbine with the overlap ratio of blades of 0.35 is tested, in order to determine its actual power coefficient and power extracted from the wind. According to the tests, a power coefficient of 0.3 was obtained for wind speeds of 4 and 5 m/s and the maximum power at a wind speed of 7 m/s. With the values obtained, for this type of turbine, different configurations of Savonius turbines have been dimensioned to supply an energy-efficient street lighting pole.

1. Introduction

One of the current trends regarding public lighting is to ensure the independence of its electricity supply from the public electricity grid, this being achieved by using renewable energy (in most cases with solar energy through photovoltaic panels) or hybrid solutions. This is not possible if high-pressure sodium lamps, which are the most widespread, are still used for street lighting, because they have a very low efficiency (low lumen/W ratio). The best solution for the replacement of high-pressure sodium lamps, to ensure the lowest energy consumption, achieved with the condition of preserving or even improving lightning quality are LED lamps. Their low consumption makes the solution of energy supply from renewable sources much easier to implement, thus being able to ensure the independence of these installations.

Wind energy is not as widely spread as solar energy in powering street lighting consumers. The energy contained in wind can be transformed into electrical energy through wind turbines. Since the beginning of wind energy conversion technologies development, installations of different types and forms have been created and developed. Thus, wind turbines can be classified according to several criteria, but the most important ones are based on rotors operation principle and those that refer to their constructive form [1].

Considering the aerodynamic principles on which the operation of wind turbines is based, they can be divided into two categories, namely, wind turbines whose rotors use exclusively the effect of aerodynamic lift, also called "lift-type rotors", and wind turbines whose rotors use only the aerodynamic drag effect to create a rotational movement, also called "drag-type rotors", category in which Savonius turbines are included [2].
However, in most cases the wind turbines are classified according to their constructive form, and in this situation, the most convenient classification is that according to the position of the rotor axis. Depending on its position, wind turbines are divided into two categories: Horizontal Axis Wind Turbines (HAWT) and Vertical Axis Wind Turbines (VAWT - Vertical Axis Wind Turbines) [3].

The most used type of turbine for electricity production is the turbine with horizontal axis with propeller rotor. The main advantage of this type of turbine is the high-power coefficient, with values between 0.35 and 0.45. Because propeller-type turbines use only the aerodynamic lift effect to create rotational motion, their proper locations are areas with high wind potential, i.e. areas where the average annual wind speed exceeds 5-7 m/s [1,4].

In contrast, wind turbines with vertical axis (VAWT) may represent the future solution for power generation in areas with low air stream speeds (between 2 m/s to 5 m/s) or in areas where the wind has a turbulent character, even if the power coefficient registers values between 0.2 and 0.3 [3,5-8]. In addition to this, turbines with vertical rotors have the main advantage that they can operate and produce energy in severe weather conditions, with low intensity or turbulent wind of nature and frequent changes of direction [1-3].

Due to the simple design and low costs of production and operation, Savonius rotors, have become increasingly interesting for electricity production by converting wind energy into mechanical energy and then into electricity through an electric generator.

Many studies showed that Savonius wind turbines, with different overlap ratios of blades, have a power coefficient between 0.2 and 0.3 [5-8]. Starting from these considerations, in this article, a Savonius wind turbine with overlap ratio of blades of 0.35 is tested. These tests aim to determine the actual power coefficient and power extracted from the wind at different air speeds. Then, based on the values obtained from the tests, a Savonius turbine is dimensioned to power an energy-efficient street lighting pole.

2. Materials and Methods

2.1. Materials

For the test part, a Savonius rotor with semi-cylindrical blades was manufactured [9,10]. The rotor has the overlap ratio of blades (e/D) 0.35. In figure 1 is presented the constructive shape of the turbine and in table 1 are shown the dimensional characteristic of the turbine.

![Figure 1. Savonius turbine constructive shape used in experiments.](image)

![Figure 2. Scheme with operation principle of Savonius turbine.](image)

| Rotor diameter, D (cm) | Blade diameter, d (cm) | Rotor height, H (cm) | Endplate diameter, D0 (cm) | Overlap distance, e (cm) | Overlap ratio, e/D (-) |
|------------------------|-----------------------|----------------------|---------------------------|------------------------|----------------------|
| 18                     | 12.2                  | 18 cm                | 19 cm                     | 6.3                    | 0.35                 |

The semi-cylindrical blades placed in “S” shape, as it’s shown in figure 1 and 2 (figure 2 - the operating principle of a Savonius turbine), make up the rotor. The concave and the convex side of the
rotor are simultaneously under the wind influence [11]. The rotation of the rotor is possible due to different values of the drag coefficient of the two blades during the wind action - the drag coefficient of the concave surface of the blade is greater than that of the convex one. This has a direct influence on the forces acting on the two blades: the force acting on the concave blade is greater than the force acting on the convex blade. Thus, the moment generated by the first force is also greater than the one given by the second force, thereby ensuring the rotation of the vertical axis rotor [2, 9].

Plastic was used for the wind turbines rotor blades. The end plates were made of comatex. A silicone-based adhesive was used for blade assembly with the end plates and with the rotor shaft. Then, the rotor was mounted on a metal frame by means of thrust bearings [12, 13].

The wind turbine was tested in front of an open subsonic wind tunnel (see figure 3). The wind tunnel simulates wind speeds from 0 m/s up to 7 m/s. The wind tunnel has three different sections and all of them are made of galvanized steel sheet. The inlet section of the tunnel is imposed by the axial fan diameter. The second section makes the transition from circular to square section. The outlet section requires a size of 1.2-1.5 times higher than the rotor in order the airflow coming out of the tunnel to cover the entire surface of the turbine [12, 13]. All the tunnel dimensions are presented in the figure below.

![Figure 3. Open-circuit subsonic wind tunnel. [12, 13].](image)

The air stream given by the tunnel was measured with a high precision anemometer, AM 50. The anemometer was placed at the outcome of the aerodynamic tunnel. With an accuracy of ±3% the anemometer can measure airflow speeds between 0 and 45 m/s. The rotation speed of rotor was recorded with a digital tachometer, Volcraft DT-10L, which was placed at approximately 35 cm. The measuring range of the tachometer is from 2 to 99,999 rotation per minute with an accuracy of ±0.05%. The recommended measurement distance is between 5 and 50 cm. In order to measure the angular velocity a torque meter, PCE-TM 80, was used. This torque meter records values from 0 to 147 (N·cm) and has an accuracy of ±1.5%. The sensor of the torque meter was placed on the rotor shaft.

Preliminary determinations proved that a distance about 3 to 5 equivalent diameters of the wind turbine from the wind tunnel outlet section, was the best solution in obtaining a laminar airflow regime [12].

The operational scheme of the experimental stand is presented in figure 4.
For the dimensioning part of the Savonius turbine, the principle diagram of an energy-efficient outdoor lighting pole is presented in figure 5.

2.2. Mathematical equations

The mechanical power, $P$, which may be absorbed from the air streams by means of a wind rotor, can be expressed by the following equation [14]:

$$ P = \frac{1}{2} \rho A v^3 C_p $$

where: $\rho$ – air density [kg/m$^3$]; $A$ – rotor area [m$^2$]; $v$ – wind speed [m/s]; $C_p$ – power coefficient.
The rotor area of Savonius turbine can be assimilated with the area of a rectangle defined by diameter D and height H of rotor, as it can be seen in the next relationship [3, 14]:

\[ A = D \cdot H \]  (2)

The power coefficient, \( C_p \), express the amount of energy extracted from wind by using Savonius rotor. It has variable values depending on the tip speed ratio (\( \lambda \)) and coefficient of torque (\( C_t \)) [4,15]:

\[ C_p = \lambda \cdot C_t \]  (3)

The tip speed ratio is determined with the following equation [2, 4]:

\[ \lambda = \frac{\omega R}{v} \]  (4)

where: \( \omega \) - angular speed [rad/s]; \( R \) – rotor radius [m]; \( v \) – wind speed (m/s).

Coefficient of torque is given by the next formula [3, 4]:

\[ C_t = \frac{2\pi}{\rho v^2 A R} \]  (5)

where: \( T \) - torque (N·m).

3. Results and discussions

The objective of this study was to determine the actual power coefficient and mechanical power extracted from the wind using a Savonius turbine. The wind turbine was tested at airflow speeds between 0 and 7 m/s. These speeds were obtained by modifying the fan speed with the speed regulator which the open subsonic aerodynamic tunnel is equipped. The turbine rotation speed, instantaneous airflow velocity and angular velocity were recorded using a laser tachometer, an anemometer with propellers respectively a torque meter. Regarding the rotor speed, the minimum, average and maximum values corresponding to the different wind speeds in the range 0 to 7 m/s were recorded.

Using average values obtained from test, a graph was drawn that shows the curve of variation of the rotor speed according to the speed of the air flow, graph shown in figure 6.

![Figure 6. Rpm-v variation curve.](image)

Analysing the figure above, it can be observed that rotation per minute increases with air speed. For wind speed between 1 and 3 m/s the rpm values increase rapidly, a slowdown is observed from 3 to 4 m/s, from 4 to 5 m/s rpm values increase rapid again and then again slowdown from 5 to 7 m/s. In table 2 are presented the medium torque values recorded during tests for rpm average values.
Table 2. Torque’s medium values.

| v (m/s) | 1  | 2  | 3  | 4  | 5  | 6  | 7  |
|---------|----|----|----|----|----|----|----|
| T (N·cm)| 0.06 | 0.16 | 0.36 | 0.95 | 1.31 | 2.4 | 3.12 |

By comparing the values from the above table with the rpm-v curve evolution, it is observed that the torque is inversely proportional to the increase of the rotations per minute curve. Torque values, for wind speeds from 1 to 3 m/s, have a slowly increase compared with rpm values where have a rapid increase, then from 3 m/s the torque values increase rapidly and the rpm values slowdown.

Knowing the curve and the variation equation of the rotor speed for any value of airflow velocity is very useful in the process of choosing the electric generator that will fit the wind turbine. The electric generator can be connected directly to the rotor shaft or coupled to it by a gearbox or speed multiplier [13].

In order to obtain the curve and the variation equation of rotor speed, the experimental data obtained were processed using the CurveExpert calculation program. Figure 7 shows the rpm-v variation curve, and in Table 3 the equation of the rpm-v characteristic curve of the tested turbine is presented.

Figure 7. Rpm-v characteristic curve for Savonius turbine.

Table 3. Equation of the rpm-v characteristic curve.

| Function type | Function | Coefficients | Standard error | Correlation coefficient |
|---------------|----------|--------------|----------------|------------------------|
| Polynomial degree 4 | rpm = a + bv + cv² + dv³ + ev⁴ | \(a=-358.714\) \(b=617.523\) \(c=-209.25\) \(d=33.813\) \(e=-1.9848\) | E=11.1714 \(C=0.99778\) |  |

From the analysis of the data processed with CurveExpert it is observed that the equation of the characteristic curve of turbine operation is a polynomial of degree 4. The standard error obtained must be as small as possible, ideally the residual values at the reference points are balanced over the whole range, ie the sum of the positive errors should be approximately equal to the sum of the negative errors. The correlation coefficient must have a value as close as possible to the unit, and for this turbine the difference is only 0.2%.

To establish the mechanical power available at the rotor shaft, the power coefficient of the turbine needs to be determined. With equation (3) is determined the power coefficient. The tip speed ratio (\(\lambda\))
was calculated with relation (4). The power coefficient, \( C_p \), is determined based on tip speed ratio, \( \lambda \), and on coefficient of torque, equation (5). In figure 8, variation of power coefficient is presented.

![Figure 8. Variation of the power coefficient.](image)

In figure 8 is observed that the power coefficient of Savonius turbine increases from wind speed 3 to 6 m/s. The highest values obtained are for wind speed of 4 and 5 m/s. At 7 m/s wind speed, \( C_p \) decreases as a probable consequence of air stream turbulence.

Returning to relation (1), the mechanical power available at the rotor shaft was determined, values presented in table 4.

| \( v \) (m/s) | \( P \) (W) |
|---------------|-------------|
| 1             | 0.005       |
| 2             | 0.04        |
| 3             | 0.16        |
| 4             | 0.48        |
| 5             | 0.8         |
| 6             | 1.24        |
| 7             | 1.7         |

Table 4. Mechanical power extracted from wind.

From the values presented in table 4 is observed that with the increase of air speed, the mechanical power extracted with Savonius turbine increases.

Following tests performed, a Savonius wind turbine was dimensioned to supply electricity to an energy-efficient street lighting pole. The vertical axis wind turbine must supply energy to a led lamp of 36 W that operates approximately 10 h/day. The energy provided by the turbine, under these conditions is 0.36 kWh/day, which is equivalent to a turbine power of 15 W. Area of the turbine is determined using relation (1). The values taken in the turbine sizing calculation are presented in table 5.

| \( v \) (m/s) | \( Cp \) [-] | \( \rho \) [kg/m³] |
|---------------|-------------|-------------------|
| 4             | 0.3         | 1.225             |

Table 5. Values considered from tests for Savonius turbine dimensioning.

In these conditions, the area of the Savonius wind turbine is \( A = 0.72 \text{ m}^2 \). If it’s wanted that the shape ratio of the rotor, \( H/D \) to be unitary, meaning the diameter and the height rotor to have equal dimensions, the actual dimensions of the rotor are determined and presented in table 6, along with other possibilities of configuration of the rotor.

| Application           | Energy consumed (kWh/day) | Turbine’s power (W) | Dimensions D x H (m) | Blade diameter, d (m) |
|-----------------------|---------------------------|---------------------|----------------------|-----------------------|
| Street lighting       | 0.360                     | 15                  | 0.85 x 0.85          | 0.51                  |
|                       |                           |                     | 0.6 x 1.2            | 0.36                  |
|                       |                           |                     | 0.72 x 1.0           | 0.43                  |

Table 6. The calculated dimensions of the Savonius turbine.
4. Conclusions
Following tests performed, it was observed that the power coefficient reaches maximum value 0.30, at wind speeds of 4 and 5 m/s. The power extracted from wind increases proportionally with the air speed.

The values considered for the wind turbine dimensioning were chosen for a lower wind speed, 4 m/s, where were obtained good results for the power coefficient. At an air speed of 4 m/s, a horizontal axis wind turbine is not efficient, the best option to supply energy to a street-light lamp is the vertical axis wind turbine.

For the street-lighting pole was imposed a led lamp of 36 W that operates 10 h/day. The area of the Savonius wind turbine was calculated, 0.72 m$^2$. For this required area three different configuration of dimensions were presented and each one can assure the energy for the led lamp. The Savonius turbine can be placed directly on the pillar supporting the luminaire of the street lighting pole, either in the axis of the pillar or on a console. This greatly reduces the investment required to build the wind turbine, as it is no longer necessary to build a separate structure for the turbine’s location.

If it is necessary to equip the pillar with two or more luminaires, the electricity requirement can still be ensured, either by installing a larger turbine or by installing several identical turbines, each having the capacity necessary to ensure the consumption of a lighting lamp.

Also, the turbines with vertical axis are suitable for electricity supply for the lighting of bus stations, pedestrian crossings, road markings and advertising panels, giving them the possibility of energy independence.

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