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A BRAKELESS SAVONIUS TURBINE

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Abstract: *The research presents a constructive solution and the related mathematical model of a Savonius turbine that can self-stabilize its rotational speed without braking. Beyond a certain value of the wind speed, it is desired that the rotational speed of the turbine becomes constant. So far, this has been achieved using a brake. The present work proposes a constructive solution with mobile blades that, under the action of centrifugal force and of some springs, adjusts the area of the turbine's blade, according to the wind speed, so that the rotational speed remains almost insensitive to the wind speed variations. The mathematical model needed to dimension the features of the main components is presented. Experimental tests validate the theoretical research.*
Keywords: *Savonius turbine, optimization, rotors, blade, computational fluid dynamics.*

1. INTRODUCTION

The Savonius turbines are vertical-axis wind turbines (VAWT). They are extensively used because of their advantages: simple to design, manufacture, and install, good self-starting capability, ability to operate at low wind speed, and they are independent of the wind direction.

However, they have some drawbacks, such as the low rate of capturing wind energy and a variable rotational speed, depending on the wind speed.

For decades, scholars have been concerned with Savonius turbines and how they can be improved in any aspect. A way to improve the rate of capturing wind energy is to show the wind only the active side of the blade, the so-called partially blocked rotor [1, 2] . A technical solution to enhance the ability to start operating under low-speed wind, and to generally improve the performance of Savonius turbine was to combine it with the Darrieus turbine, that is to design hybrid Savonius-Darrieus turbines [2–4]. Another study proposed using a horizontally displaced Savonius turbine in a hybrid Savonius-Magnus combination [5].

The blade profile of the Savonius turbine can significantly influence its performance, so it was extensively studied [6, 7]. The general condition was that the optimal profile depends on many factors, among which, one of the most important is the location where the turbine is placed in – built-up area, mountains, and others. Another solution that was studied was clustering several Savonius turbines [8]. It was found that a cluster of three turbines optimally placed can increase the total power offered by 30% against three insulated turbines

Some innovative constructive solutions for Savonius turbines aim to improve performance using variable blade geometry [9, 10]. What is common to these studies is that the variability of the blade geometry is static. Some features of the blades can be adjusted when the turbine is stopped, to fit specific wind conditions.

The geometry of the blade that can be adjusted while the turbine is operating is proposed in [11]. It aims to reduce the negative torque on the rotor when the convex side of the blade faces the air source. An improvement in power collection of 16%-25% was observed, depending on the wind speed.

A problem with the Savonius turbine installed in the mountain area is its behaviour in strong wind circumstances. A strong wind may cause the over-speeding of the rotor, and from here to mechanical damage to the turbine is just a step.

So far, a single way to prevent this is to slow down the rotation, or even blocking the turbine using a brake [12]. This is not an appropriate solution, because it counteracts a negative phenomenon that already occurred: the overspeed of the rotor. Furthermore, blocking the rotor subjects it to torsional overuse, which might cause mechanical damage. Some possible solutions to overspeed the rotor are offered in [13]. Using a variable geometry of the blades, they can reduce the area that faces the wind when this increases in speed. The direct consequence of the increase in wind speed is the increase in rotational speed of the rotor.

Based on the centrifugal force, the configuration of the blades is changed (surface decreasing), hence limiting the rotor speed. In this way, the overspeed of the rotor is prevented, instead of being counteracted after it has already occurred. This is the novelty that this paper claims.

The present research continues [13] by adding a mathematical model that allows choosing the limit speed to be stabilized (prevent its increasing beyond the desired limit).

The paper is further structured as follows: material and method, which deals with a general theoretical frame, the constructive solution, and a mathematical model, followed by a discussion and conclusion.

2. MATERIAL AND METHOD

In many applications of turbines for generating electricity, a constant rotational speed is wanted, without being a condition [14]. However, the overspeed of the turbine is to be avoided, because it subjects the machine elements to mechanical damage.

2.1 A general theoretical frame

The main formulae used to calculate the wind energy captured are as follows [14].

- The wind power delivered by the air stream;

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

Where P [W] is the power delivered by the air stream, ρ []kg/m^3] denotes the air density, A is the area of the blade exposed to the wind, and v [m/s] denotes the wind speed. By exposed area, one must understand the *swept area* or the *projected area*. In these terms, the area (A) to be considered in computing the captured power is calculated by eq. (2).

$$A = As = 2 * R * h \tag{2}$$

Where A, As [m^2] is the swept area, R [m] denotes the radius of the turbine, and h [m], its height.

- The power collected by the Savonius turbine;

$$Ps = Cp * Pw \tag{3}$$

Where Ps and Pw [W] are the power captured by the turbine and power delivered by the wind, respectively, and Cp is the turbine. According to the literature [14] the Cp falls in the range of 0.15 .. 0.3, depending on the geometrical and constructive features of the turbines.

- The torque the turbine generates;

$$T = {}^{Ps}/_{\omega} \tag{4}$$

Where T []Nm] is the torque and ω [rad/s] denotes the rotational speed of the turbine.

- The tip speed ratio (TSR);

$$\lambda = {}^{R * \omega}/_{v} \tag{5}$$

Where λ (non-dimensional coefficient) is the tip speed ratio (TSR), that is the speed ratio at the outer diameter of the rotor, R [m] denotes the rotor radius, and ω [rad/s] is the rotational speed. In other sources ω is called angular velocity.

- The effectiveness of the turbine;

$$\eta = {}^{Ps}/_{Pw} \tag{6}$$

Where η is the effectiveness of the turbine. It appreciates the capability of the turbine to convert the power of the wind to useful power. This is in fact a particular value of Cp used and explained in (2). Ps and Pw have the significance given in (2).

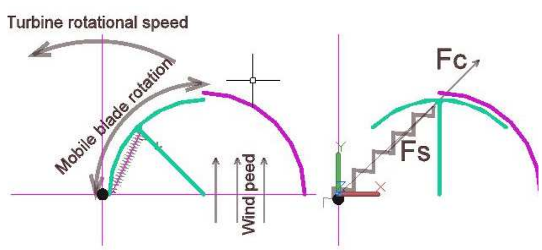
Generally speaking, the yield of the turbine expresses its capability to convert the power of the wind to another type(s) of power. It depends mainly on the shape and size of the blades and the quality of the bearings,

According to [14] the recommended rotational speed for producing electricity is 300 rpm, which for the common size of the turbine of R=0.5 m and $\lambda = 1$ corresponds to a wind speed of about 15 m/s. Considering this recommendation and the appropriate mechanical conditions of work for the turbine, the rotational speed should be limited (restricted) for a wind speed higher than 15 m/s – such a wind speed often occurs in the mountain area, and not only there. This can be done naturally, without a brake or any other means, by putting the centrifugal force to act towards reducing the area of the turbine blades that faces the wind.

The direct consequence of this is reducing λ, and hence achieving a decrease in rotational speed. The way this can be applied is described in the next section of the paper.

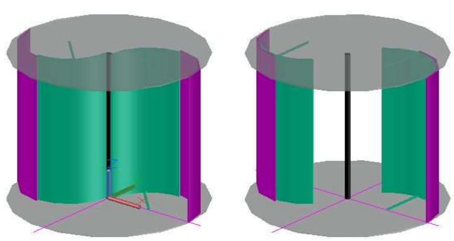
2.2 The original constructive solution

The constructive solution for the turbine is to build each blade into two parts: a fixed part and a mobile one. Both of them are assembled in the upper and lower discs. The mobile blade is inserted into the discs using two arms articulated at the center of the blade, so it can rotate against its axis under the effect of the centrifugal force.



(a) (b)

Fig. 1. The principle of rotational speed limitation of the turbine. (a) the rest position of the mobile blade; (b) the rotated position of the mobile blade.



(a) u (b)

Fig. 2. The concept of the turbine. (a) the rest position of the mobile blade; (b) the rotated position of the mobile blade.

When the mobile blade rotates outward, it partially hides behind the fixed one. Hence, the total area of the blade decreases, and the rotational speed does not increase anymore in a direct relationship with the wind speed variation.

If the wind speed slows down, the mobile side of the blade is brought to its home position under the action of a spring.

The principle of work is sketched in Figure 1, and in Figure 2 the simplified concept of the turbine is shown.

The mobile blade gets its balance position under the combined action of the centrifugal force (Fc in Figure 1) and that of the spring (Fs in Figure 1), since the centrifugal force depends on the rotational speed, on the one hand, and on the mass of the mobile blade on the other hand, The paper must answer the following statement: the limit position of the mobile blade can be controlled either by pre-setting its mass or selecting a spring with an appropriate constant.

The main formulae used to calculate the required mass of the mobile blade or the spring constant necessary to limit the turbine's rotational speed at 300 RPM for a certain wind speed are demonstrated in the next section.

2.3 Mathematical model

The mathematical model aims to determine the mathematical relationships between the different sizes of a Savonius turbine. and the wind speed, so that the equilibrium conditions between spring force and centrifugal force, which act on the mobile blade, to be achieved as a condition to limit the rotational speed of the turbine to a certain value (300 RPM).

The given data are λ=0.5 .. 1.2 [14]. Let us consider λ=1 for ease of the computations. The limited rotational speed, which being achieved, triggers the mechanism of limitation, based on centrifugal force: n=300 [min^{-1}]:

According to Hook's law (7)

$$Fs = k * \Delta l \qquad (7)$$

Where Fs [N] is the force that stretches the spring, k [N/m] is the spring constant, and Δl $[m]$ denotes the spring deformation.

$$Fc = m * \omega^2 * R \qquad (8)$$

Where Fc [N] is the centrifugal force, m [Kg] denotes the mass of the mobile blade, ω [rad/s] denotes the rotational speed, and R [m] is the radius of the turbine.

$$n = \omega * \frac{60}{2 * \pi} \qquad (9)$$

Where n [min^{-1}] is the rotational speed. The equation (9) describes the way to convert the rotational speed expressed in [rad/s] to the one measured in [min^{-1}]. Considering (6), (9), and λ=1, a relationship (10) between n and v is found.

$$v=\frac{\pi*n*R}{30} \quad (10)$$

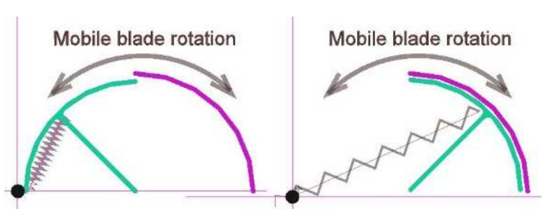
In the given conditions, that is n=300 [min^{-1}] and R=0.5 m, approximately v=16 [m/s]. This is the wind speed beyond which the rotational speed should no longer increase.

At the equilibrium, when Fc=Fs, for constant wind speed, whichever is higher than 16 m/s (57.6 km/h) Fc becomes bigger than Fs, and moves the mobile blade outward. Combining (7), (8), and (10), one can find the balance equation of the system (11).

$$k*\Delta l=m*\frac{v^2}{R} \quad (11)$$

All the symbols in (11) have been explained before.

Any increase in the wind speed beyond 16 [m/s] causes a tendency to speed up the rotation of the rotor, increases the centrifugal force that moves outward the mobile blade, and decreases the area of the rotor that faces the wind. On the other hand, if the mobile blade has left its home position, a decrease in wind speed allows the spring to retract the blade proportionally. In this way, the variation of the wind speed at a higher speed than 16 [m/s] will automatically adjust the equilibrium position and thus keep the rotation speed almost constant.



(a) (b)

Fig. 3. The length of the spring (a) the rest position of the mobile blade; (b) the extremely rotated mobile blade.

Equation (11) suggests two possible action ways to set up one of the variables of the system: either choose a spring with the appropriate constant, according to the mass of the mobile blade (12), or adjust the mass of the mobile blade according to the spring stiffness.

$$k=m*\frac{v^2}{R*\Delta l} \quad (12)$$

$$m=\frac{k*\Delta l*R}{v^2} \quad (13)$$

In (12), *k* is the spring constant, and in (13) *m* is the mass of the mobile blade, which are needed to limit the rotational speed at about 300 [RPM],

The mass can be controlled by adding adequate weights (13).

Based on Figure 3, Δl can easily be calculated, as the difference between the length corresponding to the extreme positions of the mobile blade: fully open and closed. Applying Pitagora's generalized theorem in a triangle with two sides equal to r, and one side the length of the spring.

$$l_0=\sqrt{r^2+r^2-2*r*r*\cos(\pi/4)} \quad (14)$$

$$l=\sqrt{r^2+r^2-2*r*r*\cos(3*\pi/4)} \quad (15)$$

Where r [m] is the rotation radius of the mobile blade, R [m] is the radius of the turbine, and l_0 [m], l [m] denote the length of the spring corresponding to the rest position and extremely extended state, respectively. According to Figure 3, r=R/2, hence performing the calculations, one can obtain that

$$\Delta l=l-l_0=0.54*R, \quad (16)$$

3. DISCUSSION

The relationships presented above are determined for a targeted rotational speed of the turbine of 300 RPM. In the case of a turbine with R=0.5 [m] and $\lambda=1$, this is achieved for a wind speed of approximately 16 [m/s]. For a lower wind speed, the rotational speed of the turbine is accordingly smaller. When the wind speed reaches the mentioned value, the turbine speed limitation system is put to work.

Using the provided relationships, the calculi can be customized to fit any dimension of the turbine or value of λ. If another turbine speed is targeted, based on it and the geometrical features of the turbine, the corresponding wind speed can be determined. This new value can be used in (11) and/or (12) to determine the values of the spring constant or the mobile blade mass that are supposed to stabilize the turbine speed.

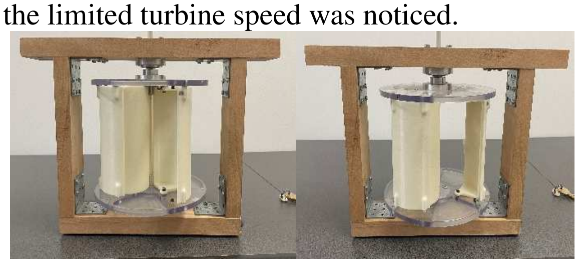
It is obvious that for economic reasons and based on strength criteria, the mobile blades are designed with their minimum mass; hence, to achieve the balance of the turbine speed, only the increase of their mass can be considered. Otherwise, the adjustment can be done by choosing a spring with a different constant. In [13] some ways to attach additional mass to the mobile blade of the turbine are presented.

To prevent the centrifugal force from moving the mobile blades even at a wind speed lower than 16 [m/s], the spring must be appropriately pre-tensioned. The pretension, that is, the initial deformation Δl_0 can be calculated with (17), which is directly obtained from (12).

$$\Delta l_0 = m * \frac{v^2}{R * k} \tag{17}$$

Whre v [m/s] is the wind speed desired to trigger the turbine speed limitation mechanism.

A small-scale model of the Savonius turbine was built to prove the validity of the mechanism of limiting/stabilizing the turbine's rotational speed. It is presented in Figure 4. Experimental tests were carried out in laboratory conditions, and they were successful: the turbine speed did not exceed a certain value because the mobile blades opened. Furthermore, by replacing the springs with some tougher ones, an increase in the limited turbine speed was noticed.



(a) (b)

Fig. 4. The small-scale model. (a) closed mobile blades; (b) open mobile blades.

4. CONCLUSION

The paper claims the novelty of the principle of slowing down the turbine if needed, without using a brake, which might cause mechanical damage to the turbine in the case of strong wind.

Despite the theory was validated in terms of its quality by experimental tests, further practical research is needed because of the many factors that might affect the accuracy of the output; the value of the TSR coefficient which is strongly influenced by the geometrical and functional features of the turbine, the stiffness of the springs, and others. Hence, more tests must be performed to fine-tune the limited rotational speed and the wind speed to which it corresponds. The pre-tensioning of the springs is crucial to accurately trigger the opening of the mobile blades.

For special situations, when there is a need to stop the turbine fully, this can be covered by a bell-shaped cover, or a mechanical break can be used, if it is smoothly actuated.

For the future, as a continuation direction of the research, the CFD analysis must be mentioned, along with other constructive solutions, which would allow the mobile blades to be placed outwards, so that retracting, they decrease the diameter of the turbine.

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O turbină Savonius fără frână

Lucrarea prezintă o soluție constructivă și modelul matematic aferent al unei turbine Savonius care își poate autostabiliza turația fără frânare. Dincolo de o anumită valoare a vitezei vântului,este de dorit ca viteza de rotație a turbinei să devină constantă. Până acum, acest lucru se realiza folosind o frână. Lucrarea de față propune o soluție constructivă cu pale mobile care, sub acțiunea forței centrifuge și a unor arcuri, reglează aria palei turbinei, în funcție de viteza vântului, astfel încât turația să devină aproape insensibilă la variațiile vitezei vântului. Este prezentat modelul matematic necesar pentru dimensionarea componentelor principale. Cercetarea teoretică este validată prin teste experimentale.

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