Propelling torque of the self-adjusting vertical-axis rotor

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Abstract. The paper presents an innovative solution of the self-adjusting system of the wind turbine with horizontal axis, consisting of two-blade, carousel rotor with vertical axis and two-position self-adjusting mechanism. The procedure of computing power and propeller torque of rotor with self-adjusting system as a function of the angle of wind attack, the design and principles of operation of the adjusting turbine were presented. And also the proposal to use it as a self-adjusting system on the wind direction and at the same time as a protection of the main rotor HAWT (Horizontal Axis Wind Turbine) against excessive speed in strong winds. The proposed system can replace the most common solution like the directional rudder or the auxiliary wind motor, which generally requires the generator rotor brake.

1. Introduction

Analyzing the work of the self-adjusting system on wind direction of the wind turbine with vertical axis VAWT (Vertical Axis Wind Turbine) described in the patent of J. Ryś [1], it was noted that this system can also be used as a adjusting rotor in the popular today’s horizontal axis wind turbine. Modification of this type of system by adding the turbine blades adjusting system, allows the free work of the turbine’s main rotor, regardless of the changes of direction and speed of the wind stream. The goal of paper is the use of theoretical calculations and an analyze of the design and operation [2] for the proposed solution in order to eventually use of this turbine in exchange for a traditional adjusting system of turbine HAWT.

Figure 1. Neutral (a) and active (b) blades position of the self-adjusting turbine.
The theoretical calculations concerned definition and determine the value of the propeller torque $M$ per 1m² of blade as a function of the angle of wind attack, the flat two-blades of rotor adjusting system of turbine, arranged relative to each other so that the axes of the cross-section blades are perpendicular to each other. It should be noted, that the blades are moving of planetary motion and the adjusting system changes the position of the blades in terms of yourself with the neutral position, which follow the wind direction (Figure 1a), onto the active position, (Figure 1b), which deflects the turbine when the main rotor speed exceed the limit value [3-10]. In this case the blades are changing position relative to each other via rotation around their own axis by an angle of 45°, and there are remaining in this position until fall of the speed of the main rotor onto the speed limit. Theoretical calculations for the active position are unnecessary.

Based on presented at the research of the work [11], the procedure of the propeller torque and the computing power and also the propeller torque of rotor with self-adjusting system as a function of the angle of wind attack were prepared. The resultant torque for the self-adjusting turbine:

$$M(\alpha_s) = \left( (M_{1q\xi}(\alpha_s) + M_{1q\eta}(\alpha_s)) - M_{1p}(\alpha_s) \right) + \left( (M_{2q\xi}(\alpha_s) + M_{2q\eta}(\alpha_s)) - M_{2p}(\alpha_s) \right),$$

is the sum of the propeller torque generated by the first and second rotor blade, where, the torques from the first blade in the moving coordinates $\xi$ and $\eta$ are described by equations:

$$M_{1q\xi}(\alpha_s) = 0.5 \left( \frac{V_q(\alpha_s)}{W} \right)^2 \cdot k_{n\xi},$$

$$M_{1q\eta}(\alpha_s) = \left( \frac{V_q(\alpha_s)}{W} \right)^2 \cdot k_{n\eta} \cdot \sin \left( \frac{\alpha(\alpha_s)}{2} \right) \cdot \text{sign}(V_q(\alpha_s)),$$

$$M_{1p}(\alpha_s) = s_{n\xi} \left( \frac{V_q(\alpha_s)}{W} \right)^2 \cdot k_{n\eta} \cdot \cos \left( \frac{\alpha(\alpha_s)}{2} \right) \cdot \text{sign} \left( \cos \left( \frac{\alpha(\alpha_s)}{2} \right) \right),$$

and the torques generated from the second rotor blade:

$$M_{2q\xi}(\alpha_s) = 0.5 \left( \frac{V_q(\alpha_s + 180)}{W} \right)^2 \cdot k_{n\xi},$$

$$M_{2q\eta}(\alpha_s) = \left( \frac{V_q(\alpha_s + 180)}{W} \right)^2 \cdot k_{n\eta} \cdot \sin \left( \frac{\alpha(\alpha_s + 180)}{2} \right) \cdot \text{sign}(V_q(\alpha_s + 180)),$$

$$M_{2p}(\alpha_s) = s_{n\xi} \left( \frac{V_q(\alpha_s + 180)}{W} \right)^2 \cdot k_{n\eta} \cdot \cos \left( \frac{\alpha(\alpha_s + 180)}{2} \right) \cdot \text{sign} \left( \cos \left( \frac{\alpha(\alpha_s + 180)}{2} \right) \right).$$

The remaining values in the equations it the relative velocity components $V_q$ and $V_\xi$ [m/s] for the moving coordinates system associated with a turbine blade $\xi$ and $\eta$, the wind speed $W$ [m/s], the rotor speed $V_o$ [m/s], the angle of the rotor rotation $\alpha$, and the angle of the wind attack $\beta$ (wind direction). The coefficients associated with the components of the wind speed relative to the blade $k_n$, $k_\xi$, $k_{n\xi}$ and also the ratio of the frontal surface to the lateral surface of the rotor blade $s_{n\xi}$ (650x250x6 size of turbine’s blade), as the average values, which have been set on the basis of experimental tests carried out in a wind tunnel the Wind Engineering Laboratory Cracow University of Science and Technology [12, 13] were taken: $k_n=0.05$; $k_\xi=1$; $k_{n\xi}=0.05$; $s_{n\xi}=0.1$.

The formula of the propelling torque at the end was described:

$$M = I_2 \cdot \rho \cdot R \cdot W^2,$$

where $R$ is the radius of the turbine, $\rho$ - density of the air [kg/m³] and $I_2$ is the mean torque of the self-adjusting turbine with two blades [Nm]:
\[ I_2 = \left( \int_0^{360} M(\alpha_s)d\alpha_s \right) \]

\[ N = M \cdot \frac{V_o}{R} = M \cdot \omega. \]

Power N [W] per one square meter of the self-adjusting turbine blade (\(\omega\) – angular velocity of the rotor):

In the calculations two cases were considered. The first for the speed rotor self-adjusting turbine equal to zero \(V_o=0\) with including three different angles of wind attack \(\beta\) and the second for the speed of the turbine rotor which shall be different from zero \(V_o=1\) and also the four different wind directions (the angle \(\beta\)). In both cases, the wind speed \(W=5\).

The examples values of torque and power for the computing procedure below in tabular form were shown.

**Table 1.** The values of torque M and power N the self-adjusting turbine onto the direction wind, depending on the wind direction \(\beta\) for rotor turbine speed \(V_o=0 (\omega=0)\) and \(V_o=1 (\omega>0)\). The negative value of the power means braking power rotor.

| \(\beta\)  | 0°   | 78.5° | 90°  | 101.5° | 180° |
|--------|------|-------|------|--------|------|
| M [Nm] \((V_o=0)\) | 6,11155 | 1,218444 | 0    | -1,218444 | -6,11155 |
| N [W] \((V_o=0)\)   | 0     | 0     | 0    | 0      | 0    |
| M [Nm] \((V_o=1)\) | 3,911392 | -0,003785 | -1,246515 | -2,582774 | -8,800632 |
| N [W] \((V_o=1)\)   | 13,037973 | -0,012618 | -4,155051 | -8,609248 | -29,335439 |

2. Interpolation of the propelling torque of the self-adjusting turbine

For as adopted form of the calculations, the propeller torque of the self-adjusting turbine, for the constant value of the radius of rotor equal \(R=0,3m\) as a function of the angle of wind attack \(\beta\) can be formulated as follows \(M(\beta)\):

\[ M(\beta) = 0,2445 \cdot W^2 \cdot \left( 1 - \frac{5}{4} \cdot \frac{V_o}{W} \right) \cdot \cos \left( \beta + \arctg \frac{V_o}{W} \right). \]

The propeller torque of the self-adjusting turbine \(M(\beta)\) for any value of the rotor radius \(R\) at the function of the angle of the wind attack on the rotor \(\beta\):

\[ M(\beta) = 0,2445 \cdot \frac{R}{0,3} \cdot W^2 \cdot \left( 1 - \frac{5}{4} \cdot \frac{V_o}{W} \right) \cdot \cos \left( \beta \pm \arctg \frac{V_o}{W} \right). \]

The characters in the formula (10) are indicating on the rotor speed: (+) refers to \(\omega>0\), (−) refers to \(\omega<0\). In the case, when 90° > (−) 0° the torque on the directional rotor is positive (right rotation of the rotor), when 180° > β > 90° is negative (left rotation of the rotor).

With this arrangement, any change of the wind direction causes tilt of the resultant force and the emergence of the torque on the axis of turbine. The torque of the self-adjusting gear, transferred to the bearing structure, gives the adjusting displacement in the direction of reducing the angle between the axis of the main rotor jib of the turbine nacelle, to which is attached the rotor of self-adjusting turbine, and the wind direction.

Adjust the blade position at an angle of 45° from the neutral position Figure 1a, an the active position Figure 1b, result in the self-adjusting system positive or negative value of the propeller torque, thanks to that the system can adjust the main rotor on new neutral position by changing the position of the main rotor.

The obtained results allow to illustrate the principle operation of the self-adjusting rotor, as were shown in Figure 2a and Figure 2b.
Figure 2. Graph of the propeller torque for two flat symmetrical blades of the self-adjusting system at a function of wind direction $M(\beta)$: $W=5 \ [\text{m/s}]$; $R=0.3 \ [\text{m}]$; $V_o=0 \ [\text{m/s}]$; $V_o/W=0$ (a) and $V_o=1 \ [\text{m/s}]$; $V_o/W=0.2$ (b).

3. Example of use of the self-adjusting turbine

The properties described above allows to protect the main rotor HAWT against excessive speed in strong winds. The design solution of the self-adjusting system in detail in the patent application were discussed [2].

Figure 3. Kinematic scheme of the turbine with the self-adjusting system to protection the main rotor turbine against exceeding the speed limit, where:

A - main rotor of the horizontal axis wind turbine, B - rotor of self-adjusting turbine with the planetary motion of the two-blades to adjusting on wind direction the horizontal axis wind turbine, C - electromagnetic actuator or stepper motor of the self-adjusting system, which is forcing change the position of blades, 1 - shaft of the nacelle mounted with bearings on the supporting structure, 2 - supporting structure of the horizontal axis wind turbine (flagpole), 3 - jib of the self-adjusting system, 4 - axis of the adjusting rotor, 5 - supporting beam of the adjusting rotor, 6 - axis of the lobe of the adjusting rotor, 7 - lobe (blade) of the adjusting rotor, 8 - transmission gears with a ratio 1:2, 9 - self-locking worm gear, 10 - bevel gear, 11 - gear wheel mounted on the supporting structure, 12 - self-locking worm gear, 13 - generator of the main rotor.
In Figure 3 the scheme of the self-adjusting turbine on the wind direction were shown, equipped with an even number of blades with have a symmetrical cross-section, combined with the worm gear and the protection system of the main rotor HAWT against excessive speed in strong winds. These connections provide the perpendicular arrangement to each other the opposite aerofoils and change their position from neutral to active. In this case, the leaning gear is propels from the axis of the rotor, which on, with the end part is finds the bevel gear, which is connects to self-locking worm gear, and coupling here with the support structure wheel of the mast of the main rotor turbine, allows the main rotor axis deviation by a certain angle relative to the wind direction.

4. Conclusions
The obtained results allowed to analyze work of the rotor, used as the adjusting turbine of the main rotor of horizontal axis wind turbine. The self-adjusting vertical-axis turbine described in the paper, provides continuous setting of the main rotor turbine HAWT to the wind direction at the same time securing it against a strong wind, which could lead to damage the turbine. This solution is not required the brake of the generator rotor, as it is generally used in conventional constructions.

Changing the setting of the main rotor turbine to the wind direction is in the manner set without negative impact to the turbine, having a low gyroscopic torque. The self-adjusting system with the system of turbine protection against exceeding the speed limit does not require additional electric power from outside. At the time when the terminal voltage of the generator equal 230V, at the time when the terminal voltage of the generator equal 230V, the electromagnetic actuator started work via the contactor powered with phase of the generator.

Under conditions of strong wind (about 10m/s) self-adjusting system provides a practical constant voltage on the generator, in the case of an asynchronous generator - voltage 3x400V.

We anticipate build the prototype of the mobile turbine 3.5kW, based on prepared the documentation, for heating water in agricultural. The apply solution of the self-adjusting system according to the patent application [2] will significantly reduce the cost of the turbine due to the simplicity of design and ease of assembly and disassembly.

5. References
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