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VERTICAL AXIS WIND TURBINE WITH ADJUSTABLE BLADES

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Abstract—*It is researched the problem of energetic efficiency increasing of wind energy plant with vertical axis of rotation. For the solution of this problem it is proposed to use the adjustable blades. It is determined the optimal angle of attack of different wind velocities as a result of Navier–Stokes equations solution under different initial conditions (different values of attack angles and wind velocities). It is proposed the approach for the realization of control system of blade angle rotation based on PID-Controller. It is developed the algorism of adaptive PID-Controller. It is developed a Simulink model for this control system.*

Index Terms—Vertical-axis rotor; Darrieus rotor; angle of attack; power of wind turbine; wind turbine efficiency.

I. INTRODUCTION

At present, in the world operated fleet of wind power plants, horizontal-axial or, so-called propeller type installations make up more than 90%.

The lag in the development of vertical-axis wind turbines (VAWT), despite their advantages, as absence of aerodynamic noise, starting at low wind speeds and independence from wind direction, is caused by several reasons. A wind generator with a vertical axis of rotation was invented later by horizontal-axial propeller. In addition, the main disadvantage of vertical wind generators was mistakenly considered that for them it is impossible to obtain a ratio of the maximum linear velocity of the working bodies (blades) to wind speed greater than 1 (for horizontal-axis propeller wind turbines this ratio is more than 5: 1), which necessitated the use of multiplier systems or more massive low-speed generators.

There are exist such types of vertical-axial wind turbines: theSavonius rotor, the Darrieus turbine and the Darrieus H-rotor (Fig. 1).

The main advantage of vertical-axial wind turbines over horizontal-axial is their independence to the direction of the wind [1]. Vertical-axial wind turbine with correctly calculated aerodynamics and geometrical relationships, is capable of self-starting at any direction of the wind, whereas, high power propeller type wind turbines at some angles of inward wind flow relative to the working plane of the windwheel, an additional source of energy is needed to remove the wind turbine's gondola to the wind or change the angle of attack of the blades.

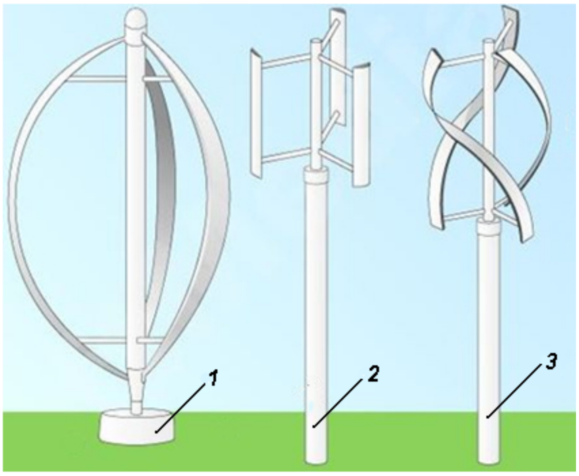

Fig. 1. Types of vertical axial wind turbines:
1 is the Darrieus rotor; *2* is the Darrieus H-rotor;
3 is the Helic rotor

Coefficient of wind utilization of vertical wind turbines of industrial type (Darrieus H-rotor is considered), varies in the range 0.28–0.40. This value is slightly less than horizontal-axial, but the design of these wind generators is simpler [2].

This paper is dedicated to investigations the efficiency of VAWT at different wind speeds, depending on the angle of attack of the rotor blades.

II. PROBLEM STATEMENT

Due to the fact that that mentioned above, vertical axial wind turbines by its energy characteristics lag behind horizontal-axial wind turbines, so the task is to investigate the effect of the changing value of the angle of attack of the blade on the power coefficient of the wind turbine.

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These investigations would allow us to develop new principles for constructing vertical-axial wind turbines with a variable angle of attack of the blades in order to increase the energy efficiency of VAWT.

III. Problem Solution

One way to adapt the properties of a wind turbine to changing wind conditions can be method of power control of wind turbine by changing the angle of attack of the blades.

During the circular motion, the Darrieus rotor blade operates in a periodically changing in non-stationary flow. The projection of the resultant aerodynamic force arising during the airfoil flowof blade profile to the circular trajectory of the blade gives the force that creates the torque on the shaft of the wind turbine. Since typical blade profiles are used for designing blades, the main parameter that determine the magnitude and direction of the force acting on the profile, is called the angle of attack. The nature of the motion of the blade in the rotor with a fixed position of the blades is such that on a very large part of its trajectory the angles of attack become supercritical. This leads to a breakdown of the flow and a sharp decrease in the value of the useful component of the aerodynamic force so that on some sections of the trajectory the blade even brakes the wind turbine. However, if it is possible to simulate the rotor at various angles of attack, that the airfoil flow of the blade occurs at the optimum angle, it is possible significantly increase the value of the torque on the axis of the rotor.

During the modeling we used the viscous gas flow model with averaging of turbulent characteristics (Reynolds-averaged Navier–Stokes equations for an incompressible fluid)

$$\frac{\partial u_j}{\partial x_j} = 0,$$
$$\frac{\partial u_j}{\partial t} + \frac{\partial (u_j u_i)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\nu_{\text{eff}}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right], \quad (1)$$

where $x_i, i = 1,2$ is Cartesian coordinates (x, y) t is time; u_i is the projection (u, v) of the average velocity on the Cartesian coordinate axes; p is pressure; ρ is density; $\nu_{\text{eff}} = \nu + \nu_t$ is effective coefficient of kinematic viscosity; ν and ν_t is molecular and turbulent coefficients of kinematic viscosity.

Boundary conditions (BC). For the side surface of the blade G BC are defined by expression:

$$\vec{U}_{x,\, y\, \in G} = \vec{\omega} \times \vec{r}, \quad \left(\frac{\partial p}{\partial n}\right)_{x,\, y\, \in G} = 0, \quad (2)$$

where $\vec{r} = \{x, y\}$ is vector-radius of the point on the blade surface G; n is a normal to the blade surface G.

Conditions for the input boundary of a parallelepiped:

$$U_x = U_\infty,\ U_y = 0,\ p = p_\infty. \quad (3)$$

For the initial boundary of a parallelepiped the Neumann conditions are performed:

$$\frac{\partial U_x}{\partial x} = 0,\ \frac{\partial U_y}{\partial y} = 0,\ \frac{\partial p}{\partial x} = 0,\ \frac{\partial p}{\partial y} = 0. \quad (4)$$

For the lateral boundaries of the parallelepiped, the reflection conditions are performed:

$$\frac{\partial U_x}{\partial n} = 0,\ \frac{\partial U_y}{\partial n} = 0,\ \frac{\partial p}{\partial n} = 0, \quad (5)$$

where n is a normal to the boundary of the region.

Using the following equations, for calculating the power coefficient on the wind velocity range for each rotor, tip speed ratio (TSR) and torque coefficients are used. In order to find the torque coefficient for each turbine, we must first calculate the swept area of the rotor using equation

$$A = DH, \quad (6)$$

where H is rotor height in m and D is overall diameter in m. A swept area schematic is shown below (Fig. 2).

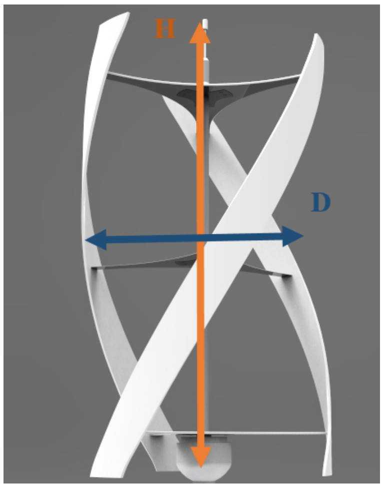


Fig. 2. A swept area of wind turbine

The swept area is used as a reference value for solving torque coefficients. The nondimensional torque coefficient is calculated using equation:

$$C_m = \frac{T}{\frac{1}{4}\rho A D V^2}, \quad (7)$$

where$T$ is a torque in N·m; ρ is air density in kg/m^3; A is a rotor area in m^2; V is an air velocity m/s^2.

The nondimensional term for comparing efficiency of VAWTs is the power coefficient. First the angular velocity of the rotor must be calculated by equation

$$\omega = \frac{2\pi N}{60}, \qquad (8)$$

where N is the measured rotations per minute. Once the angular velocity is determined, the tip-speed ratio of the rotor is solved from equation

$$\gamma = \frac{\omega D}{2V}. \qquad (9)$$

The power coefficient is then calculated. As can be seen by equation, the power coefficient is found from the product of tip-speed ratio and torque coefficient.

$$C_p = \frac{P}{0.5\rho A V^3} = \frac{T\omega}{0.5\rho A V^3} = \gamma C_m. \qquad (10)$$

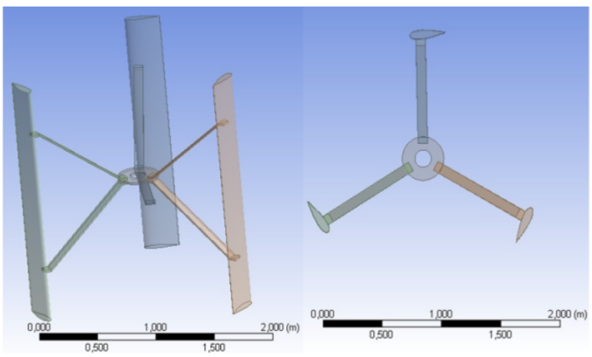
Power P of wind turbine is calculated by equation

$$P = \frac{\left(\rho 2 R C_p V^3\right)\cdot 0.9}{2}, \qquad (11)$$

where ρ is air density, R is a radius of wind turbine, C_p is power coefficient, V is air velocity, 0.9 is transformation coefficient of electric generator.

Because the investigations in the wind tunnel are very expensive, it is necessary to simulate the wind turbine rotor in the Ansys software, using the Fluid Flow (Fluent) tool.

Foreachchangingtheangleofattackoftheblades, 3D model was created (Fig. 3), which was sampled using an instrument Ansys Meshing (Fig. 4).



(a) (b)

Fig. 3. 3D model of investigated wind turbine: (a) side view; (b) top view

Using software Ansys it is possible to obtain the value of torque coefficient C_m, on the basis of which the power of the wind turbine is calculated. Dimensionless coefficients are used for comparison with other similar investigations and for testing the experiment. For this study, three dimensionless quantities are considered. The power coefficient describes the energy conversion efficiency of the turbine. The torque coefficient is a dimensionless representation of the torque that is proportional to the output. The TSR is defined as the ratio of the speed of the end of the blade to the speed of the wind.

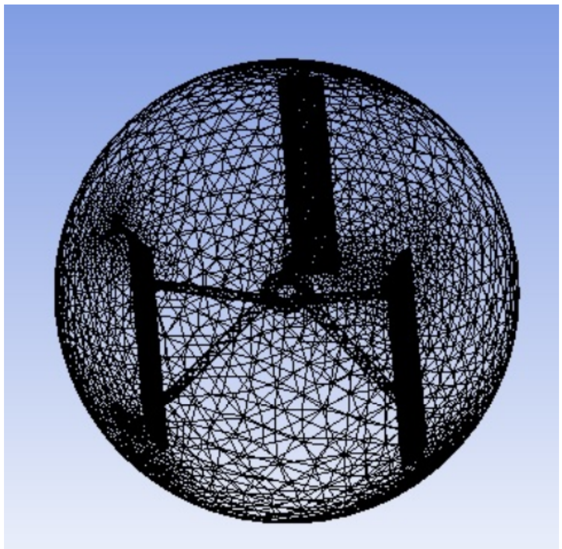


Fig. 4. Sampled model

The object of the investigation was a three-bladed Darrieus rotor. The rotor was tested 30 times with a change in the angle of attack λ of the blade (Fig. 5) in the range from 0 to 10 degrees in steps of 2 degrees and with a change of wind speed in the range from 4 to 12 m/s, respectively.

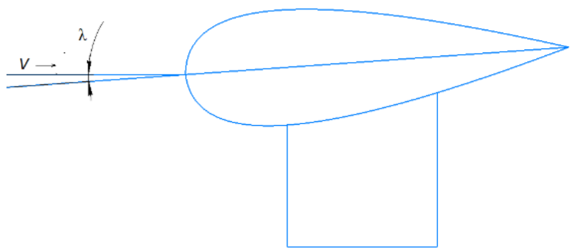


Fig. 5. Schematic representation of the angle λ

The resulting graphs of the effect of changing the angle of attack λ on the power of the wind turbine represented on Fig. 6 (power is calculated using equation (11)).

While power is captured by the wind, it is desirable that the power that has been captured has been maximized. In addition, it should be ensured that the turbine does not compromise security under any circumstances. Thus, power control is a very important feature of the wind turbine. In order to avoid damage to the wind turbine at very high wind speeds, it is possible to control aerodynamic forces on the rotor in order to limit the power recorded. The following methods are used for the same.

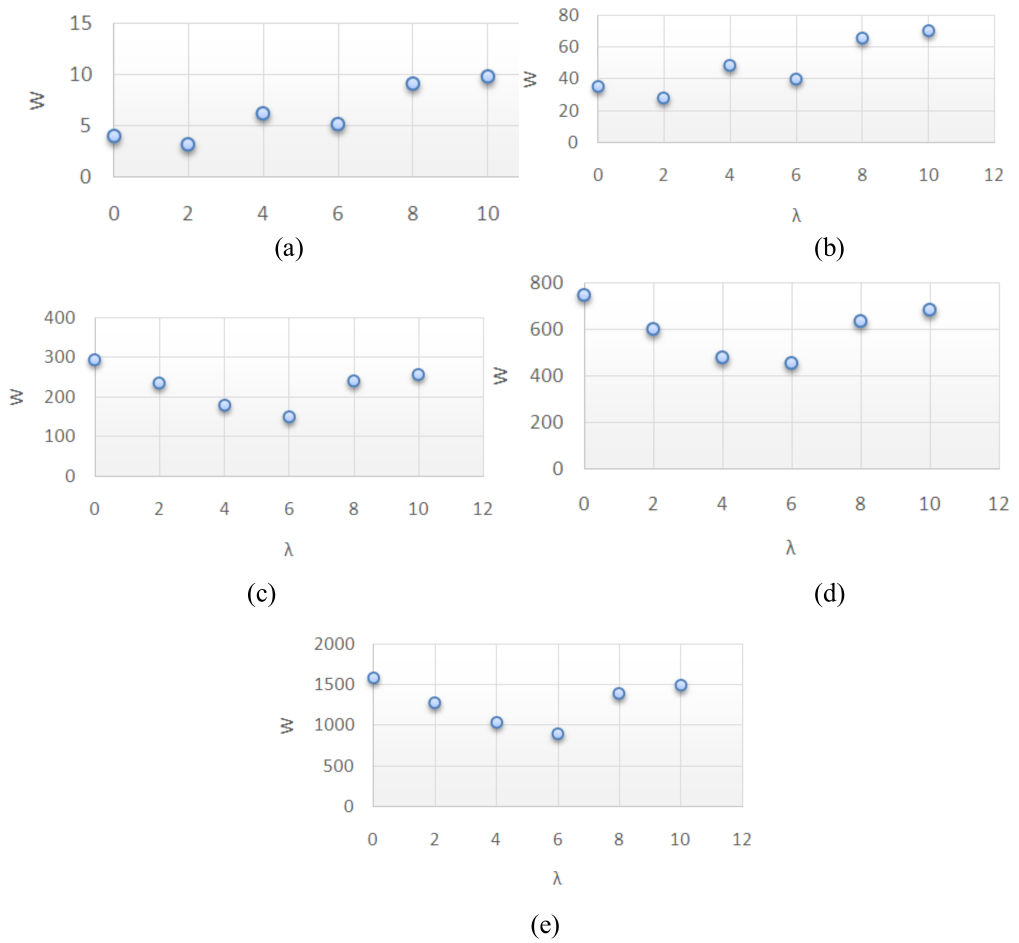


Fig. 6. The graph of the dependence of the power of the wind turbine (in Watts) on the angle λ at wind velocity: (a) 4 m/s, (b) 6 m/s, (c) 8 m/s, (d) 10 m/s, (e) 12 m/s

Pitch control. Through pitch control, blades can be turned or directed to the wind [3]. This leads to a change in wind force on the rotor shaft:

- good power control;
- initial start and emergency stop.

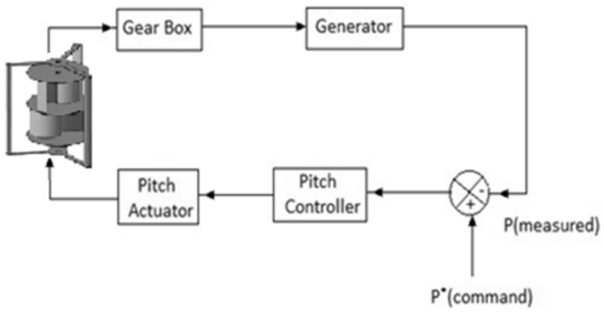


Fig. 7. Feedback scheme for pitch angle control

At high wind speeds, pitch control can be used to maintain power close to the rated power of the generator. A disadvantage in this case is the added complexity of the pitch control system and high volatility at high wind speeds. Due to the presence of impulses, the instantaneous power fluctuates around the nominal average power value.

Passive stall control. Stall control is the simplest control technology for a wind turbine, whose blades are fixed to the sleeve at a certain angle. The rotor blades are arranged in such a way that when the wind speed exceeds a certain level, there is a stop. That is, the lifting force on the rotor decreases as a result of which the turbines brake and restrain themselves at the permissible speed limit. Thus, at high wind speeds, the turbine is protected. This is the simplest and most reliable power management technology. The disadvantage is that turbines operate at an efficiency lower than the nominal value at low wind speeds. In addition, the variations in air density and mesh frequencies lead to changes in maximum stationary power.

Active stall control. Active control (Fig. 8) of the stall occurs as a development of passive control. Instead of a natural breakdown, this system uses a pitch to actively control the blade stall. Thus, at low wind speeds, maximum efficiency is achieved by breaking the blades, as in a controlled pitching turbine. On the other hand, at high wind speed blades are in the opposite direction of the main pitch controlled turbine, to make them move to a more profound breakdown.

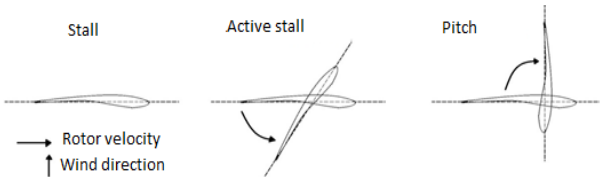


Fig. 8. Image of a stall technique, a pitch and an active stall

Electronic power control. This control will be applied in systems that include an electronic power interface between the generator and the load [4].

The instantaneous difference between mechanical power and electric power changes the speed of the rotor, following the equation:

$$\frac{jd\omega}{dt} = \frac{(P_m - P_e)}{\omega},$$

where j is the polar moment of inertia of the rotor, ω is the angular velocity of the rotor, P_m is the mechanical power produced by the turbine, and P_e is the electric power going to the load.

Integrating this equation, we obtain:

$$\frac{1}{2}J(\omega_2^2 - \omega_1^2) = \int_{t1}^{t2}(P_m - P_e)dt.$$

Using the electronic power converters, the value of P_e can be controlled. Thus, the change is a speed and, therefore, the final speed of the turbine can be controlled. This method of speed control provides uninterrupted operation, since it does not involve any mechanical action. On the other hand, if you need a quick change of speed, you need a big difference between input and output power. The load on the blade increases due to the large torque. Continuous control of the speed of the rotor with this method leads to a constant fluctuation of output power to the grid.

IV. CONCLUSION

After processing the experimental data from the Ansys software, it was concluded that at the low wind speeds (up to 6 m/s) the maximum power can be obtained at the angle α value of 8–10 degrees. At high wind speeds (more than 6 m/s), an increase in of angle α value leads to a braking of the rotor of the wind turbine, which negatively effects on the power of the wind power plant.

It is proposed the approach for the realization of control system of blade pitch angle based on PID-controller. It is developed the algorism of adaptive PID-controller. It is developed a Simulink model for this control system.

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В. М. Синєглазов, І. С. Швалюк. Дослідження впливу величини кута атаки лопаті на потужність вертикально-осьової вітроенергетичної установки

Досліджено проблему підвищення енергетичної ефективності вітроенергетичної установки з вертикальною віссю обертання. Для вирішення цієї проблеми пропонується використовувати лопаті з можливістю регулювання кута атаки. В результаті рішення рівнянь Нав'є–Стокса при різних початкових умовах (різних значеннях кутів атаки і швидкостей вітру), визначено оптимальний кут атаки при різних швидкостей вітру.

Запропоновано підхід до реалізації системи управління кутом повороту лопаті на основі PID-контролера. Розроблено алгоритм адаптивного PID-контролера. Також для цієї системи управління розроблена модель в Simulink.

Ключові слова: вертикально-осьовий ротор; ротор Дар'є; кут атаки; потужність вітроустановки; ефективність вітроустановки.

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В. М. Синєглазов, И. С. Швалюк. Исследование влияния величины угла атаки лопасти на мощность вертикально-осевой ветроэнергетической установки

Исследована проблема повышения энергетической эффективности ветроэнергетической установки с вертикальной осью вращения. Для решения этой проблемы предлагается использовать лопасти с регулируемым углом атаки. В результате решения уравнений Навье–Стокса при различных начальных условиях (различных значениях углов атаки и скоростей ветра), определен оптимальный угол атаки при различных скоростей ветра. Предложен подход к реализации системы управления углом поворота лопасти на основе PID-контроллера. Разработан алгоритм адаптивного PID-контроллера. Также для этой системы управления разработана модель в Simulink.

Ключевые слова: вертикально-осевой ротор; ротор Дарье; угол атаки; мощность ветроустановки; эффективность ветроустановки.

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