UDC 620.9
DOI: 10.15587/1729-4061.2023.277896

DETERMINING A MODEL OF THE BLADE IN A WIND TURBINE FOR REGIONS WITH LOW WIND SPEEDS

Oleksandr Yurchenko
Postgraduate Student
Department of Applied Hydroaeromechanics*
Oleg Radchuk
PhD, Associate Professor
Department of Engineering Systems Design**
Hanna Barsukova
PhD, Associate Professor
Department of Energy and Electrical Engineering Systems**
Marina Savchenko-Pererva
Corresponding author
PhD, Associate Professor
Department of Nutrition Technology**
E-mail: marina.saw4encko2011@gmail.com
Oleksandr Ivchenko
PhD, Associate Professor
Department of Manufacturing Engineering, Machines and Tools*
Vitaliy Kolodnenko
Senior Lecturer
Department of Transport Technologies**
Denys Fesenko
Postgraduate Student
Department of Manufacturing Engineering, Machines and Tools*
*Sumy State University
Rimskogo-Korsakova str., 2, Sumy, Ukraine, 40007
**Sumy National Agrarian University
Herasyma Kondratieva str., 160, Sumy, Ukraine, 40021

The object of research is the shape of the blade of a vertical-axis installation. The problem solved in this work is to find the optimal shape of the blade for a wind power installation for operation at low wind speeds or in areas where its flow is limited. In the course of the work, the interaction between each blade option and the wind flow depending on the shape of the blade was considered. With the help of a reduced model of the wind turbine, a flat blade, a blade with a «pocket», and a blade with a «pocket» and a slit were tested. The test results prove the effectiveness of the designed and manufactured blade with a «pocket» and a slit. This was confirmed by the study results, according to which, during the experiment, the number of revolutions of a wind turbine with blades made with a «pocket» and a slit was the largest. In comparison with flat-shaped blades, the increase was 20 %, and, in comparison with blades with a «pocket», the increase was 10 %. In order to compare wind turbines that have flat-shaped blades and blades with a «pocket» and a slit, experimental studies and calculations of the power factor Cp were carried out. A flat-blade wind wheel has $Cp_1=24$; a blade with a «pocket» – $Cp_2=52.9$; a blade that has a «pocket» and a slit – $Cp_3=58.7$. Therefore, one can assume that the power generated by the wind wheel with the above blades is also the largest, $P_3=98$ W, compared to two other shapes of blades: flat, $P_1=32.3$ W; with a «pocket», $P_2=88.2$ W. It would increase during the test time from zero speed to reaching a constant rotational speed.

The studies confirm that the wind wheel, which has blades with a «pocket» and a slit, has the highest speed of rotation over the entire period of time when measurements were performed

Keywords: wind power, blades with slit, rotational force of wind wheel, vertical axial wind turbine

Received date 20.02.2023
Accepted date 21.04.2023
Published date 28.04.2023

How to Cite: *Yurchenko, O., Radchuk, O., Barsukova, H., Savchenko-Pererva, M., Ivchenko, O., Kolodnenko V., Fesenko, D. (2023). Determination of model of blade for wind turbine for areas with low wind speeds. Eastern-European Journal of Enterprise Technologies, 2 (8 (122)), 44–52. doi: https://doi.org/10.15587/1729-4061.2023.277896*

1. Introduction

The increase in the scale of electricity generation by alternative energy systems is a common trend. Wind turbines are one of the types of such systems and, moreover, are one of the most widespread types.

Wind energy is free, so the possibility of using it to generate electricity is fully justified. However, there is not always the presence of the necessary wind speed or wind speed in general so that its energy can be transformed into electrical energy. This is due to climatic conditions, as well as the location of the installation in the territory where there will be restrictions on the operation of the wind flow. Such restrictions may be facilities, buildings, vegetation, etc.

Therefore, research from the point of view of finding the optimal design of the installation for working at low wind speeds is an important issue.

In addition, it should be noted that certain territories are characterized by certain climatic characteristics. Quite a large number of areas have low and medium wind speeds, which affects the possibility of obtaining a large amount of energy at wind turbines.

Designing a system capable of operating at low wind speed is one of the tasks for many manufacturers of alternative energy systems, both in a particular country and around the world.

Wind turbines with a vertical axis of rotation have a significant advantage over wind turbines with a horizontal axis of rotation – they do not require orientation to wind direction. But installations with a vertical axis of rotation need a certain start to work.

Slowness is one of the signs of wind turbines of this type. For use in such installations of electric generators as a converter of mechanical energy of a windmill into electrical energy, it is necessary to use a gearbox or multiplier. Such additional equipment complicates the structure and affects the increase in the mass and size of the wind generating unit. Also, the use of a gearbox or multiplier increases the torque that must be developed by the wind wheel during start-up and during operation. Therefore, for vertical-axial wind turbines, it is necessary to increase the torque that the wind wheel develops. This problem must be solved at the design stage of the blade structure and when determining their number. It is also necessary to improve the starting system of such wind turbines, which will allow them to be launched at low wind speeds. To this end, it is necessary to reduce the starting load torque that the wind wheel must develop when starting.

Optimization of plants and development of new models aim to improve the quality of the process being executed. Among the possible options is the design of a new blade shape for the installation. By changing the structure of the installation, the torque that the wind wheel develops increases, its rotational speed increases.

The blades are one of the key components of a wind power plant. The utilization rate of air flow *Cp*, at the same size for different blade shapes, is different, which leads to different values of torque that the wind wheel can develop.

In this regard, designing a wind turbine with a vertical axis of rotation, in which the blades could significantly improve starting, is an urgent issue. This also requires appropriate research in order to design an installation for working at a low-speed wind flow.

2. Literature review and problem statement

The pace of development of energy systems in various industries today require considerable attention, putting forward a number of requirements for designers [1]. This is due to energy saving at enterprises, residential and industrial facilities. When operating modern equipment and machinery at processing enterprises, energy-intensive processes are used to obtain products of raw material treatment [2]. By calculating reasonable volumes of energy consumption and achieving them, by optimizing heat transfer between processes, methods of energy supply, and improving the characteristics of technological processes [3, 4], it is possible to determine the amount of energy required for production. Accordingly, it is possible to apply a similar amount of renewable energy sources that have high efficiency. Secondary energy sources are necessary in the study of man-made impact on the environment, through the use of chemical compounds and reagents. Technological processes in the chemical industry, as a rule, require a large amount of energy. One of the ways to reduce the energy dependence of such enterprises is the use of alternative energy sources, which should be highly efficient [5]. Saving the use of electricity in the areas of service and management leads to the actualization of the issue of energy-efficient use of thermal energy. The introduction of measures for the use of secondary energy resources is the main direction of reducing the cost of maintaining premises and buildings [6]. Also, the issue of providing the population with a sufficient amount of electricity has always been quite acute [7]. Each of these requirements implies the development of measures for energy saving and energy-efficient use of existing energy resources and the introduction of new alternative energy sources. The structures of such alternative energy sources need to be improved to increase their efficiency of use. The considered alternative energy sources have a certain efficiency, which is necessary to increase through the use of new structural solutions [8, 9].

Improvement of wind power plants occurs by sophisticating the design of the wind wheel, control system, generator structure. This makes it possible to achieve more stable operation of the wind turbine but also leads to an increase in mass, which implies an increase in the material consumption of the structure as a whole [10, 11].

Wind power plants, depending on the position of the axis of rotation of the wind wheel, can be of two types. The first is with a horizontal axis of rotation, when the axis of rotation is parallel to the wind direction. The second is with a vertical axis of rotation, when the axis of rotation is perpendicular to the wind direction [12]. Studies of the optimal shape of the blades of the wind power installation were carried out on the basis of a wind turbine with a vertical axis of rotation of the wind wheel [13]. Among vertical-axial wind turbines, the most common are wind turbines with rotor types Savonius, Evans, Musgrove, and Darrius with a wind flow power utilization factor of up to 40 %. Increasing this indicator will significantly increase the efficiency of wind generating plants [14, 15]. An important quality of the structure of wind turbines of this type is that they do not need orientation to the direction of the wind flow. Due to the geometry of the blades, such wind turbines are always in working position. The design of wind turbines with a horizontal axis of rotation involves changing the orientation of the wind wheel to the wind flow, which is a significant drawback of such structures [16].

However, for structures with a vertical axis of rotation, an initial start of the wind wheel at the start is necessary [17]. Another disadvantage of installations of this type is the low speed of the wind wheel. In this regard, there is a need to use gearboxes in the design of such wind turbines, which make it possible to increase the speed of rotation of the generator [18].

At the same time, installations with a vertical axis of rotation are distinguished by simplicity of design and relative cheapness of the materials from which the blades are made. No need for orientation of the wind wheel in the direction of wind flow allows it to be used in places with a constant change in the direction of action of the wind flow. These can be areas that have obstacles, for example, buildings or structures [19].

With the development of technology and focus on the use of renewable energy sources, the issue of maximizing the use of wind, solar, water, and other alternative sources is actualized. That is, there is a tendency to get energy from these resources to the maximum as possible. One of the representatives of such energy is wind energy. The design, selection, and construction of wind turbines for areas with low wind speeds is associated with a number of technical and financial problems. And this, in turn, requires maximizing the efficiency of converting wind energy into electrical energy and minimizing the cost of power equipment [20]. In the vast majority of areas where wind turbines were researched, low-speed winds prevailed. To study the structure of the wind generating plant, a multiparameter method was used in the cited work. The parameters included tip speed factor, power factor, lift, number of blades, and rim diameter. Studies have shown a significant impact on the performance of the wind turbine exerted by the number of blades and rim diameter. It was found that a twofold reduction in the number of spokes (from 64 to 32) in four investigated wind wheels with different rim diameters reduces the efficiency by 0.19 %.

This could reduce the purchase price by 42 %, the cost of installation work by 42 %, and weight by 28 %. A fourfold reduction in the number of spokes (from 32 to 16) reduces efficiency by 0.31 %, reduces installation and purchase costs by 35.5 % and 36 %, respectively. At the same time, the mass of the wind turbine decreased by 19.2 %. Studies were conducted for one type of blade.

Improving the parameters of wind turbines is achieved in various ways. Paper [21] considers an installation that works by tilting the sail and using a flywheel. This flywheel is used to drive the generator. The installation consists of a sail, which is attached to the mast, and moves with a torsion spring. The oscillatory movement of the sail is converted into a rotating movement of the flywheel. In the course of the study, the equations of the dynamics of the wind turbine were derived, which were used to analyze the time characteristics of the installation. One can also improve the parameters of the wind turbine by connecting large flywheels to the rotor. Work [22] reports the modeling and control of such a system. The torque of the wind wheel with the flywheel is directly related to the generator rotor. The transmission has the ability to disconnect the turbine shaft from the generator shaft to ensure independent regulation of angular velocities. Thus, the quality of electricity generated by the wind turbine could improve as power fluctuations caused by changes in wind speed decrease. In the cited work, attention was not paid to the efficiency of converting wind energy into mechanical energy.

To increase the use of wind energy, the size of wind turbines is changed. This leads to tightening requirements for the design of wind turbines. Some of these requirements can be met by additional wind turbine control mechanisms. In [23], the mechanism is considered, which is a kind of hydropneumatic flywheel system in the rotor of a wind turbine. The composition includes two hydropneumatic piston batteries in the system of all rotor blades. The fluid in the batteries moves, alternately filling the blades. When it changes, their inertia also changes. Thanks to this system, power stabilization, fast frequency response, stabilization of the power supply system are achieved. In addition, it can reduce the load on the mechanisms of the wind turbine due to imbalance, the action of gravity on the blades, and the processes of emergency braking and vibration. The main direction of increasing the efficiency of a wind turbine is to increase its size, not the shape of the blades.

Modeling the streamlined shape of a wind wheel with rotating cylinder blades can also improve wind energy efficiency, especially for areas with low wind speeds. In paper [24], wind turbines with rotating cylindrical blades are considered. The advantage of such installations, in comparison with traditional blade installations, is the receipt of energy from the wind speed of 2–3 m/s and self-starting. A mathematical model of the vortex flow that rotates the wind wheel has been built. This model should be used at high values of the Reynolds number. The basis for the model is the Navier-Stokes level in a rotating system. For such blade shapes, the wind flow utilization ratio does not exceed 30 %, which is low, given that wind flow with speeds up to 3 m/s has potentially low power.

The number and shape of the blades affect the technical performance of the wind turbine. In [25], the influence of wind speed and fluctuations, the number of wind turbine blades on the power reached, is considered. The wind wheel was investigated in several variations of blades. The material of the blades is wood. The results of the study showed that when the wind speed is less than 5 m/s, it is better to have a small number of blades, and, at a wind speed of more than 7 m/s, it is better to use a wind wheel with a large number of blades.

Studies that are carried out to optimize the design of wind turbines often lead not to a simplification of the design of the wind turbine but on the contrary, to its complication. In work [26], an installation with an auxiliary wind wheel, which is located on the same axis of rotation with the main wind wheel, is considered. The auxiliary wind wheel has 8–12 blades and is used in a complete set of five types of models of double wind turbines. Analysis of such models showed that double wind turbines can increase the use of wind energy. The best effect was shown by a double wind turbine with a 10-blade auxiliary wind wheel. When the wind speed is 3 m/s, compared to the original model, the power of the two-wheel installation is increased by 14.17 %, and the wind energy utilization factor is increased by 4.53 %. The wind speed in the area close to the base of the blades of the main wind wheel is relatively reduced, while in the area close to the top of the auxiliary wind wheel is relatively higher. The auxiliary wind wheel converts some of the wind energy, and therefore the kinetic energy in the keelwater is significantly reduced.

Wind turbines, with a horizontal axis of rotation of the wind wheel and with a vertical axis of rotation, can be connected to a stationary air concentrator, which is performed with guide plates. This air concentrator is made using two cone-shaped cups with holes in the bottom of the cups. Between the cups are air duct plates and a rotor. This shape of the air concentrator forms narrowing channels in the horizontal and vertical directions [27]. The model was based on the task of creating a wind turbine in which it would be possible to increase the power and efficiency of its operation. Such wind turbines additionally require orientation relative to the direction of the wind flow.

Thus, wind turbines with a vertical axis of rotation of the wind wheel have a significant advantage over wind turbines with a horizontal axis of rotation of the wind wheel – there is no need to orient the wind wheel to the direction of wind action. There is also a significant drawback of such a wind wheel – the need for high torque at the start of work. Wind turbines with a vertical axis of rotation of the wind wheel have a low rotational speed and require additional gearboxes or multipliers to increase the speed of rotation of the shaft to use electric generators. This, in turn, complicates the design of the wind turbine and requires an increase in the torque of the wind wheel. The cited studies consider wind turbines under conditions of medium and high wind speeds, due to the high energy potential of wind flows. Consideration of the possibility of obtaining energy at low wind speeds carried out by the authors of [20, 25] allows one to use from 20 to 50 percent of the energy of the wind stream. Increasing this indicator will make the wind power installation more efficient.

As a result of our review, it was found that the easiest to use are wind power plants with a vertical axis of rotation, which do not require orientation of the wind wheel to the direction of wind action. Such wind power plants have a wind power utilization factor of up to 50 %. Given that for low winds, up to 5 m/s, the potential power of the wind flow is low, so an increase in this indicator is necessary to increase the efficiency of the wind turbine. It is advisable to increase the utilization factor of wind power by reducing weight and simplifying the design of the wind wheel.

3. The aim and objectives of the study

The purpose of this work is to determine the shape of the blade for a wind power plant with a vertical axis of rotation with a wind flow energy utilization coefficient of more than 50 percent, which can be used in regions with low wind speeds.

To accomplish the aim, the following tasks have been set:

– to conduct experimental studies in the wind tunnel of a model of a wind wheel with different shapes of blades;

– to consider experimental studies and determine the rotational frequency of the wind wheel for different shapes of blades;

– to carry out calculations to determine the efficiency of using the wind flow by different shapes of blades by determining the power factor *Cp* of the wind wheel.

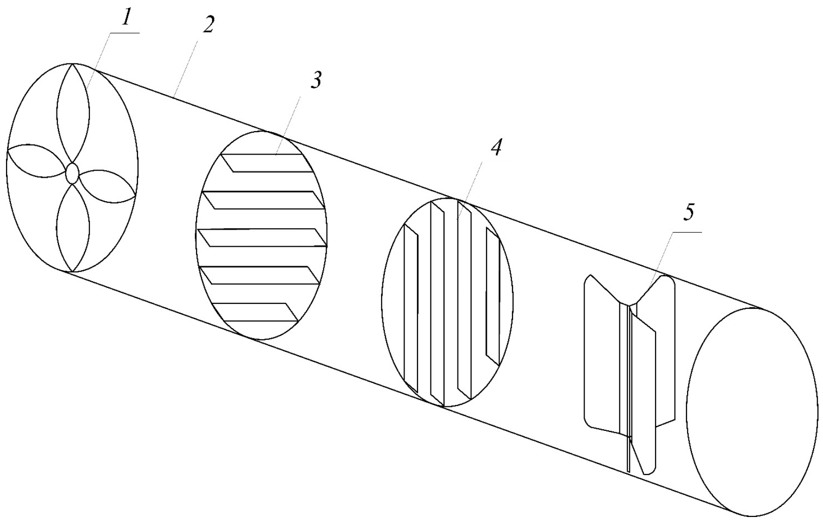

Fig. 2. Experimental wind turbine: 1 — fan; 2 — wind tunnel body; 3 — horizontal air flow equalizer; 4 — vertical air flow equalizer; 5 — investigated wind turbine

4. The study materials and methods

The object of research is the blade of a wind power installation with a vertical axis of rotation, which has a high coefficient of use of wind flow energies. The hypothesis of the work assumes the possibility of using the energy of the wind stream by the wind wheel of a vertical-axial wind turbine with a power factor *Cp* above 50 %, by using blades that have a «pocket» and a slit. The main characteristic of the wind turbine is the coefficient of wind energy use, *Cp*, (power factor) close in content to efficiency [28]. For different shapes of blades, this indicator is different. The higher the wind turbine energy utilization factor, the more wind flow energy will be converted into mechanical energy of rotation of the wind wheel and, accordingly, the electrical energy of the electric generator. Our studies are aimed at determining the coefficient of wind energy use *CP* of a wind turbine with different shapes of blades and determining the most effective blade for this indicator.

Fig. 1 shows the shapes of three manufactured blades (cross section), which were compared with each other.

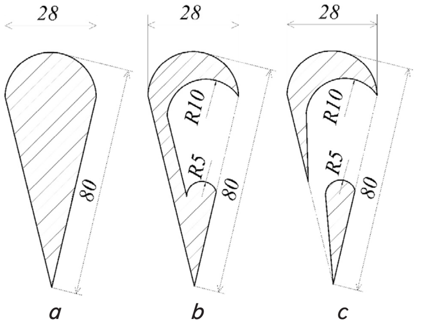

Fig. 1. Shapes of wind wheel blades: *a* — flat blade; *b* — blade with «pocket»; *c* — blade with «pocket» and slit

The study of the dependence of the number of revolutions of the windmill on time was carried out on a separately manufactured and installed mini model of the wind turbine, which was placed in the wind tunnel according to the scheme in Fig. 2.

The airflow in the wind tunnel 2 is created by fan 1. The air flow passing through the alignment device, vertical 3 and horizontal 4, falls on the wind turbine 5, which is being investigated. The wind turbine has three blades. The experiment is carried out for different shapes of blades under the same conditions. These conditions include the distance from the fan to the wind wheel, the air flow rate V; the blades have the same height and dimensions. The experiment was conducted alternately with different blade shapes. Three blades with the same cross-section were connected to the wind wheel; the fan was started. After that, the wind flow rate provided by the fan using the W87B Wintact impeller anemometer was measured with a measurement accuracy of 0.01 m/s and a flow rate measurement error of 5 %. The constancy of the wind flow was ensured by turning on the fan through a voltage regulator.

Next, the wind wheel was released into free rotating motion from a state of rest. The wind wheel self-started in rotating motion. The experiment was conducted by two researchers. One counted the number of full revolutions of the wind wheel according to the mark, which was glued to one blade. The second researcher kept a record on the stopwatch of the number of full revolutions. Counting accuracy was ±0.12 revolutions. The experiment was repeated three times for one type of blades, all indicators of the experiment coincided. The total time allotted for one experiment was 100 seconds. This period of time was enough for the wind wheel to move from accelerated circular motion to constant circular motion, that is, the circular rotational speed became a constant value. The experimental data were recorded for further calculations.

5. Results of investigating the blades of various shapes for a wind power installation

5. 1. Results of investigating the various shapes of blades in the wind tunnel experimentally

The study used the shape of the blades, which had different cross-sections. The scheme of blade *A*, which is shown in Fig. 1, has a well-known shape [28]. The surface area of such a blade $A_1=0.083$ m^2. The diagrams of blades *B* and *C*, which are shown in Fig. 1, have special holes that are designed to increase the use of wind flow energy. The surface area of such blades is the same: $A_2=A_3=0.103$ m^2. According to the results of the experiment, the number of revolutions made by the wind wheel for a certain period of time was obtained. The results of the experiment are recorded in Table 1.

Table 1

Experiment results

Rotation time, p	5	15	24	35	40	47	60	72	76	80	87	90	95	100
The number of revolutions revolutions of a wind wheel with blades of type 1	1	4	8	14	16	21	28	35	38	40	44	46	50	54
The number of revolutions of a wind wheel with type 2 blades	1	4	9	15	18	23	32	40	41	44	50	53	57	60
The number of revolutions of a wind wheel with blades of type 3	1	5	10	17	21	26	35	43	47	50	56	59	63	67

We conditionally designated the blades, which are shown in Fig. 1, as follows: *A* – blades of type 1, *B* – blades of type 2, *C* – blades of type 3. All further designations near physical quantities with index 1 will refer to the blade of type 1, with index 2 to the blade of type 2, with index 3 to the blade of type 3.

5. 2. Treatment of experimental studies and determination of the rotational frequency of the wind wheel for different shapes of blades

The rotating frequency of the wind wheel can be found by the formula:

$$n=\frac{60N}{t}, \tag{1}$$

where n is the rotating frequency of the wind wheel, rpm; N – number of revolutions of the wind wheel; t – time during which the wind wheel made N revolutions, s.

Using the results of the experiment in Table 1, we calculate the rotational frequency of the wind wheel for 1, 2, 3 types of blades. The results of calculations are given in Table 2.

Graphical interpretation of our calculations is shown in Fig. 3.

Analyzing the results obtained during the experiment, the following conclusions can be drawn:

1. For blades of type 1, the rotational frequency of the wind wheel, which is a constant value for the experimental conditions, is n_1=32.1 rpm.

2. For blades of type 2, the rotational frequency of the wind wheel, which is a constant value for the experimental conditions, is n_2=36.0 rpm.

3. For blades of type 3, the rotational frequency of the wind wheel, which is a constant value for the experimental conditions, is n_3=40.0 rpm.

Table 2

Results of calculations of the circular frequency of the wind wheel for the 1, 2, 3 types of blades

Rotation time, s	5	15	24	35	40	47	60	72	76	80	87	90	95	100
n_1	12.0	16.0	20.0	24.0	24.0	26.8	28.0	29.2	30.0	30.0	30.3	30.7	31.9	32.1
n_2	12.0	16.0	22.5	25.7	27.0	29.4	32.0	33.3	32.4	33.0	34.5	35.3	36.0	36.0
n_3	12.0	20.0	25.0	29.1	31.5	33.2	35.0	35.8	37.1	37.5	38.6	39.3	39.9	40.0

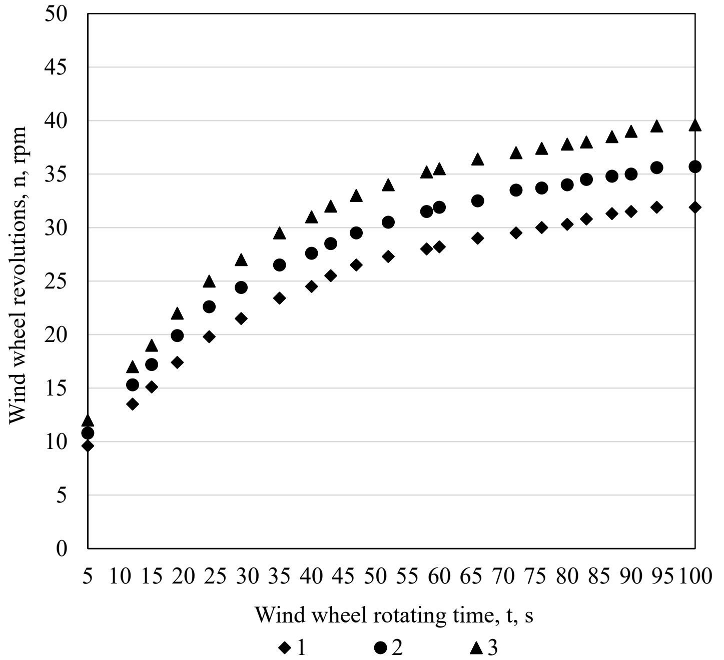

Fig. 3. Dependence of the rotational frequency of the wind wheel on time: 1 – for type 1 blades; 2 – for type 2 blades; 3 – for type 3 blades

5. 3. Power factor *Cp* calculations for a wind wheel with different blade shapes

The calculation of the power factor *Cp* of the wind wheel with different shapes of blades was carried out in the following sequence:

1. Drawing up a design scheme.

Fig. 4 shows a design scheme for determining the rotating force with which the wind wheel moves under the action of the wind flow.

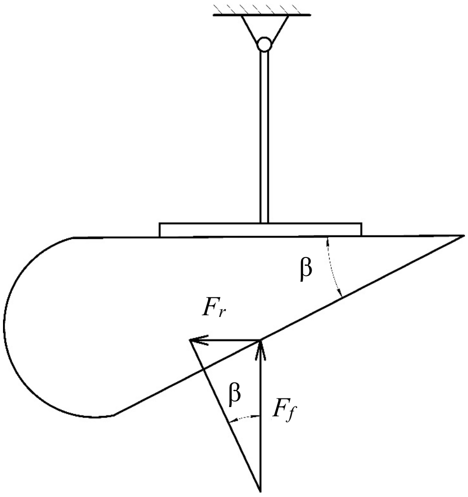

Fig. 4. Scheme for calculating the rotating force F_r

The force of the wind flow acting on the blades of the wind wheel can be calculated by the following formula [28]:

$$F_f=0.5\rho V^2AC, \quad (2)$$

where F_f is the wind flow force on the blade, N; ρ – air density, kg/m^3 (equal to 1.2); V – wind flow rate, m/s (equal to experimental conditions 3); A – blade surface area, m^2 (equal to the experimental conditions $A_1=0.083$, $A_2=0.103$, $A_3=0.103$); C – air resistance coefficient (for the shape of the blades adopted in the experiment, 1.28).

According to the results of calculations, the wind flow strength for different types of blades $F_{f1}=0.57$ N, $F_{f2}=0.71$ N, $F_{f3}=0.71$ N.

2. Determination of the rotating force of the wind wheel.

The rotating force of the wind wheel, according to the design scheme, which is shown in Fig. 4, is calculated by the following formula:

$$F_r=F_f\text{tg}\beta, \quad (3)$$

where β is the angle of inclination of the blade to the direction of the wind flow, degrees.

According to the calculations, the rotational force of each blade is $F_{r1}=0.25$ N, $F_{r2}=0.32$ N, $F_{r3}=0.32$ N.

3. Determination of wind wheel power.

The power that the wind wheel can pull is calculated by the following formula [28]:

$$P=2\pi Mn, \quad (4)$$

where P is the power that the wind wheel can pull, W; M – moment of force on the shaft of the wind wheel, N·m; n – wind wheel speed, rpm.

For a three-bladed wind wheel, according to the design scheme, which is shown in Fig. 3, the moment of force on the shaft is calculated by the following formula:

$$M=3\,F_r\cdot d_w/2, \quad (5)$$

where d_w is the diameter of the wind wheel, m (according to the experimental conditions, 0.42).

According to the calculation results, $M_1=0.16$ N·m, $M_2=0.39$ N·m, $M_3=0.16$ N·m, $P_1=32.3$ W, $P_2=88.2$ W, $P_3=98$ W.

4. Determination of wind energy utilization factor.

The wind energy utilization factor *Cp* (power factor) is the ratio of the power that a wind wheel can pull to the power of the wind stream, which comes to the area of the wind wheel and is calculated by the following formula [28]:

$$Cp=\frac{P}{0.5\rho AV^3}. \quad (6)$$

According to the results of calculations, the following was obtained: $Cp_1=24$, $Cp_2=52.9$, $Cp_3=58.7$.

Comparing the numerical values of the coefficient of use of wind energy *Cp* for blades of different profiles, which were used in the experiment, it was found that the blades of type 3, which are shown in Fig. 1, *c*, have the highest value of this indicator. Thus, a wind turbine with such blades has the ability to convert 58.7 % of the energy of the wind stream that comes to the area of the wind wheel. Of the three shapes of profiles, which are shown in Fig. 1, a profile with a «pocket» and a slit is the most efficient in converting wind flow energy into mechanical energy of a wind wheel and, accordingly, electrical energy of an electric generator. This indicator is much higher compared to those considered in [20, 25], which are from 20 to 50.

6. Discussion of results of determining the blade model for a wind power plant with a vertical axis of rotation

According to the results of the study, the proposed blade models show a significant increase in the efficiency of wind flow energy use by a wind wheel with a vertical axis of rotation compared to each other. The wind wheel with type 1 blades has a wind energy utilization coefficient $Cp_1=24$, with type 2 blades – $Cp_2=52.9$, withtype 3 blades – $Cp_3=58.7$. When using all three types of blades, the wind wheel self-started from a resting position. When comparing the 1st and 3rd types of blades, the use of wind energy by the wind wheel increases by 2.4 times. Thus, the blade with a «pocket» and a slit corresponding to the type 3 blades is most effective in converting wind flow energy into mechanical energy of a wind wheel. Also, the material consumption of such a blade is less, which during the rotational movement of the wind wheel will reduce the centrifugal forces acting on the structure. Reducing the mass of the blades and their impact on the material consumption of the wind wheel as a whole can be a separate scientific study.

Based on the results of the experiment, according to Table 1, in 100 seconds, the wind wheel with all types of blades used in the experiment went from a state of rest to a state of rotation, that is, self-starting occurred. Quantitatively, the largest number of revolutions was made by a wind wheel with type 3 blades, which indicates a greater efficiency of such blades compared to types 1 and 2.

Calculations of the rotating frequency of the wind wheel are given in Table 2 and in Fig. 3. They indicate that in 100 seconds the wind wheel with all types of blades used in the experiment switched from accelerated rotational motion to constant rotational motion. This indicates that the moment of resistance forces of the wind wheel is equal to the moment of force that occurs under the action of the wind flow. A wind wheel with blade 3 type has the highest speed, n_3=40,0 rpm, compared to type 1 and 2 of blades, which have rotational speeds n_1=32.1 rpm and n_2=36.0 rpm, respectively. This confirms that type 3 blades are the most effective. A wind wheel with such blades will make more revolutions in a certain period of time, which will lead to the highest number of revolutions of the electric generator compared to other blades that participated in the experiment.

The main characteristic of the wind turbine is the coefficient of wind energy use, *Cp* (power factor), close in content to efficiency [28]. Calculations were performed for 1, 2, 3 types of blades; this indicator, respectively, has the following values: Cp_1=24, Cp_2=52.9, Cp_3=58.7. The highest value of this indicator is for a wind wheel with type 3 blades. This indicates that such blades allow the most efficient use of wind flow energy compared to the type 1 and type 2 blades.

The defined 3rd type of blades with a profile shape with a «pocket» and a slit is the most effective in converting wind flow energy into mechanical energy of a wind wheel and, accordingly, electrical energy of an electric generator. The hypothesis hhas been fully proven. The coefficient of wind flow energy use Cp_3=58.7, which is higher than 50.

The use of forces of moving air masses is a global phenomenon [29]. Therefore, determining the influence of the shape of the blades and the angle of attack of the blade on the efficiency of obtaining mechanical energy from wind energy plays an important role in the design of new alternative energy installations. Wind energy is converted into mechanical energy by a rotary wheel using blades and positioned in terms of optimal performance and specific shape. Our work reports the aerodynamic characteristics of profiled blades for use in wind turbines.

The peculiarities of the proposed method and our results, in comparison with existing blade studies [30], relate to the blades of a wind turbine with a distributed axis. Their stiffness, damping ratio, and frequency are improved for the first time with the concave wing. A prerequisite for this was the preservation of output power. Studies have shown that wing concavity can better control the position and influence of airflow convergence ranges. The concave profile makes it possible to increase the damping coefficient of the wind wheel by 3–9 %, increase the blade stiffness by 32 %. The maximum displacement and deformation are effectively reduced by 28 %. The use of a concave aerodynamic profile in the design of wind turbine blades provided a new method for the production of a family of aerodynamic wings. The blade with «pockets» and slits shown in this paper has a significant advantage – a concave shape and a slit on the opposite side, which makes it possible to concentrate the air flow on both sides.

In [31], the dynamic behavior of a wind turbine with a vertical axis of rotation was investigated. Torque is modeled on the basis of Navier-Stokes calculations with averaged Reynolds values for two-, three-, and four-blade rotors. For each of the proposed rotor configurations, the effect of the number of blades on aerodynamic characteristics was discussed. The relationship between aerodynamic parts and dynamic vibration of gear systems by studying the influence of dynamic vibration on some design parameters of the transmission system in non-stationary mode has been established. The main problem of wind engineering is the number of blades. Numerical results are given, showing that the number of blades has a significant impact on the efficiency of the installation and the dynamic response of the system under study. The blade with «pockets» and slits can significantly compensate for losses by increasing the number of blades or their overall dimensions. Although, the latter will also lead to an increase in the mass of the wind wheel, which means a decrease in torque.

The angle of attack of the blade is considered to be one of the most important factors affecting the aerodynamic characteristics of a wind turbine with a vertical axis [32, 33]. For 1 kW wind power plants with a vertical axis and a symmetrical aerodynamic profile, theoretically optimal angles of attack have been determined. These angles are 10.7° and −10.7° of wind and weathered wind turbine areas in order to obtain the maximum coefficient of wind force use by the wind wheel. Based on the theory of multi-threaded control of a dual drive disk, the results of the study show that the power factor of a wind turbine can be increased by 11.03 %. This is implemented using the real-time blade angle control law proposed in this paper. However, improved start and rotational speed by as much as 17 % in the blade with a «pocket» and a slit prove the advantage of the «bilateral» efficiency of the blade, rather than just adjusting its angle.

To determine the characteristics of wind turbines, in study [34], a new type of wind turbine with a horizontal structure of a wind turbine in combination with the characteristics of a wind turbine with a vertical axis and a wind turbine with a horizontal axis is investigated. The structure of the turbine and the distribution of the surrounding flow field are investigated using software. At the same time, for generators installed on wind turbines, a synchronous generator is offered. The paper investigated and simulated the flow field around the wind turbine. The results showed that the new plant design can improve wind energy use and make better use of wind energy. The feasibility of such a structure is verified by modeling, which provides a further basis for optimization. It should be noted that such complexity of the design will not entail the «modernization» of the wind turbine. And the optimization of its individual parts, as shown in the version with a blade with a «pocket» and a slit, improves the use of wind flow without complicating the design of the mechanism itself. In addition, there is no need for simulations based on the manufacturer's software.

The study has specific limitations, characterized by the achievement of the maximum speed of rotation in the studied region. Such studies showed a maximum number of revolutions per minute, which is 140. As a result, it can be assumed that a gearbox between the wind wheel and the generator or a low-speed generator for a wind power plant can be made.

The disadvantages in the study include the fact that experimental data were obtained on the model of a wind wheel. For more accurate confirmation of the results, before industrial implementation, it is desirable to conduct a study confirming the results on a full-size version of the wind wheel. This will make it possible to obtain the actual characteristics of such a wind wheel for different wind speeds and the expected power that the wind wheel can pull, to choose the right related equipment.

The current study can be advanced through further ways to optimize for reducing the mass of the wind wheel, which will lead to more revolutions. This is possible due to the replacement of existing material for the wind turbine with a new one. For example, replacing iron with plastic, which could significantly reduce the weight of the wind wheel.

As a result of our study, an experimentally and computationally improved model of the blade of a wind power installation with a «pocket» and a slit for use in areas with low wind speed is substantiated. It has been experimentally proven that the constant speed of rotation of a wind wheel with this blade shape is the highest compared to other blade shapes used in the experiment. Calculated for a blade with a pocket and a slit, the wind energy utilization factor is the highest compared to similar indicators for the other two blade shapes for which calculations were performed.

7. Conclusions

1. Experimental studies were carried out of a model of a wind wheel with three shapes of blades in the wind tunnel: flat, with a «pocket», and with a «pocket» and a slit. The results of the study show that the wind wheel with blades with a «pocket» and a slit has 67 revolutions per 100 seconds. This is the highest number of revolutions compared to the other two blade shapes: flat, 60 revolutions; with «pocket», 54 revolutions.

2. According to the results of processing experimental data, it was established that the constant speed of rotation of the wind wheel with blades having a «pocket» and a slit is 40 rpm. This indicator is 10 % higher than that of a wind wheel with blades with a pocket, and 20 % higher than that of a wind wheel with flat blades.

3. Based on the results of our calculations to determine the efficiency of using the wind flow in terms of the power factor, it was found that the flat-blade wind wheel has $Cp_1=24$; with a blade that has a «pocket», $Cp_2=52.9$; with a blade that has a «pocket» and a slit, $Cp_3=58.7$.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

Funding

The study was conducted without financial support.

Data availability

All data are available in the main text of the manuscript.

References

1. Yurchenko, O. Y., Barsukova, H. V., Tymoshenko, H. A. (2022). Development of a wind turbine blade for areas with low wind speed. Bulletin of Sumy National Agrarian University. The Series: Mechanization and Automation of Production Processes, 2 (48), 94–100. doi: https://doi.org/10.32845/msnau.2022.2.14
2. Sabadash, S., Savchenko-Pererva, M., Radchuk, O., Rozhkova, L., Zahorulko, A. (2020). Improvement of equipment in order to intensify the process of drying dispersed food products. Eastern-European Journal of Enterprise Technologies, 1 (11 (103)), 15–21. doi: https://doi.org/10.15587/1729-4061.2020.192363
3. Sukmanov, V., Radchuk, O., Savchenko-Pererva, M., Budnik, N. (2020). Optical piezometer and precision researches of food properties at pressures from 0 to 1000 MPa. Journal of Chemistry and Technologies, 28 (1), 68–87. doi: https://doi.org/10.15421/082009
4. Savchenko-Pererva, M. Yu., Yakuba, O. R. (2015). Improving the efficiency of the apparatus with counter swirling flows for the food industry. Eastern-European Journal of Enterprise Technologies, 3 (10 (75)), 43–48. doi: https://doi.org/10.15587/1729-4061.2015.43785
5. Barsukova, H. V., Savchenko-Pererva, M. Y. (2020). Reducing the technogenic load on the environment due to the technical solution for the disposal of iron sulphate. Journal of Chemistry and Technologies, 28 (2), 168–176. doi: https://doi.org/10.15421/082018
6. Savchenko-Pererva, M., Radchuk, O., Rozhkova, L., Barsukova, H., Savoiskyi, O. (2021). Determining heat losses in university educational premises and developing an algorithm for implementing energy-saving measures. Eastern-European Journal of Enterprise Technologies, 6 (8 (114)), 48–59. doi: https://doi.org/10.15587/1729-4061.2021.245794
7. Yurchenko, O. Yu., Barsukova, H. V. (2021). Suchasna sytuatsiia enerhetyky ukrainy: haluzi, vidsotky, konkurentospromozhnist. Fundamental and applied research in the modern world. Boston: BoScience Publisher, 660–663.
8. Xu, X., Wei, Z., Ji, Q., Wang, C., Gao, G. (2019). Global renewable energy development: Influencing factors, trend predictions and countermeasures. Resources Policy, 63, 101470. doi: https://doi.org/10.1016/j.resourpol.2019.101470
9. Potić, I., Joksimović, T., Milinčić, U., Kićović, D., Milinčić, M. (2021). Wind energy potential for the electricity production – Knjaževac Municipality case study (Serbia). Energy Strategy Reviews, 33, 100589. doi: https://doi.org/10.1016/j.esr.2020.100589
10. Lu, X., McElroy, M. B. (2017). Chapter 4 – Global Potential for Wind-Generated Electricity. Wind Energy Engineering, Academic Press, 51–73. doi: https://doi.org/10.1016/b978-0-12-809451-8.00004-7
11. McKenna, R., Pfenninger, S., Heinrichs, H., Schmidt, J., Staffell, I., Bauer, C. et al. (2022). High-resolution large-scale onshore wind energy assessments: A review of potential definitions, methodologies and future research needs. Renewable Energy, 182, 659–684. doi: https://doi.org/10.1016/j.renene.2021.10.027
12. Kudelin, A., Kutcherov, V. (2021). Wind ENERGY in Russia: The current state and development trends. Energy Strategy Reviews, 34, 100627. doi: https://doi.org/10.1016/j.esr.2021.100627
13. Rozhkova, L., Savchenko-Pererva, M., Radchuk, O., Sabadash, S., Kuznetsov, E. (2022). Innovative Hybrid Power Plant Design. Advances in Design, Simulation and Manufacturing V. Vol. 2: Mechanical and Chemical Engineering. Poznan 299–308. doi: https://doi.org/10.1007/978-3-031-06044-1_29

14. Rotter, Ch. (2019). Collapse of Wind Power Threatens Germany's Green Energy Transition. WUWT. Available at: https://www.netzerowatch.com/collapse-of-wind-power-threatens-germanys-green-energy-transition/
15. Fried, L., Shukla, Sh., Sawye, S. (2017). Growth Trends and the Future of Wind Energy. Chapter 26 – Global Wind Energy Council. Wind Energy Engineering, 559–586. Available at: https://www.oreilly.com/library/view/wind-energy-engineering/9780128094297/xhtml/chp026.xhtml
16. Ueckerdt, F., Pietzcker, R., Scholz, Y., Stetter, D., Giannousakis, A., Luderer, G. (2017). Decarbonizing global power supply under region-specific consideration of challenges and options of integrating variable renewables in the REMIND model. Energy Economics, 64, 665–684. doi: https://doi.org/10.1016/j.eneco.2016.05.012
17. Bhattacharya, S., Wang, L., Liu, J., Hong, Y. (2017). Chapter 13 – Civil Engineering Challenges Associated With Design of Offshore Wind Turbines With Special Reference to China. Wind Energy Engineering. Academic Press, 243–273. doi: https://doi.org/10.1016/b978-0-12-809451-8.00013-8
18. Dai, H., Fujimori, S., Silva Herran, D., Shiraki, H., Masui, T., Matsuoka, Y. (2017). The impacts on climate mitigation costs of considering curtailment and storage of variable renewable energy in a general equilibrium model. Energy Economics, 64, 627–637. doi: https://doi.org/10.1016/j.eneco.2016.03.002
19. Msuya, R., Kainkwa, R., Mgwatu, M. (2017). Design of a Small Scale Wind Generator for Low Wind Speed Areas. Tanzania Journal of Science, 43 (1), 136–150. doi: https://tjs.udsm.ac.tz/index.php/tjs/article/view/294
20. Peimani, H. (2021). Appropriate Technologies for Removing Barriers to the Expansion of Renewable Energy in Asia: Vertical Axis Wind Turbines. ADBI Working Paper 1250. Tokyo: Asian Development Bank Institute. Available at: https://www.adb.org/sites/default/files/publication/696291/adbi-wp1250.pdf
21. Adeyeye, K. A., Ijumba, N., Colton, J. S. (2021). Multi-Parameter Optimization of Efficiency, Capital Cost and Mass of Ferris Wheel Turbine for Low Wind Speed Regions. Energies, 14 (19), 6217. doi: https://doi.org/10.3390/en14196217
22. Gielen, D., Boshell, F., Saygin, D., Bazilian, M. D., Wagner, N., Gorini, R. (2019). The role of renewable energy in the global energy transformation. Energy Strategy Reviews, 24, 38–50. https://doi.org/10.1016/j.esr.2019.01.006
23. Akbari, R., Izadian, A. (2021). Modelling and Control of Flywheels Integrated in Wind Turbine Generators. 2021 IEEE International Conference on Electro Information Technology (EIT), 9491886, 106–114. doi: https://doi.org/10.1109/eit51626.2021.9491886
24. Jauch, C. (2021). Grid Services and Stress Reduction with a Flywheel in the Rotor of a Wind Turbine. Energies, 14 (9), 2556. doi: https://doi.org/10.3390/en14092556
25. Tanasheva, N. K. (2021). Numerical simulation of the flow around a wind wheel with rotating cylindrical blades. Eurasian Physical Technical Journal, 18 (1), 51–56. doi: https://doi.org/10.31489/2021no1/51-56
26. Syuhada, A., Maulana, M. I., Syahriza, Sani, M. S. M., Mamat, R. (2020). The potential of wind velocity in the Banda Aceh coast to the ability to generate electrical energy by horizontal axis wind turbines. IOP Conference Series: Materials Science and Engineering, 788 (1), 012082. doi: https://doi.org/10.1088/1757-899x/788/1/012082
27. Li, J., Li, Z., Jiang, Y., Tang, Y. (2022). Typhoon Resistance Analysis of Offshore Wind Turbines: A Review. Atmosphere, 13 (3), 451. doi: https://doi.org/10.3390/atmos13030451
28. Wong, K. H., Chong, W. T., Sukiman, N. L., Poh, S. C., Shiah, Y.-C., Wang, C.-T. (2017). Performance enhancements on vertical axis wind turbines using flow augmentation systems: A review. Renewable and Sustainable Energy Reviews, 73, 904–921. doi: https://doi.org/10.1016/j.rser.2017.01.160
29. Chyzhma, S. N., Molchanov, S. V., Zakharov, A. Y. (2018). Criteria for choosing the type of windmills for mobile wind-solar power plants. Vestnyk Baltyiskoho federalnoho unyversyteta ym. Y. Kanta. Seriia: Fyzyko-matematycheskye y tekhnycheskye nauky, 1, 53–62. Available at: https://journals.kantiana.ru/eng/vestnik/3930/10941/
30. Pytel, K., Gumula, S., Dudek, P., Bielik, S., Szpin, S., Hudy, W. et al. (2019). Testing the performance characteristics of specific profiles for applications in wind turbines. E3S Web of Conferences, 108, 01015. doi: https://doi.org/10.1051/e3sconf/201910801015
31. Kern, L., Seebaß, J. V., Schlüter, J. (2019). The Potential of Vertical Wind Turbines in the Context of Growing Land use Conflicts and Acceptance Problems of the Wind Energy Sector. Zeitschrift für Energiewirtschaft, 43, 289–302. doi: https://doi.org/10.1007/s12398-019-00264-7
32. Bashir, M. B. A. (2021). Principle Parameters and Environmental Impacts that Affect the Performance of Wind Turbine: An Overview. Arabian Journal for Science and Engineering, 47 (7), 7891–7909. doi: https://doi.org/10.1007/s13369-021-06357-1
33. Zhang, L., Zhao, X., Wang, H., Liu, Y. (2018). Study on the Real time and Efficient Adjustment Law for H-Type Vertical Axis Wind Turbine. Journal of Mechanical Engineering, 54 (10), 173–181. doi: https://doi.org/10.3901/jme.2018.10.173
34. Li, Z., Yu, X., Han, R. (2017). Modeling and wake characteristics analysis of a new vertical axis wind generation system. IECON 2017 – 43rd Annual Conference of the IEEE Industrial Electronics Society, 8590–8595. doi: https://doi.org/10.1109/iecon.2017.8217509