

The object of research is a wind generator with counter-rotating blades. A special feature of this design is the presence of two wind wheels that rotate in opposite directions. Wind wheels are on the same axis, between them there is a certain distance, which is determined based on research data. The problem of modern wind power is the low range of operating wind speeds, weak generation at low wind speeds. The upper speed limit is 25 m/s, exceeding which leads to breakdowns of various units of the wind station, especially this affects the integrity of the blades, rupture of the wind wheel, cracking of the metal parts of the bearings and their fasteners. The wind turbine presented in the article allows to achieve an increase in the generation of electric energy by 50–70 %. This is achieved by increasing the relative rotational speed of the rotor relative to the stator. Therefore, even at low speeds, the rotor speed relative to the stator increases, which leads to an increase in power generation. The design of the device includes: two wind wheels, one transmits its rotation to the stator, the second to the rotor axis, a metal base, a current collector mechanism. For conducting the research, an experimental model and a semi-industrial installation were used. Results studies have confirmed the theoretical increase in the generation of electrical energy by this design. The peculiarity of the obtained results is connected with the determination of the distance between two wind wheels, the optimal distance between them corresponds to the maximum energy generation. A distinctive feature of the results obtained can be considered an increase in the number of blades on the second wind wheel

Keywords: wind device, multidirectional wind wheels, gap, blades, model, wind speed

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DEVELOPMENT OF A WIND TURBINE WITH TWO MULTIDIRECTIONAL WIND WHEELS

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1. Introduction

Climate changes caused by greenhouse gas emissions oblige the application of measures to decarbonize the global economy. One of the ways to reduce carbon dioxide emissions is the development of wind energy and the use of efficient devices for converting wind energy into electrical energy.

The scientific topic of studying wind devices is an important element in the development of renewable energy in order to decarbonize global energy and fulfill obligations under the Paris Agreement.

Existing wind stations are not able to operate and generate energy at low wind flow speeds. Improving the efficiency of the wind generator at low wind speeds is an important task of our day.

The most common type of wind turbines used on an industrial scale are wind turbines with a horizontal axis of rotation. However, this type of windmill has a general disadvantage of generating at low wind speeds of up to 4 m/s, and with gale-force winds above 25 m/s. In this regard, the task is to increase the efficiency of wind turbines at the specified wind speeds.

Extracting energy from wind is one of the most popular and environmentally friendly forms of renewable energy. This is the aerodynamic process by which kinetic energy from the wind is converted into electrical energy by wind turbines.

Wind generator with counter-rotating wind wheels is a new technology that allows to efficiently convert wind energy into electricity. In this article, it is possible to look at the principle of operation of such a device and its advantages over traditional wind turbines.

Wind generator with counter-rotating wind wheels is a new technology that allows to efficiently convert wind energy into electricity at low wind speeds. The principle of operation of such a device and its advantages over traditional wind turbines will be studied on an experimental model, where it is possible to change the distance between wind wheels and the number of blades.

However, the problem with classic wind turbines is that they are not able to operate efficiently in high-speed winds. This is due to the fact that under such conditions there are large forces acting on the wind turbine blades, which can lead to damage and even destruction. Increased load leads to a decrease in the reliability of the system as a whole [1, 2].

Since almost 90 % of wind turbines used in the world have a horizontal axis of rotation, it is more profitable from a practical and economic point of view to modernize this particular design. As a result, a model of the wind generator design with counter-rotating blades with a horizontal axis of rotation was constructed [3].

Since almost 90 % of wind turbines used in the world have a horizontal axis of rotation, it is more profitable from a practical and economic point of view to modernize this particular design. To increase the efficiency of the wind generator with a horizontal axis of rotation, an experimental model of a wind device with two oppositely rotating wind wheels and the ability to change the distance between them and the number of blades on them was developed [3].

The topic of increasing the efficiency of wind devices with a horizontal axis of rotation is associated with the low efficiency of such stations, as well as a small operating range of speed changes. The initial velocity is approximately 3–4 m/s and the upper limit is 25 m/s. Considering that the average speed on the surface of the earth near settlements is about 1–2 m/s, the decrease in the initial speed of rotation of the wind wheel to 1–2 m/s is an important direction in modern conditions.

Increasing the efficiency of wind devices can help in solving the problems of climate change and decarbonization of the economy, as well as reducing the destructive impact of energy on the environment.

Therefore, the studies on the development of a wind device with two oppositely rotating wind wheels, which provide stable energy generation and effective operation of the wind device at low wind flow values are relevant.

2. Literature review and problem statement

Studies of the influence of the atmospheric boundary layer on the aerodynamics of a two-rotor wind turbine have been studied, but the simulation was carried out using the line-of-drive method, in which the rotor blades are modeled as body forces. The results show that a two-rotor wind turbine improves the aerodynamic characteristics of an isolated turbine by approximately 5–6 % [4]. The study of a wind turbine of this modification requires further study due to the fact that the presented studies use rotors of various diameters at a distance of $0.2R$ of the main screw, which is a fundamental difference in comparison with a design with two wind wheels of the same radius with a distance between them of more than R .

Studies of the aerodynamics of wind turbines with a horizontal axis of rotation show that there is a non-effective area in the area of the hub base. The study was carried out by the method of mathematical programming [5]. The results of mathematical modeling do not allow to describe the impact of wind wheels on each other, as well as to determine the distance between them for optimal generation.

The concept of a wind turbine with two wind wheels was used to charge batteries and power consumers. Magnets with alternate polarity are fixed on each of them by the rotor. This concept was used for a wind turbine with two multidirectional wind wheels [6]. The presented concept for charging batteries does not take into account the influence of the number of blades on wind wheels for optimal power generation.

Studies of wind wheels with counter-rotating wind wheels were carried out on the basis of mathematical model-

ing programs MATLAB and Simulink. One of the presented studies confirms the earlier moment of starting a wind turbine with counter-rotating wind wheels [7, 8]. The data obtained by mathematical modeling does not allow to determine the moment of starting the wind wheel and it is not possible to determine the initial speed of the wind flow at which both wind wheels begin to rotate.

Studies of wind turbines with two wind wheels show that the main power is generated by the first wind wheel in the wind direction, especially at low wind speeds. The output power of the second wind wheel varies and depends on the operating conditions [9]. At the same time, the output power depends on the distance between the wind wheels, as well as on the number of blades on them, which has not been studied in this case.

The performance of a wind turbine with two multidirectional wind wheels, thanks to the addition of the axial distance factor between the rotors, showed that the power factor of the front rotor continues to grow, approaching the performance of a single rotor, while the rear rotor will continue to decline. However, the overall performance was relatively stable after the distance ratio $Z/D1=0.5$ [10]. The design of the assembled layout allows to adjust the distance between wind wheels, thereby determining the optimal one for increasing generation.

Static and dynamic wind loads acting on these turbine models were investigated. In addition, a high-resolution digital particle image velocimetry (PIV) system was used to quantify the flow characteristics in the short-range tracks of the air models, which makes it possible to track the air flow and swirls in various regions of the installation's airspace [11]. The digital velocimetry system does not allow to determine the effect of wind wheels on each other, as well as the effect of flow turbulence on the second wind wheel.

According to research, it has been demonstrated that the aerodynamic advantage obtained by vortex mass recovery has virtually no effect on the performance of a wind turbine. In addition, it has been shown that the angular induction coefficient of the track is close to zero, since the swirl velocity created by the front rotor is compensated by the rear rotor rotating in the opposite direction [12]. The effect of the first wind wheel on the performance of the second depends on the distance between them, which was not investigated in this work.

Currently, a prototype wind generator with differently sized wind wheels is being developed, which allows to save the torque of the blades and increase generation in comparison with «traditional windmills» [13]. In this work, the possibility of using a different number of blades on wind wheels, on which the performance of the wind turbine depends, is not considered.

According to the patent [14] the design has a special feature in the form of two bushings to which two wind wheels are attached, i.e., to create such a wind turbine, a special design of the electric generator is required.

The analysis of the literature data shows that there are unsolved problems in the study of wind turbines with two multidirectional wind wheels. It has also been established that the influence of wind wheels on each other is important for the efficient operation of a wind turbine.

The first wind wheel acts destructively on the rotation of the second wind wheel, at the same time their interaction depends on the distance between the wind wheels. The wind flow after the first wind wheel is turbulated and passing

a certain distance, the degree of turbulence decreases and this distance has not yet been determined. To optimize power generation, it is necessary to know the distance of wind flow alignment after the first wind wheel, in order to reduce the negative impact on the second.

The maximum power generation depends not only on the distance between the wind wheels, but also on the number of blades on the wind wheels. To improve power generation, it is also important to reduce the value of wind speed for starting the wind wheels.

3. The aim and objectives of the study

The aim of the study is to develop a wind turbine with two multidirectional wind wheels. This design will have increased efficiency, in comparison with existing ones, by reducing the wind speed for starting wind wheels, determining the optimal distance between wind wheels, as well as increasing generation depending on the number of blades on a wind generator with two multidirectional wind wheels.

To achieve this aim, the following objectives are performed:

- eliminate the starting resistance of the wind wheel at low wind flow speeds, use two wind wheels with a low starting rotation speed, which increase the relative speed of the two propellers;
- determine the optimal distance between the wind wheels to create conditions for maximum conversion of wind energy into mechanical energy of rotation of the rotor and stator;
- determine the optimal number of blades on the wind wheels to increase the relative speed of rotation.

4. Materials and methods

The objects of the study are two multidirectional wind wheels, the distance between them, as well as the number of blades on the wind wheels. It is assumed that the use of two wind wheels increases the sweeping area on which electricity generation depends. The level of turbulence of the air flow from the first wind wheel will fade at a certain distance, which needs to be determined. It was assumed that the efficiency of the wind turbine will depend on the number of blades on the wind wheels.

During the study of the new design of a wind device with two multidirectional wind wheels, experimental research methods were used in laboratory models (Fig. 1).

On experimental models, it is possible to establish different wind wheels, change the distance between them and the number of blades on them.

Wind wheels are installed on one axis, rotation of the first one is transmitted to rotor, and of the second one – to generator stator. The use of two wind wheels doubles the projected area, which increases the level of possible generation. It also affects the initial rotational speed of the wind wheels. By changing the distance between wind wheels, it is possible to determine the optimal distance between them at which maximum generation occurs. Its magnitude is also influenced by the number of blades on the wind wheels, which can be varied depending on energy generation.

Wind flow running into the wind wheel was created using a fan. Changing the wind speed during experiments, the dependence of generation on the wind force was determined.

At the first stage, the readings were taken during the operation of one wind wheel, then two wind wheels. At the second stage, the distance between the wind wheels changed. And at the third stage, the readings were taken with different numbers of blades on the wind wheels.

Experimental research methods involve obtaining data on the magnitude of the wind flow velocity, measuring the electrical characteristics of generation, depending on the distance between the wind wheels, as well as the number of blades on the wind wheels. These data are entered into tables, then processed and arranged in the form of dependency graphs. The experimental data obtained make it possible to determine the optimal dimensions of the structure for maximum power generation.

During the experiments, the effect of wind flow on wind wheels was studied in order to determine the speed of the wind wheels. During the experimental study of the design, the optimal distance between the wind wheels was revealed, which minimizes the negative effect of turbulence of the air flow from the first wind wheel to the second. The maximum power generation depends on the number of blades on the wind wheels, which was determined experimentally by varying the number of blades.

The experimental installation consists of two wind wheels mounted on the same axis, with the possibility of changing the distance between them, as well as changing the number of blades on them. The simulation of the air flow was carried out by an industrial fan, which made it possible to create a directional wind flow in the range from 1 to 10 m/s. An industrial fan is installed in front of the wind turbine and is directed at the first wind wheel of the windmill. An anemometer was used to measure wind speed, and a multimeter was used to measure the generated voltage. The devices are installed on the structure of the wind turbine, the readings of which are displayed on an electronic scoreboard. The results of the experiments were recorded in a special observation log and processed in tabular form in Microsoft Excel to obtain dependency graphs. The drawings and technical documentation for this wind turbine design were designed using Autodesk Autocad 2020.

5. Research results of a wind turbine with two multidirectional wind wheels

5.1. Two wind wheels with low starting speed

The study of the starting process and the starting speed of wind wheels were studied on a model of a wind device with two wind wheels (Fig. 1, description of the experiment, starting schedule).

The blades are curved tapering profiles with variable cross-section. The blades have a certain angle of attack, which converts the energy of the wind flow into the rotational movement of the wind wheel. The blade profile is selected according to the reference data, the angle of attack is 30°. Such characteristics of the wind wheel blades allow to reduce the starting speed to 1 m/s.

To conduct experimental studies, let's use the first version of a wind generator with counter-rotating wind wheels, shown in Fig. 1, *a*.

The specified version of the wind generator is achieved by changing the generally accepted design and adding an additional wind wheel, which rotates in the opposite direction relative to the first one in the wind direction.

Fig. 1, *b* shows an alternative design of a wind generator with counter-rotating wind wheels. This structure was designed and assembled after conducting experimental studies with the structure shown in Fig. 1, *a*.

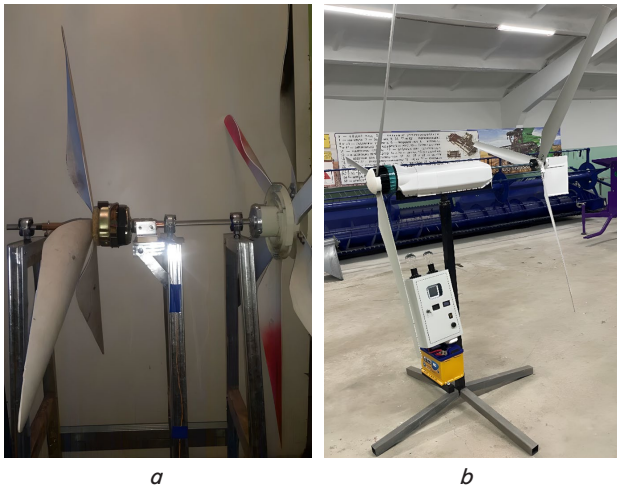


Fig. 1. Models of a wind device with two wind wheels: *a* – the first model; *b* – the second model

The second design of the wind generator has large weight and size dimensions and initially assumes a large production of electric energy. The length of the blades of the first structure is 0.5 m, while the second structure has a radius of wind wheels of 1.5 m.

The experimental studies presented in this article were carried out with the first type of construction. After successful research results, a second model was constructed.

Taking into account the dimensions of the second design, experiments were carried out that were identical to the studies of the first version of the windmill. The data obtained during the experiments correspond to the expected increase in the generated power in proportion to the increase in the dimensions of the structure.

Fig. 2 shows a graph of the start of starting wind wheels with different numbers of wind wheels involved and combinations of the number of blades.

As can be seen from the graph, there is a relationship between the number of blades involved and the initial speed of rotation of wind wheels. So, when using 3 blades on one wind wheel (with the second one locked), the average starting speed is 1.63 m/s.

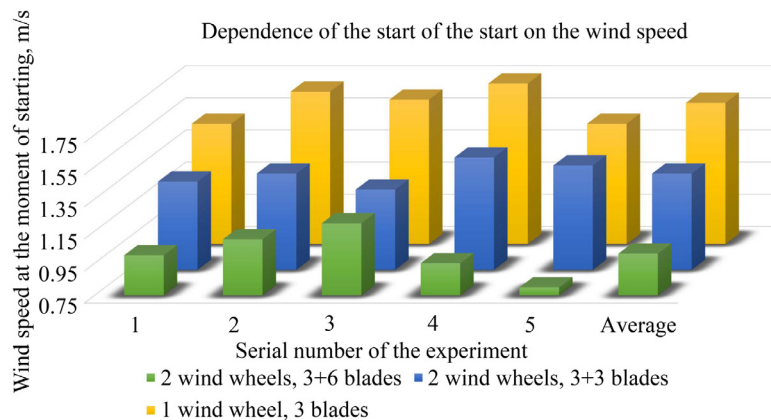


Fig. 2. Beginning of starting of wind wheels

When using two wind wheels with 3 blades on each, the average starting speed is 1.35 m/s, which is 20 % less than when using a single wind wheel.

The third type of measurement was carried out when 3 blades were deployed on one of the wind wheels. When using this technological solution, the average starting speed of the wind wheel is 1.01 m/s, which is more than 30 % more in comparison with the second experiment and more than 60 % more in comparison with the first.

Based on these data, it is possible to safely conclude that with an increase in the number of blades and the addition of an additional wind wheel, the necessary wind speed to start starting the wind wheel decreases.

5. 2. Optimal distance between wind wheels

To determine the optimal distance between wind wheels, conditions were created on the model in which it was possible to adjust the distance between wind wheels. (Fig. 3) To maximize the transfer of wind energy, the optimal distance between wind wheels is selected, at which the wind flow stabilizes after the first wind wheel and has the maximum impact on the second.

As can be seen in Fig. 3, when operating this device, three conditionally selected areas of air flow movement are formed that affect the operation of the wind generator:

- air flow area before interaction with the first wind wheel;
- the area located between the first and second wind wheels;
- the area located after the second wind wheel.

Air flow area before interaction with the first wind wheel. This area does not differ from the area in front of a traditional wind generator. The Fig. 3 shows the air flow in area I.

When the air flow moves on the active screw of the wind wheel, the blades form drag. According to Newton's third law, the force acting on the blades, which is converted into the rotational motion of the propeller, is equal to the force of drag of the blades. These two forces are directed in opposite directions. However, a wind generator with a horizontal axis of rotation (used in the study) gets its rotation from the lifting force F_l , which has a direction of 90° , relative to the direction of wind movement [5].

Fig. 3 shows the conditional areas of air flow.

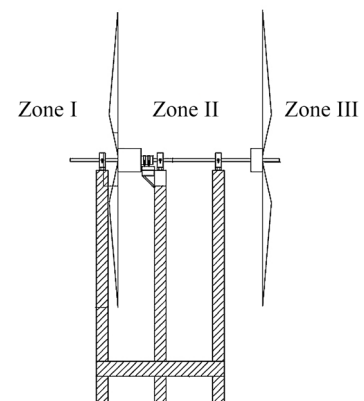


Fig. 3. Conditional areas of air flow

The area located between the first and second wind wheels. This area has specific properties and features. In this space, the air flow passing through the area of rotation of the first wind wheel twists. Since wind wheels rotate in opposite directions, the air flow when moving

from the first wind wheel to the second, passes a spiral geometry first in one direction, then in the other. Mathematically, it is possible to describe the direction of the air flow with opposite signs. At the moment of changing the direction of movement, swirls occur.

Fig. 4 shows a description of the air flow of zone 1, i.e. before interaction with the wind generator. This zone is identical to a traditional wind turbine. The air flow has a linear direction up to the first wind wheel, crossing the first blades enters zone 2.

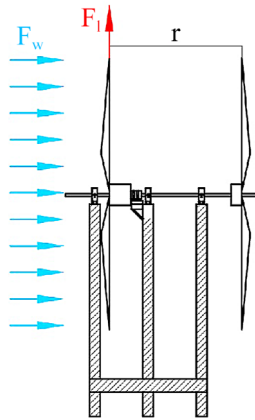


Fig. 4. Direction of air flow in area I: F_w – force of air flow; F_l – lifting force

These swirls negatively affect the conversion of wind energy into electrical energy, since the second wind wheel does not receive an equivalent amount of straight-line air flow in comparison with the first wind wheel. Swirls of air flows during the operation of an unconventional type of wind generator are shown in Fig. 5.

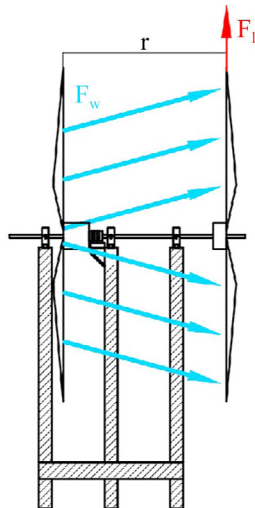


Fig. 5. Direction of air flow in area II: F_w – force of air flow, F_l – lifting force

The third area, located after the second wind wheel, does not participate in energy generation, since only the energy of the air flow passes there, which is not involved in generating electric energy.

The amount of undeveloped wind energy is determined by the Betz limit. The wind energy utilization rate is 0.593. That is, of 100 % of the wind energy that passes through the wind-

mill area, 59 % is used to generate electricity. Fig. 6 shows the air flow of the third area.

Therefore, when calculating power, it is necessary to take into account the fact that the second wheel receives less wind energy than the first one by a factor of k .

It should be assumed that this coefficient depends on several parameters:

- wind speed, V , m/s;
- air flow density, P , kg/m³;
- number of blades n , pcs;
- wind wheel rotation speeds v , rpm;
- distances between wind wheels l , m.

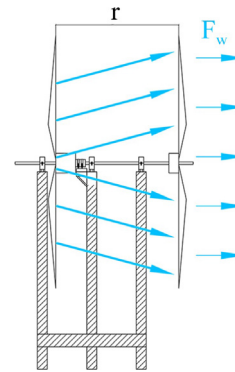


Fig. 6. Air flow of the third area: F_w – force of air flow

Based on the above parameters, it can be seen that the most convenient function to change is the distance between wind wheels.

Obviously, with an increase in the inter-wheel distance, the interaction between the air flows created by the wind wheels will decrease, because when passing the first wind wheel, the air flow will have more time to restore straight properties, which will favorably affect the rotation of the second wind wheel. The straightness of air flows at different wheel distances is shown in Fig. 6.

As can be seen in Fig. 7, the curvature of the straightness of the air flow decreases as the distance between the first and second wind wheels increases. Since the curvature decreases, the impact on the blades increases and thereby a higher rotation speed is achieved and, accordingly, the generation of electrical energy.

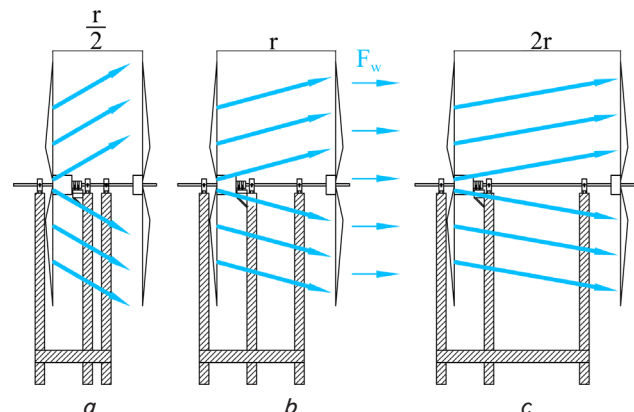


Fig. 7. Straightness of air flows at different wheel distances: F_w – force of air flow: a – the distance between the wind wheels equals $r/2$; the distance between the wind wheels equals r ; the distance between the wind wheels equals $2r$

Under ideal conditions, it can be assumed that the opposite rotation of the stator and rotor will increase the power generated by 2 times. However, this is practically impossible to achieve due to the impact of multidirectional eddy currents. Therefore, the coefficient of added generation due to the second wind wheel has the following value:

$$1 < k < 2.$$

Since there is a directly proportional relationship between the wind energy absorbed by the second wind wheel and the generated power of the wind generator, it should be assumed that the coefficient of energy generated by a wind generator with counter-rotating wind wheels P_{ww} relative to a traditional wind generator P_w has the following relationship:

$$P_{ww} = kP_w, \tag{1}$$

where k – the coefficient of energy generated by a wind generator with counter-rotating wind wheels; P_{ww} – the power of a wind generator with counter-rotating blades; P_w – the power of a traditional wind generator.

To confirm or refute the theoretical assumption of the value of the coefficient of energy generated by a wind generator with counter-rotating wind wheels, experimental work was carried out with the wind generator model and the obtained values were analyzed.

5. 3. Optimal number of blades on wind wheels

To study the effect of the number of blades on the generation capacity, the model was equipped with the function of unfolding additional blades on one of the wind wheels (Fig. 8).

To study the effect of counter-rotating propellers and the deployment of additional blades on one of the wind wheels, it is necessary to compare several options. To do this, experiments were conducted that made it possible to create dependency graphs that justify the choice of a particular windmill option.

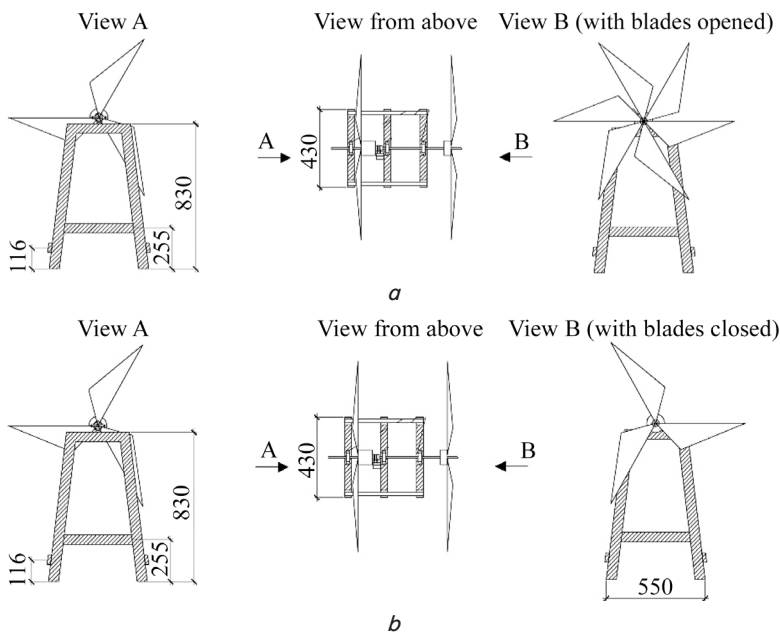


Fig. 8. External view of a wind generator layout with two multidirectional wind wheels: *a* – with the wind wheel blades folded; *b* – with the wind wheel blades open

For experiments, the design of a wind generator with a variable number of blades was used. The wind generator function, which allows to change the number of blades on one of the wind wheels, allows to get more detailed data and create dependencies for different types of wind wheels. The appearance of the wind generator is shown in Fig. 9.



Fig. 9. General view of the wind generator layout

For different numbers of blades, five measurements were made at different wind speeds.

The first experiment consists of measurements made on a three-bladed wind generator, the blades of which are fixed to the rotor, with the stator stationary. To ensure the immobility of the stator with blades, the stator of the experimental installation was locked with the help of fasteners.

Fig. 10 shows a general view of the windmill installation on which the measurements were made for this experiment.

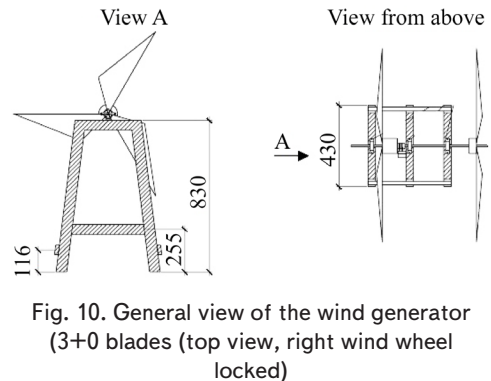


Fig. 10. General view of the wind generator (3+0 blades (top view, right wind wheel locked))

The first experiment, an idling experiment. The results of the idling experiment are presented in Table 1.

Based on the results of the data presented in Table 1, it is possible to draw up a graph of the dependence of the generated voltage on wind speed, Fig. 11.

As can be seen in Fig. 11, there is practically no voltage generation up to 6 m/s. However, after that, generation increases with increasing speed. So, at 9 m/s (the maximum in the ex-

periment), a 12V voltage is generated. Next on the chart, the forecast is based on known data. High and low probability bindings correspond to errors in the calculation.

Table 1
Results of experiments of a wind generator with 3 blades and a locked stator at idle

$V_w, \text{m/s}$	1	2	3	4	6	8	10
Measurement #1, V	0.4	0.45	0.5	0.9	1.8	4.1	10.5
Measurement #2, V	0.39	0.44	0.52	0.87	1.78	4.4	10.9
Measurement #3, V	0.35	0.47	0.55	0.96	1.87	3.89	9.98
Measurement #4, V	0.41	0.5	0.52	0.82	1.92	4.25	10.1
Measurement #5, V	0.43	0.4	0.49	0.93	1.71	3.98	9.7
Average, V	0.4	0.4	0.52	0.9	1.82	4.12	10.24

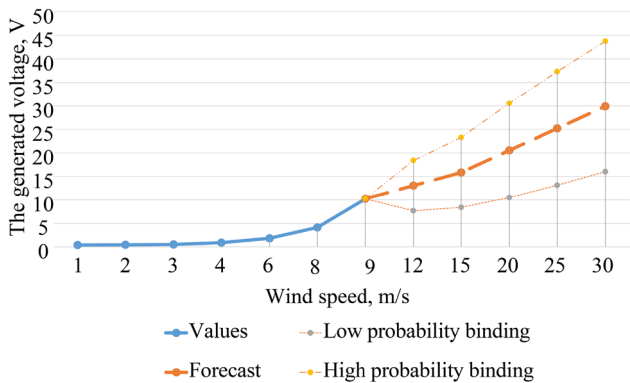


Fig. 11. Experimental data at idle (3 blades on the rotor, stator locked)

According to the forecast, energy generation under these conditions increases almost linearly after reaching the wind speed of 9 m/s.

The second experiment, an experiment under the load of PVR-50. The results of the experiment under load are presented in Table 2.

Table 2
Experimental results of a wind generator with 3 blades and a locked stator under load

$V_w, \text{m/s}$	1	2	3	4	6	8	10
Measurement #1, V	0.28	0.32	0.35	0.63	1.26	2.87	7.35
Measurement #2, V	0.3	0.32	0.36	0.6	1.2	2.72	7.11
Measurement #3, V	0.25	0.29	0.32	0.55	1.16	2.6	7
Measurement #4, V	0.35	0.37	0.39	0.66	1.31	2.79	7.19
Measurement #5, V	0.26	0.32	0.38	0.59	1.21	2.93	7.29
Average, V	0.29	0.32	0.36	0.61	1.23	2.78	7.19

According to the obtained measurements, it is possible to draw up a graph of the dependence of the generated voltage on the wind speed, with a load of PVR-50. The graph is shown in Fig. 12.

As can be seen in the graph below, a noticeable increase in generation occurs at wind speeds of 8–9 m/s. According to the available data, the forecast of an increase in generation at speeds above 9 m/s is linear. So, at a wind speed of 20 m/s, the generation will be 15 V, at 30 m/s 20 V.

When comparing idle and loaded graphs, it is possible to conclude that generation under the selected load is re-

duced by 30 %, which can be traced along the entire length of both graphs.

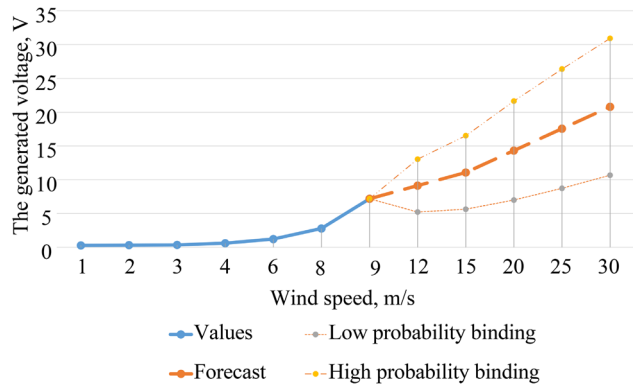


Fig. 12. Curve based on measurements under the load of the PVR-50 (3 blades on the rotor, the stator is locked)

The second experiment consists of measurements made on a six-blade wind generator, on the stator of which there are 3 blades rotating in one direction, and there are 3 blades rotating in the opposite direction on the rotor.

Fig. 12 shows a general view of the windmill installation on which the measurements were made for this experiment.

The results of experimental studies with a wind generator with counter-rotating wind wheels at idle (3 on the stator, 3 on the rotor) are shown in Table 3.

Based on the obtained data obtained experimentally, it is possible to plot the dependence of the generated voltage on the wind speed. The graph is shown in Fig. 13.

Table 3
Measurement results on a wind generator with counter-rotating wind wheels at idle (3 on the stator, 3 on the rotor)

$V_w, \text{m/s}$	1	2	3	4	6	8	10
Measurement #1, V	0.5	0.5	0.6	1.1	2.4	5.8	16.8
Measurement #2, V	0.46	0.47	0.62	1.05	2.3	5.55	15.1
Measurement #3, V	0.56	0.55	0.64	1.09	2.8	5.31	17.8
Measurement #4, V	0.51	0.52	0.63	1.16	2.4	5.92	18.1
Measurement #5, V	0.47	0.46	0.55	1.13	2.25	5.84	16.5
Average, V	0.5	0.5	0.608	1.106	2.43	5.684	16.86

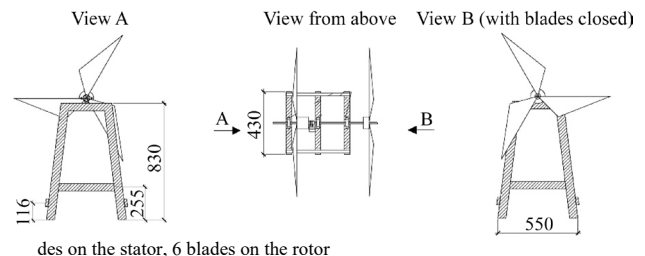


Fig. 13. General view of the wind generator (3+3 blades)

As can be seen in Fig. 14, there is practically no voltage generation up to 6 m/s, as in the previous experiment with a locked rotor. However, after that, generation increases with increasing speed. So, at 9 m/s (the maximum in the experiment), 18 V voltage is generated. Next on the chart, the forecast is based on known data. High and low probability bindings correspond to errors in the calculation.

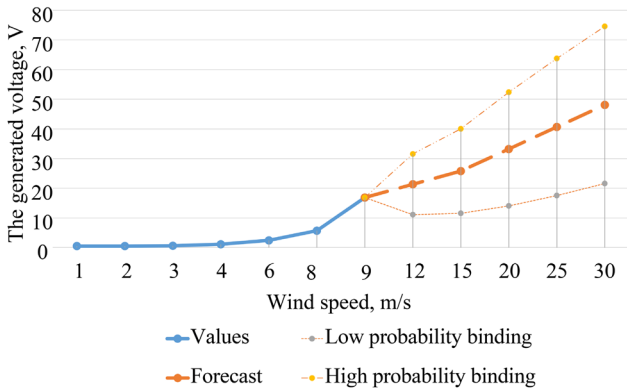


Fig. 14. Experimental data at idle (3 blades on the rotor, 3 blades on the rotor)

In comparison with the experiment with a stalled stator, the generated voltage at a wind speed of 8–9 m/s increased by 50 %.

The next experiment for a wind wheel with counter-rotating wind wheels is an experiment with a PVR-50 load. The measurement results are shown in Table 4.

Table 4

Measurement results on a wind generator with counter-rotating wind wheels under load (3 on the stator, 3 on the rotor)

V_{w} , m/s	1	2	3	4	6	8	10
Measurement #1, V	0.35	0.35	0.42	0.77	1.68	4.06	11.76
Measurement # 2, V	0.29	0.31	0.44	0.82	1.54	3.92	12.01
Measurement # 3, V	0.33	0.36	0.4	0.75	1.64	4.19	12.5
Measurement # 4, V	0.31	0.36	0.49	0.9	1.73	4.25	12.8
Measurement #5, V	0.35	0.36	0.41	0.75	1.78	4.11	11.92
Average, V	0.326	0.348	0.432	0.798	1.674	4.106	12.198

Based on the data presented in Table 4, it is possible to draw up a graph of the dependence of the generated voltage on the wind speed. The resulting curves are shown in Fig. 15.

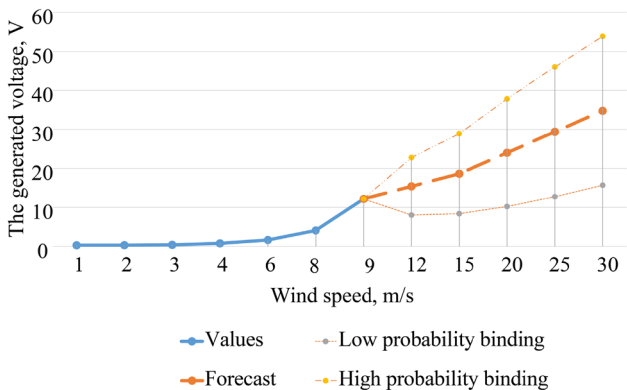


Fig. 15. Curve based on measurements under load of the PVR-50 (3 blades on the rotor, 3 blades on the stator)

As can be seen in Fig. 15, a noticeable increase in generation occurs at wind speeds of 8–9 m/s. According to the available data, the forecast of an increase in generation at speeds above 9 m/s is linear. So, at a wind speed of 20 m/s, the generation will be 24 V, at 30 m/s 35 V.

In comparison with the experiment with a stalled stator, the generation increases by almost 70 % under the same external conditions.

When comparing idle and loaded graphs, it is possible to conclude that generation under the selected load is reduced by 20–30 %, which can be traced along the entire length of both graphs.

The third experiment consists of measurements made on a nine-blade wind generator, on the stator of which there are 3 blades rotating in one direction, and on the rotor, there are 6 blades rotating in the opposite direction.

Fig. 16 shows a general view of the windmill installation on which the measurements were made for this experiment.

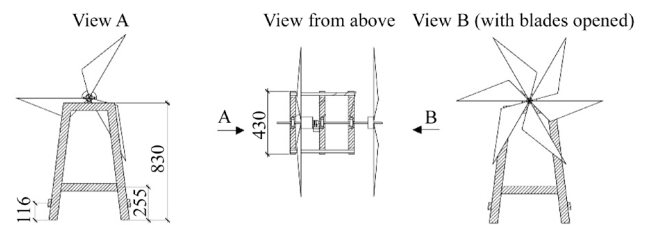


Fig. 16. General view of the wind generator (3+6 blades)

As with the previous two wind generator designs, this version has been experimentally tested, both at idle and under the load of PVR-50.

The results of idling experiments are presented in Table 5.

Based on the obtained data obtained experimentally, it is possible to plot the dependence of the generated voltage on the wind speed. The graph is shown in Fig. 17.

Table 5

Measurement results on a wind generator with counter-rotating wind wheels at idle (3 on the stator, 6 on the rotor)

V_{w} , m/s	1	2	3	4	6	8	10
Measurement #1, V	0.75	0.8	0.85	1.53	3.25	7.6	20.6
Measurement # 2, V	0.72	0.82	0.84	1.49	3.1	6.9	19.8
Measurement # 3, V	0.68	0.84	0.87	1.6	3.34	7.4	18.9
Measurement # 4, V	0.78	0.8	0.82	1.59	3.62	7.9	22.3
Measurement #5, V	0.8	0.86	0.88	1.64	3.19	7.26	21.4
Average, V	0.75	0.82	0.85	1.57	3.30	7.41	20.60

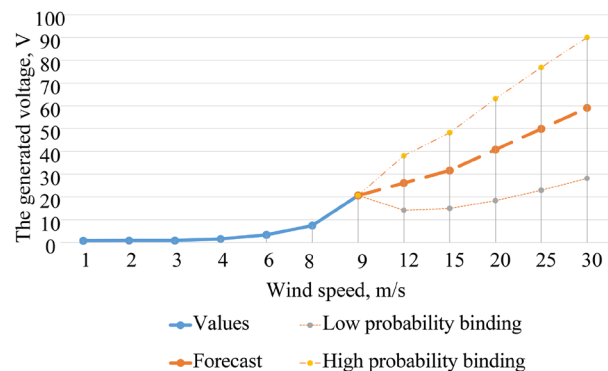


Fig. 17. Experimental data at idle (3 blades on the stator, 6 blades on the rotor)

As can be seen in Fig. 17, up to 6 m/s, voltage generation practically does not occur, as in previous experiments with a stalled rotor and a wind generator with six blades (3+3).

However, after that, generation increases with increasing speed. So, at 9 m/s (the maximum in the experiment), 21 V voltage is generated. Next on the chart, the forecast is based on known data. High and low probability bindings correspond to errors in the calculation.

In comparison with the experiment with the stator locked at idle, the voltage generated at wind speeds of 8–9 m/s increased by more than 90 %.

In comparison with the experiment with a six-blade wind generator (3+3) at idle, the voltage generated at a wind speed of 8–9 m/s increased by 20–30 %.

The following experiment for a wind wheel with counter-rotating wind wheels with 3 blades on the stator and 6 blades on the rotor was performed under a load of PVR-50. The measurement results are shown in Table 6.

Table 6

Measurement results on a wind generator with counter-rotating wind wheels under load (3 on the stator, 6 on the rotor)

V_w , m/s	1	2	3	4	6	8	10
Measurement # 1, V	0.525	0.56	0.595	1.071	2.275	5.32	14.42
Measurement # 2, V	0.49	0.51	0.574	1.12	2.13	5.11	13.85
Measurement # 3, V	0.53	0.6	0.641	1.21	2.33	5.41	14.87
Measurement # 4, V	0.45	0.53	0.66	1.31	2.4	5.5	15.01
Measurement # 5, V	0.493	0.54	0.61	0.95	2.02	5.14	14.12
Average, V	0.4976	0.548	0.616	1.1322	2.231	5.296	14.454

Based on the data presented in Table 6, it is possible to draw up a graph of the dependence of the generated voltage on the wind speed. The resulting curves are shown in Fig. 18.

As can be seen in Fig. 18, up to 6 m/s, voltage generation practically does not occur, as in previous experiments with a stalled rotor and a wind generator with six blades (3+3). However, after that, generation increases with increasing speed. So, at 9 m/s (the maximum in the experiment), 15 V voltage is generated, which is 25 % less than the experiment at idle. Next on the chart, the forecast is based on known data. High and low probability bindings correspond to errors in the calculation.

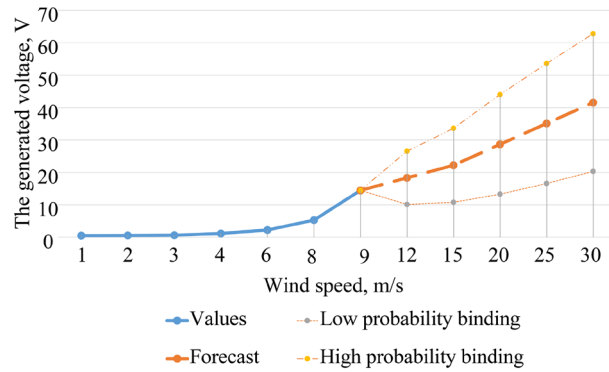


Fig. 18. Curve based on measurements under load of the PVR-50 (6 blades on the rotor, 3 blades on the stator)

In comparison with the experiment with a stalled stator under load, the voltage generated at a wind speed of 8–9 m/s doubled.

In comparison with the experiment with a six-blade wind generator (3+3) under load, the voltage generated at a wind speed of 8–9 m/s increased by 20–30 %.

At the conclusion of the comparison of experiments, it is necessary to draw up a diagram that includes the results of experiments both at idle and under load, to visually confirm the conclusions. The results of all experiments are presented in Table 7.

The final table of experimental results shows that the best generation rates are observed in a wind generator with 6 blades on the rotor and 3 blades on the stator. The final table is shown graphically in Fig. 19.

The wind turbines with two multidirectional wind wheels have been investigated in this article.

According to the data obtained during practical experiments, the coefficient of energy generated by a wind generator with counter-rotating wind wheels is equal to:

$$1.5 < k < 1.8.$$

In accordance with the conducted experimental studies, the theoretical predictions have confirmed, and the accuracy of the coefficient has been increased. However, this is not the end of the research, it continues.

Table 7

Results of all experiments, wind turbines of various designs

V_w , m/s	Voltage generated, V					
	3 blades on the rotor, stator locked		3 blades on the rotor, 3 blades on the stator		6 blades on the rotor, 3 blades on the stator	
	Idling	Under load	Idling	Under load	Idling	Under load
1	0.40	0.29	0.50	0.33	0.75	0.50
2	0.45	0.32	0.50	0.35	0.82	0.55
3	0.52	0.36	0.61	0.43	0.85	0.62
4	0.90	0.61	1.11	0.80	1.57	1.13
6	1.82	1.23	2.43	1.67	3.30	2.23
8	4.12	2.78	5.68	4.11	7.41	5.30
10	10.24	7.19	16.86	12.20	20.60	14.45
12	13.05	9.13	21.32	15.43	26.10	18.33
15	15.86	11.08	25.78	18.65	31.59	22.20
20	20.54	14.32	33.22	24.03	40.75	28.66
25	25.22	17.56	40.65	29.41	49.91	35.11
30	29.91	20.80	48.08	34.79	59.07	41.57

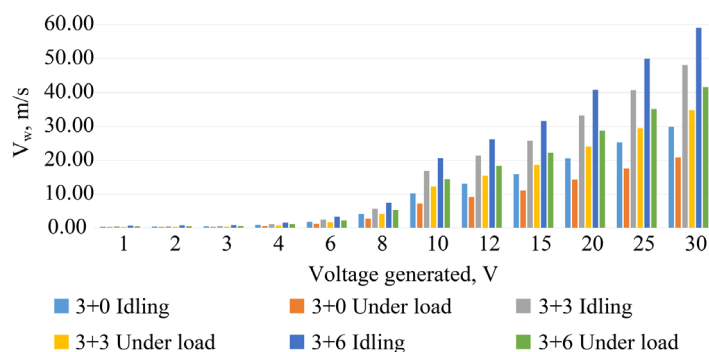


Fig. 19. Summary of experimental results: 3+0 idling – stator is locked, 3 blades on the rotor; 3+0 under load – stator is locked, 3 blades on the rotor; 3+3 idling – 3 blades on the stator, 3 blades on the rotor; 3+3 under load – 3 blades on the stator, 3 blades on the rotor; 3+6 idling – 3 blades on the stator, 6 blades on the rotor; 3+6 under load – 3 blades on the stator, 6 blades on the rotor

Wind turbines with counter-rotating wind wheels are not fully understood. This area of scientific research, wind power, and this type of wind turbines has a great potential for research.

6. Discussion of the results of the study of electric energy generation at low wind speeds

Fig. 2 shows the results of measurements of wind speed at the time of starting, with a different number of blades on two wind wheels. Based on the data presented in Fig. 2, it can be seen that with an increase in the number of blades on two wind wheels, the required wind speed decreases to start the rotation of the wind wheel.

Fig. 3–6 show the study areas of the effect of the wind wheel airflow on the first wind wheel, turbulence of flows between wind wheels and alignment of the wind flow after passing the sweeping area of the second wind wheel.

Fig. 7 shows the lines of the direction of movement of air masses between the wind wheels. Based on this, it can be seen that the optimal distance between two wind wheels is a distance equal to one radius of the wind wheel r , because at this distance, the vortices formed by the first wind wheel have the least negative effect on the rotation of the second, and accordingly on generation as a whole.

An analysis of the optimal number of blades on wind wheels is carried out. Fig. 19 shows the results of all the experiments conducted in the section summarized in Table 7. Based on the data in the table, it can be seen that when the blades on one of the wind wheels are increased to 6, generation increases almost 2 times under the same conditions.

Unlike previous studies, the design of the wind generator described in this article has a simplified electrical part, because to create a similar sample of a wind turbine, the electrical part of the electric generator does not change. Only the mechanics can be changed. In this design, the electrical part is represented by an electric generator. This device has constant characteristics and in our case is not the object of research. This increases the availability of mass creation of such devices.

Experiments conducted on the layout of a wind turbine confirm that the moment of starting the generator's wind wheels when adding wind wheels and additional sets of

blades occurs at a lower wind speed, unlike existing analogues [4].

The optimal distance between the wind wheels has been confirmed experimentally, this became possible thanks to the data presented in Fig. 7. According to the research, the distance between the wind wheels should correspond to the radius of the wind wheel, thanks to this option, the turbulence of the air flow has optimal directions for influencing the second wind wheel in the direction of wind movement.

According to research, the greatest power generation occurs when using three blades on the first and six blades on the second wind wheel, which is confirmed by the data summarized in Table 7 and graphically presented in Fig. 19.

Thanks to the conducted research, knowledge about wind turbines with two wind wheels has been further developed, in particular, the practical implementation of this task has been expanded.

Thanks to the experiments presented in this article, the theories of previous and updated studies have been confirmed in order to improve energy generation by a wind generator with two wind wheels at low wind speeds, according to Fig. 17, at a speed of 1 m/s, the generation of electric energy using two wind wheels (Fig. 14) increased compared to the use of one wind wheel (Fig. 11) by 50 %.

The design of the wind turbine presented in this study allows it to be used for decentralized energy supply with improved efficiency.

The limitation of using the design presented in the article is the need for a wind direction mechanism [7]. This problem has not yet been solved on existing wind turbines, and there is also a problem of cantilever loading of the blades at the point of attachment to the axis of rotation [9]. An additional limitation in our case is the increased dimensions of the wind turbine, which is important, during operation a large coverage area is required when working and rotating the wind wheels.

The disadvantage is an increase in the number of structural elements, which affects the frequency of maintenance and increases the risk of failure of one or another element [6].

The research carried out requires continuation in order to solve the problem of the direction of the wind wheels downwind, as well as the elimination of the cantilever load on the attachment points of the blades to the axis of rotation. It is also necessary to explore the possibility of using different blade designs to increase energy production and reduce the destructive effects of the wheels on each other.

The conducted research shows the legality of using two wind wheels of different orientation to increase the efficiency of the wind generator, as well as its generation capacity. This is confirmed by calculations and experimental data obtained on two laboratory models (Fig. 1) designed for the present research.

Further design studies suggest the following areas:

1. Maintaining the trend of increasing power, while increasing the generator power.
2. Maintaining the trend of increasing power, while increasing weight and size indicators.
3. Conducting experiments with several models to determine the effect of wind turbines with counter-rotating blades on neighboring windmills.

4. The impact of additional equipment on the increase in electricity generation.

All of the above ideas are useful for future research, will allow to refine existing results, and also have the potential to open up new opportunities for wind turbines with counter-rotating wind wheels.

7. Conclusions

1. The use of two wind wheels made it possible to use low-potential wind speeds, the moment of starting the wind wheel during experiments is equal to the wind speed of 1 m/s.

2. The distance between the wind wheels plays an important role in generating energy. The results showed that the optimal distance depends on the diameter of the wind wheel and is equal to one radius r .

3. The number of blades on the wind wheels also affects the effective operation of the wind device. Experiments have shown that the optimal option in this study is three blades on the first and six blades on the second wind wheel, with this option, maximum energy production is ensured.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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