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MINIMIZATION OF MOTION RESISTANCE IN PROSUMER WIND POWER PLANT

MINIMALIZACJA OPORÓW RUCHU W PROSUMENCKIEJ ELEKTROWNI WIATROWEJ

Summary: *By their very nature, prosumer wind farms must be installed in the vicinity of human settlements. These locations have very limited wind energy resources due to limited installation heights, terrain obstacles, tall trees and buildings. All solutions that increase their energy efficiency are of particular importance for this type of power plant. The article describes the selected design solutions of turbine rotors with a vertical axis of rotation that enable the improvement of the efficiency of prosumer power plants. A new design solution for the bearing of the power plant shaft was suggested. High durability, low noise, ease of use and safety of use characterize it. This bearing system ensures the minimization of movement resistance, in particular at start-up, which means that the power station can operate effectively at low wind speeds.*

Keywords: *prosumer wind farms, wind energy resources, energy efficiency, minimization of motion resistance, power plant*

Streszczenie: *Ze swej natury prosumenckie farmy wiatrowe muszą być instalowane w pobliżu osiedli ludzkich. Lokalizacje te mają bardzo ograniczone zasoby energii wiatrowej ze względu na ograniczone wysokości instalacji, przeszkody terenowe, wysokie drzewa i budynki. Szczególne znaczenie dla tego typu elektrowni mają wszelkie rozwiązania zwiększające ich efektywność energetyczną. W artykule opisano wybrane rozwiązania konstrukcyjne wirników turbin z pionową osią obrotu, które umożliwiają poprawę sprawności elektrowni prosumenckich. Zaproponowano nowe rozwiązanie konstrukcyjne łożyska wału elektrowni. Cechuje go wysoka trwałość, niski poziom hałasu, łatwość obsługi i bezpieczeństwo użytkowania. Taki układ łożysk zapewnia minimalizację oporów ruchu, w szczególności przy rozruchu, co sprawia, że elektrownia może efektywnie pracować przy niskich prędkościach wiatru.*

Słowa kluczowe: *prosumenckie farmy wiatrowe, zasoby energii wiatrowej, efektywność energetyczną, minimalizacja oporów ruchu, elektrownia wiatrowa*

Introduction

Prosumer power plants are designed mainly to meet the electricity demand of the users themselves, with the transfer of only the excess of generated energy to the general power grid. In the case of water or wind power plants, respectively small amounts of water or winds with limited speed are used.

Prosumer wind farms are subject to numerous environmental restrictions, as they are most often installed on buildings or in the close vicinity of residential areas. Wind conditions in these zones are often limited due to numerous terrain obstacles, tall trees and buildings. Additional restrictions follow from building regulations and the need to maintain as quiet running as possible and safety of use. The height of the installation on buildings is limited by regulations (in Poland it is currently 3 m above buildings).

Similar limitations apply when wind turbines are placed on towers in the close vicinity of human habitation [1, 8, 7].

The aforementioned limitations mean that solutions allowing for the fullest possible use of available wind energy are of particular importance. In particular, efforts should be made to minimize own motion resistance so that low-speed winds can be used and the power plant start-up is carried out at low wind speeds.

This paper presents the design solutions of the power plant elements that aim at the decrease in the start-up resistance and assuring lowest noise generation and security of its use. The requirements of minimum costs of construction and exploitation of wind power station are considered.

Turbine rotors of wind turbines with a vertical axis of rotation and improved functional properties

In the field of various designs of prosumer wind power plants, turbine rotors with a vertical axis of rotation are most often used. Their main advantage includes simple design and the ability to work regardless of the direction of the wind. Compared to the rotors with a horizontal axis, especially large wind farms, they have lower energy efficiency and a relatively large axial load [2]. The lower efficiency of rotors with a vertical axis of rotation is due to the fact that the blades of the rotors have to move "upwind" (against the direction of the wind) during part of their rotation, which absorbs part of the energy obtained on the active part of the rotation of the rotor.

The rotors of wind turbines with a vertical axis of rotation can be relatively easily modified in order to obtain more generated
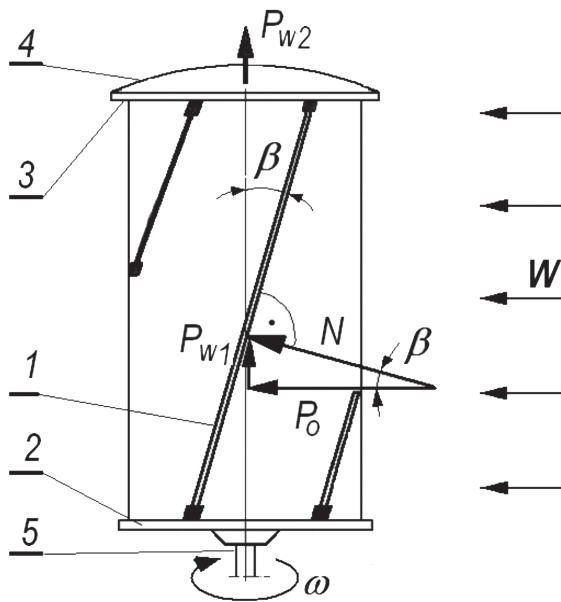
Fig. 1. Scheme of a wind turbine rotor with a vertical axis of rotation and helical blades and an aerodynamic design

power. These modifications usually have an extensive character and consist in increasing the working surface of the rotors. Enlarging the dimensions of the rotors encounters many limitations. The increase in the diameter of the rotors increases the active surface of the blades, but leads to a decrease in rotational speed and causes a significant increase in the weight of the rotors, which increases the bearing resistance. It is more effective to increase the length of the blades. With the increase in the height of the rotors, their energy efficiency improves, because the share of the unfavourable action ("escape") of the air stream at the blade ends decreases. An increase in the length of the blades, on the other hand, increases the susceptibility to generating vibrations, especially in the case of winds of variable speed.

In these cases, there are the aforementioned restrictions in the regulations and the increasing in bending moment acting on the shaft of the power plant, because the arm of the resultant wind pressure force is increased.

In the described situation, design solutions that improve the efficiency of rotor operation without excessive increase in their size become more important.

For prosumer applications, the height of rotors with a vertical axis of rotation can be advantageously assumed to be about 2 ÷ 4 times of the diameter, especially when using the rotor design modifications described below.

Instead of straight blades that are oriented parallel to the axis of rotation of the rotor, it is advisable to use skew or helical blades, which is schematically illustrated in Fig. 1. With the appropriate inclination of the blades at an angle in the range $\beta = 10^0 \div 20^0$, the acting force for each blade as a result of wind pressure N decomposes into a horizontal component $P_0 = N \cos \beta$, causing the rotor torque, and a vertical component $P_{w1} = N \sin \beta$ acting upwards. The P_{w1} component acts in the direction of unloading the shaft bearing with forces reducing its axial load. On the longitudinal

load of the shaft bearing with the vertical axis of rotation consists of the weights of the rotor itself, the shaft, which is usually long, and the weights of all moving parts mounted on the shaft. The apparent reduction of the aforementioned weights as a result of the force P_{w1} causes the reduction in the resistance to rotor movement, which is desirable, especially during start-up. It is particularly advantageous to use blades with a helical shape, because then it is possible to effectively increase the spatial stiffness of the blades without increasing their mass. Greater stiffness of the blades eliminates susceptibility to vibrations and noise generated especially when the wind speed changes.

An additional advantage of slanted, and even more preferably helical, blades is their increased degree of coverage, analogous to the helical teeth of the gear wheels. It then becomes possible to reduce the number of blades, which further reduces the weight of the turbine wheel.

Discs 2 and 3 (Fig. 1), to which the blades are attached, transfer the torque to the shaft 5. It is best to use standard expansion rings to secure the discs to the shaft, ensuring a strong, backlash-free disconnection, transferring a large torque and longitudinal forces [4]. The use of standard expansion rings to connect discs 2 and 3 to the shaft, and to connect all other rotating elements to the shaft, allows the use of a section of a thick-walled pipe in metallurgical condition as a shaft, i.e. without the need for machining the shaft. Expansion rings compensate for metallurgical deviations in making thick-walled pipes. This is of particular importance when the users themselves build prosumer wind farms.

The discs in which the ends of the blades are embedded, in particular the upper disc 3, may be equipped with tops 4 convex upwards (Fig. 1). The crown 4 with an aerodynamic profile causes the flowing wind to cause a lifting force P_{w2} in accordance with Bernoulli's law as a result of the difference in air velocity above and below the crown 4. The lift force, P_{w2}, reduces the axial load on the shaft bearing by acting with the wind pressure component P_{w1}.

In total, a significant reduction in the longitudinal load on the shaft bearing is obtained, the greater the higher the current wind speed. This is especially desirable during the start-up of the power plant, because the resting resistances are definitely increased.

With the increased height of the rotor, it is advisable to use a stacked arrangement of blades. An example of such a rotor configuration with a 3-tier arrangement of blades is shown schematically in Fig. 2. The individual stages of the blades are made with an angular displacement in relation to the blades of the adjacent stage.

This displacement shall be equal to the angle pitch of the blades on each floor divided by the number of floors. In the example in Fig. 2, it is $120^0/3 = 40^0$ (Fig. 2 cross section A-A). Such an arrangement of blades allows reducing their number; moreover, shorter blades can be made lighter while maintaining sufficient rigidity. This assures further reduction in the thrust load on the shaft bearing. Intermediate discs 4 and 5 can also be mounted on the shaft by means of expansion rings. Thanks to this, the torque from the rotor to the shaft is transmitted in a graduated manner. This provides the possibility of reducing the cross-section of the shaft in the upper zone of the rotor, which reduces its weight, reducing

the load on the bearings. The upper disc 3 can be additionally equipped with a relief crown as shown in Fig. 1. It can be used as a protection of the connection of the disc with the shaft against weather conditions. Stackable blades can be made oblique at the angle β, similarly as in Fig. 1.

The disadvantage of wind turbine rotors with a vertical axis of rotation can be partly compensated by the use of blades made of flexible material, e.g. a dense non-stretchable synthetic fabric stretched over a suitable rigid frame. Schematically, such a design solutionof the blades is illustrated in Fig. 3, which shows four phases: A, B, C and D, through which each of the blades passes during a full rotation of the rotor. In position A, the flexible blade 1 is filled under the pressure of the wind W in the shape of a sail of a sailing boat. This is the active, most beneficial phase of rotation. In position B, the flexible blade gradually folds to take a shape with significantly reduced resistance to movement of the blade moving in the opposite direction in phase C. to the direction of the wind. The folding of the paddle in phase C occurs as a result of the fact that the paddles are mounted on a frame made of bars 2, 3, and 4. During further rotation, the paddle moves to position D, in which it starts to fill,to fill up completely before taking position A. The described phases change cyclically with the rotation of the rotor, which reduces the resistance to rotor motion on its passive part. A rotor design with flexible blades can be particularly useful in the case of a wind turbine used periodically, e.g. in camping conditions, garden gazebos, campsites, etc.

In order to reduce the unfavourable flapping of the fabric when passing through the individual phases of rotation, the edg-
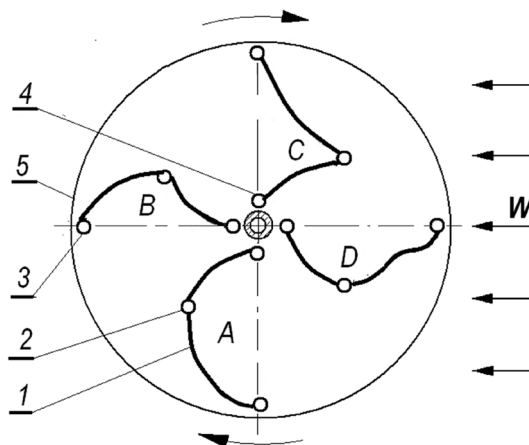

Fig. 2. Scheme of the heel arrangement of the wind turbine rotor blades with a vertical axis of rotation

Fig. 3. The concept of a wind turbine rotor with a vertical axis of rotation and flexible blades

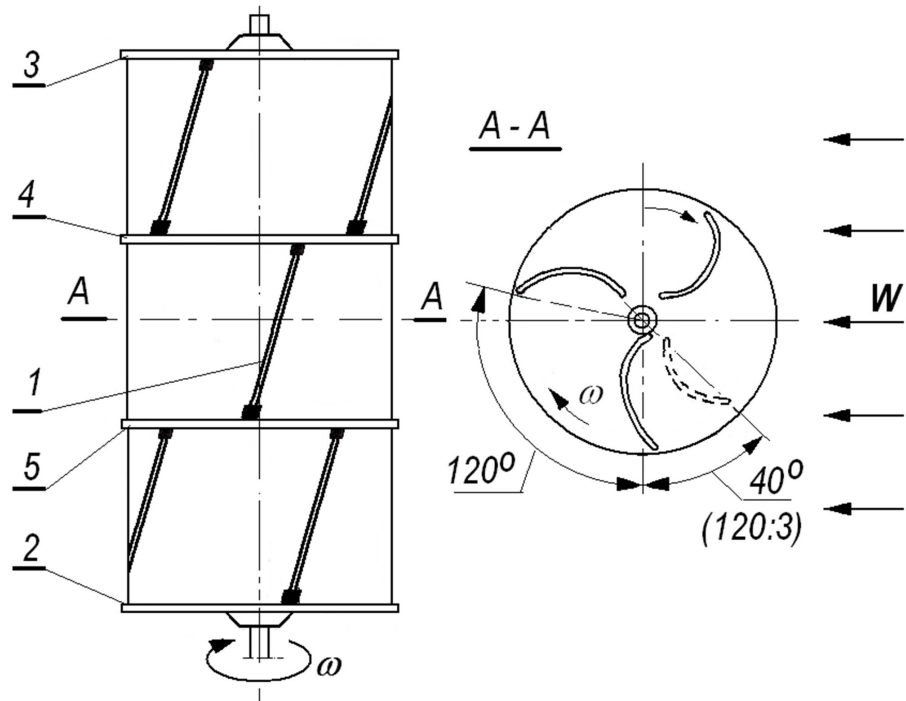es of the blades should be equipped with strips of elastic material placed, for example, at the double-layer blades in appropriately sewn pockets.

Bearing of the shaft of wind turbine with a vertical axis of rotation, characterized by low start-up and continuous operation resistance as well as high noiselessness

Shafts of wind turbines with a vertical axis of rotation are subjected to a complex state of significant loads with special characteristics. They carry a constantly heavy load from the previously described sum of the weights of the impeller, shaft and other mounted elements on the shaft. They are exposed to pendulum bending due to wind pressure on the rotor and periodically pulsating torsion due to the transmitted torque of variable magnitude. This results in special operating conditions for the bearings of the power plant shafts

Because the shaft bearings of prosumer power plants operate in the close vicinity of places where people live, the highest possible low noise level is required [5,6]. At the same time, it is desirable that the rotors of prosumer power plants start operation at the lowest possible wind speed in order to take advantage of limited wind conditions.

In order to meet these requirements, it is proposed to use a special sliding bearing with hydrodynamic lubrication equipped with a rolling starting aid system [4]. Figure 4 shows an axial section of such a combined bearing system adapted to prosumer wind turbines with a vertical axis of rotation of the turbine rotor.

On the shaft 1 made of a steel or duralumin pipe, through an expansion ring 2, a spherical journal 3 of journal bearing is mounted; this journal cooperates with a sleeve 5 permanently fixed in the lubricating liquid 6. The lubricating liquid is enclosed in a cop-
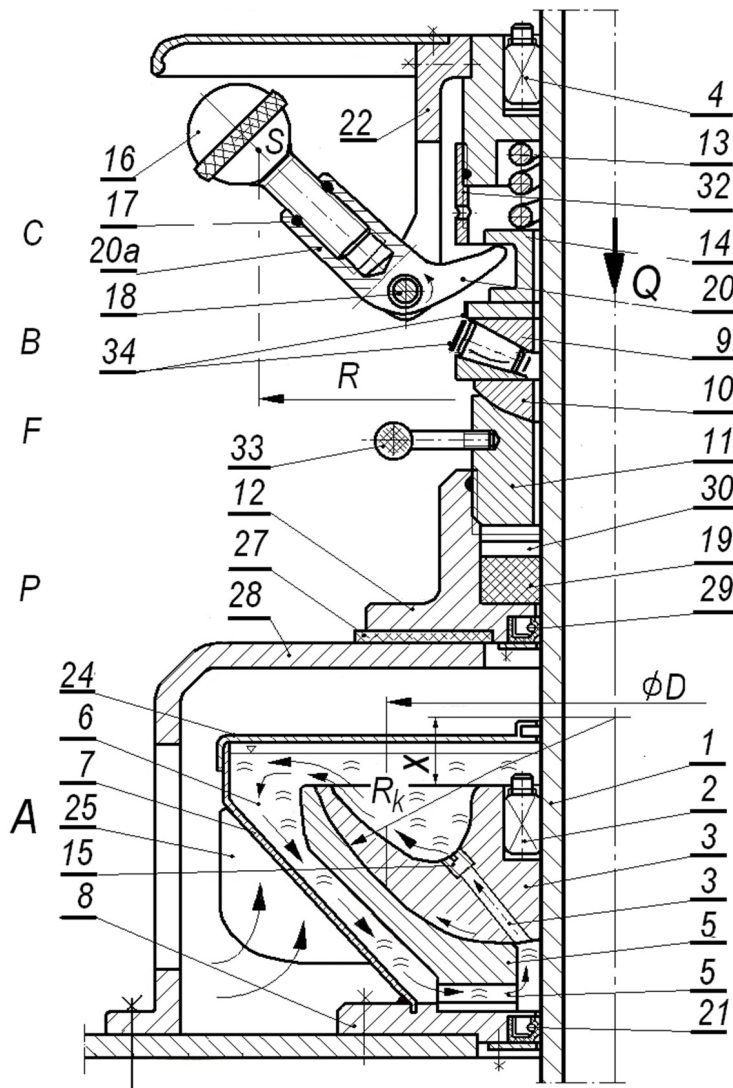
Fig. 4. Combined bearing of a wind turbine shaft with vertical axis of rotation, consisting of the main sliding bearing A with hydrodynamic lubrication, the rolling bearing B supporting the start--up and run-out and the transverse journal bearing P (laterally stabilizing the wind turbine shaft)

The bearing system consists of the following components:
A- main journal bearing with hydrodynamic lubrication operating only at a sufficiently high rotational speed to ensure smooth lubrication,
B- supporting rolling bearing operating only during start-up and slowing down,
C- sub-assembly for switching the load between bearings B and A,
F - sub-assembly of initial clearance adjustment in journal bearing A,
P - radial journal bearing which transversely stabilizes the shaft of power plant.

per or brass casing 7 with external vertical cooling ribs 25. Base of the journal bearing 8 is seated in a rigid console 28.

At rest, the full bearing load Q is carried by the supporting rolling bearing 9 which is spherically supported by the ring 10. The self-aligning spherical ring 10 is supported by on the adjustment sleeve 11 connected with a fine-thread to the base 12 fixed on the ceiling of the building or lower landing, preferably by means of a vibration damping pad 27. The rolling bearing 9 transfers the load Q as a result of the pressure of the sliding sleeve 14 resting on the compression spring 13, which is mounted in the housing 4 fixed on the shaft 1 with the expansion ring 2.

The start-up of the entire power plant system is carried out only with the participation of the rolling bearing 9, because there is a predetermined clearance in the slide bearing. As the rotation-

al speed of the system increases, the inertial weights 16 mounted on pins 18 cause increasing pressure on the sliding sleeve 14 through the levers 20. This generates a gradual smooth loosening of the starting load of the rolling bearing 9 combined with the transfer of the load to the main slide bearing A, in which, due to the slip of journal 3 after bushing 5, hydrodynamic lubrication develops. In the final stage of start-up, the supporting rolling bearing 9 is fully unloaded and stops, and the full load Q is carried by the main journal bearing A under hydrodynamic lubrication conditions.

The spherical form of the journal 3 makes, that the journal bearing A transfer, apart from the main thrust load Q, also the transverse load of the shaft 1 resulting from, among others, wind pressure on the turbine wheel mounted on the upper part of the shaft. In the journal bearing, there is an intensive circulation of the lubricant, shown by the arrows in Fig. 4. The lubricant flows through the holes 5a to the input side of the bearing, located in the vicinity of the shaft, moves in a spiral in the zone of cooperation of the pin 3 with the sleeve 5 and, under the action of centrifugal force, flows into the housing 7, lifting heat generated in the bearing. After cooling, the lubricant returns to the input side of the bearing, which is favoured by the gravitational change in its density.

The journal 3 acts as the impeller of a centrifugal pump due to the radial or helical grooves made on the working surface of the journal.

Appropriately shaped grooves in journal 3 facilitate the formation of numerous wedges, ensuring smooth lubrication in the main slide bearing, even at reduced rotational speed. The rotational speed at which the described load switching from the auxiliary rolling bearing to the main sliding bearing A takes place, is controlled by changing the radius R of rotation of the centre of mass S of weights 16 by turning the threaded connection these weights in the openings of the control levers 20a. The ring 17 made of high-friction material serves to stabilize the set position of the weights S1. Turning the weights 16, preferably in the number of three evenly spaced, should be performed equally for all weights, maintaining full balance of the subassembly C.

In the extreme position, the levers 20 rest against the adjustable stop sleeve 32 that serves to eliminate the generation of vibrations in the load switching system. An additional radial journal bearing 19 is used for transverse stabilization of the long shaft 1. A self-lubricating porous bushing 30 lubricated with plastic grease and applied during bearing assembling may be used as bearing 19.

In order to ensure that the entire bearing system operated as described, it is necessary to properly pre-adjust the bearing, which is done by subassembly F. When stationary, preferably before flooding the journal bearing with lubricant, it should be en-

sured that in the main journal bearing A, there was a clearance, of a size close to the thickness of the lubricating film at the nominal rotational speed occurring at the average wind speed. Ignorance of this quantity is not a significant obstacle. It is necessary to turn the lever 33 in such a way as to determine the position in which dry contact begins in the bearing A. The symptom is then a strongly increased resistance to rotation of the shaft 1. Then, turn the lever 33 in the direction of lifting the sleeve 11 so as to obtain a situation in which the journal bearing A will be completely unloaded, and a small load will be taken over by the supporting rolling bearing 9. The signal will be a significant decrease in the resistance to rotation of the shaft. It is desirable to increase this slight clearance by a small fraction of a millimetre using the angle of rotation of the fine thread of the adjusting sleeve 11 relative to the base 12. After bearing A has been flooded with lubricant, the entire system can be started up. The described activity is performed once, with any correction that may occur during operation, for example, with a significant difference in thermal elongation of the elements of the control bearing system.

Then, proceed to adjusting the C subassembly so that the load is switched at the assumed lowest possible rotational speed ensuring proper operation of the journal bearing. The load switching should be smooth, without the breaks. When the bearing run out occurs, e.g. when the power plant is stopped or the wind speed decreases significantly, the described load switching system works in the opposite direction and the final bearing run out takes place only with the participation of the rolling bearing 9.

The described run of bearing operation with proper adjustment causes that the slide bearing A operates only in conditions of full hydrodynamic lubrication, while the supporting rolling bearing 3 works only for short periods of time at start-up and run-out. Thanks to this, a very high durability of the elements of bearing system is obtained, and the start-up takes place with significantly reduced resistance to motion, i.e. it can take place already at the minimum wind speed.

Operational control of the operation of load switching system in both directions can be carried out by visual observation of contrasting axial stripes 34 located on the cage of the rolling bearing 9 and the sliding sleeve 14. The use of a stroboscope allows for accurate measurement of the rotational speed of switching the load between bearings A and B.

The described bearing of the prosumer wind power plant with vertical rotation is characterized by high noiselessness, because the supporting rolling bearing works for a short time and at a moderate speed of rotation. However, the journal bearing A, operating in conditions of full hydrodynamic lubrication, is practically noiseless.

The proportions between the transferred axial load Q and the transverse load can be adjusted by the appropriate selection of the radius R_k of the spherical journal 3 and the size X of the position of its upper edge. The possibility of using a sufficiently large average slip diameter D in the slide bearing A allows the use of a lubricant with the lowest possible viscosity to lubricate the slide bearing. It positively reduces the bearing resistance to the motion and improves the overall energy efficiency of the entire system

wind power plant, thanks to which it can effectively use even limited wind conditions.

Final remarks

Restrictions on the conditions for installing prosumer wind turbines mean that their users often have very limited possibilities of using energy. Therefore, any measures to increase their effectiveness are of great practical importance

The article describes selected design solutions for wind turbines with a vertical axis of rotation that allow to improve the efficiency of the wind turbine, which can be used by the users themselves at the design stage as well as during the modernization of already operated installations. Such possibilities are created by the use of helical or other blades of turbine rotors, a stacked arrangement of blades, the aerodynamic top of the rotors and blades with high flexibility. These solutions can be used separately or in various combinations, contributing to a significant improvement in the operational properties of wind turbine rotors.

Particular attention was paid to the new design of the power plant shaft bearing system with a vertical axis of rotation.

This bearing system is characterized by particularly high durability, high noiselessness, and increased safety of use and practically maintenance-free. Of particular importance are the limited resistance to motion of the described bearings system, which enable the power plant to operate at low wind speeds.

The dissemination of the described solutions in the design of prosumer wind farms can be a significant contribution to the development of distributed energy based on RES (Renewable Energy Systems).

Bibliography

[1] Ackerman T.: Wind power in power systems. John Willey and Sons. Chichester. 2009.

[2] Lubośny Z.: Wind farms in the power system. WNT, Warsaw. 2006. (in Polish)

[3] Olszowiec P.: Wind energy. Electro technical News. No. 77. 2021. (in Polish)

[4] Mikuła J., Mikuła S., and Strzelecki S.: The concept of a proconsumer hydro power plant with a special bearing for the main shaft. Polish Technical Review. Year. 1. 2022.

[5] Wegner Wind turbine noise. Springer Berlin. 1916.

[6] Zagubień A., Wolniewicz K.: Domestic sources of low-frequency noise. Environmental Protection Yearbook, No. 19, 2017. (in Polish)

[7] Regulation of the Minister of Environment of 14.06. 2007 on acceptable noise measurements in the environment. Journal Laws of 22.01. 2014 item 112. (in Polish)

[8] Jasiński A. W. and others: Wind farms in the human environment. Monograph. No. 178. Ed. Polish Academy of Sciences, Committee of Environmental Engineering, Lublin. 2022. (in Polish).