ISSN 0208-7774 TRIBOLOGIA 1/2022 p. 9–17
DOI: 10.5604/01.3001.0015.8981

Wojciech GRZEGORZEK[*], **Daniel ADAMECKI**[**], **Jarosław MIKUŁA**[***],
Wojciech BOREK[****], **Grzegorz GŁUSZEK**[*****], **Stanisław MIKUŁA**[******]

SHAFT BEARING OF WIND TURBINE WITH VERTICAL AXIS OF ROTATION

ŁOŻYSKOWANIE WAŁU SIŁOWNI WIATROWEJ O PIONOWEJ OSI OBROTU

Key words: green energy, low resistance to motion, prosumer wind turbine, quiet running and long service life, renewable energy sources (RES), water-lubricated hybrid bearing.

Abstract: This article describes a new design solution for a hybrid bearing intended for use in prosumer wind turbines with a vertical axis of rotation of the turbine rotor. The automatic rotational speed-dependent load-switching, lubrication and cooling systems applied in the hybrid bearing ensure a particularly long service life and highly quiet running while maintaining high energy efficiency over the full rotational speed range of shafts with turbine rotors. The hybrid bearing design has been adapted to the use of lubricating fluids with the lowest possible viscosity, including oil-water emulsions and even water itself. The use of water as a lubricant makes the bearing system highly environmentally friendly and completely fire-safe.

Słowa kluczowe: zielona energia, OZE, prosumencka elektrownia wiatrowa, niskie opory ruchu, łożysko hybrydowe smarowane wodą, cichobieżność i wysoka trwałość.

Streszczenie: W artykule opisano nowe rozwiązanie konstrukcyjne łożyska hybrydowego przeznaczonego do zastosowania w prosumenckich siłowniach wiatrowych o pionowej osi obrotu wirnika turbinowego. Zastosowane w łożysku hybrydowym układy automatycznego przełączania obciążenia w zależności od prędkości obrotowej, smarowania i chłodzenia zapewniają uzyskanie szczególnie długiej trwałości i dużej cichobieżności przy zachowaniu wysokiej sprawności energetycznej w pełnym zakresie prędkości wirowania wałów z wirnikami turbinowymi. Konstrukcja łożyska hybrydowego przystosowana została do wykorzystania cieczy smarnych o możliwie niskiej lepkości, w tym emulsji olejowo-wodnych, a nawet samej wody. Wykorzystanie wody jako środka smarnego powoduje, że łożyskowanie ma wysokie walory ekologiczne i całkowite bezpieczeństwo pożarowe.

INTRODUCTION

In an effort to reduce coal combustion for the needs of electricity generation, sources of so-called "green energy" are being sought that are as efficient as possible. In Polish conditions, prosumer power engineering, in which the user produces energy for his own needs and transfers any excess to the

---

[*] ORCID: 0000-0002-9086-8967. Department of Mining Mechanization and Robotisation. Faculty of Mining, Safety Engineering and Industrial Automation. Silesian University of Technology, Akademicka 2 Street, 44-100 Gliwice, Poland.

[**] ORCID: 0000-0003-2774-4088. Department of Mining Mechanization and Robotisation. Faculty of Mining, Safety Engineering and Industrial Automation. Silesian University of Technology, Akademicka 2 Street, 44-100 Gliwice, Poland.

[***] ORCID: 0000-0002-9210-7192. Department of Engineering Materials and Biomaterials. Faculty of Mechanical Engineering. Silesian University of Technology, Konarskiego 18a Street, 44-100 Gliwice, Poland.

[****] ORCID: 0000-0002-8292-4332. Department of Engineering Materials and Biomaterials. Faculty of Mechanical Engineering. Silesian University of Technology, Konarskiego 18a Street, 44-100 Gliwice, Poland.

[*****] ORCID: 0000-0002-3386-8661. Department of Mining Mechanization and Robotisation. Faculty of Mining, Safety Engineering and Industrial Automation. Silesian University of Technology, Akademicka 2 Street, 44-100 Gliwice, Poland.

[******] ORCID: 0000-0002-7906-8336. Retired researcher at the Department of Mining Mechanization and Robotisation. Faculty of Mining, Safety Engineering and Industrial Automation. Silesian University of Technology, Akademicka 2 Street, 44-100 Gliwice, Poland.

general power grid, may be based on several natural energy sources. These are mainly from waterfall energy, wind energy and solar energy. The largely lowland location of the areas inhabited by potential prosumers means that the available hydropower resources are limited to rivers and streams with a little drop, and they are only available to a very limited proportion of potential users. Hence, the importance of waterfall energy is low, especially in winter when energy needs are greatest, and ice cover often prevents the effective use of prosumer hydroelectric power plants. Periods of significant water scarcity in rivers also occur, especially in small streams, making it difficult to use small hydroelectric power plants.

Prosumer wind power engineering seems to have more potential **[L. 1–2]**, as the winds blow all year round and throughout the country **[L. 3]**. The well-known industrial wind turbines in the form of tall towers with horizontal axis turbine windmills, usually composed of three long blades, have a number of limitations in their use **[L. 4]**. They are completely unsuitable for prosumer energy purposes due to their complex construction and high cost of implementation. Most frequently, they are equipped with complex systems of adjusting the position of the horizontal axis of the rotors to the wind direction and the possibility to adjust the blade to the angle of attack. Their installation is subject to a number of regulations regarding distances from human settlements and other objects, as well as safety considerations. The long blades of these power plants, made of costly layered epoxy plastics, cause great difficulties in the process of disposal of decommissioned blades and those damaged by exposure to the phenomena of fatigue.

The low rotational speed of the long-blade rotor forces the use of multi-stage mechanical gearboxes, usually planetary gears, to adapt the rotational speed to the requirements of electric power generators. This causes the energy efficiency of the transmission system to drop and requires special cooling systems for the used gearboxes and generators. The noise generated by the mechanical systems of horizontal axis power plants and the danger to birds is also important. There is also a real danger of disturbing the architectural order due to erecting tall towers and the need to use tall cranes for installing, adjusting, and repairing these type of industrial power stations.

For prosumer needs, it is most beneficial to use wind turbine rotors with a vertical axis of rotation, whose operation does not depend on the wind direction. These rotors can be installed on utility buildings, residential buildings, or tall towers sited directly in the vicinity of the electricity consumption site. These towers may be of a design similar to power line poles, especially such with higher voltages. Several structural forms of turbine rotors with a vertical axis of rotation are known. The main ones are the Savonius, Darrieus or related systems. Their design should be as energy-efficient as possible due to the limited capacity of prosumer power plants. In addition, it must be able to withstand frequent start-ups and stoppages and reduce construction costs when constructed and financed largely by future users with limited resources **[L. 5]**.

Special requirements apply to the bearing system of the generally long shafts of wind turbines with a vertical axis of rotation. The bearing system of these turbines accommodates high thrust loads acting continuously, including at a standstill and during start-up. The vertical load on the shaft consists of the dead weights of the shafts themselves, the weight of the turbine rotor and the sum of the weights of all the rotating elements mounted on the shaft. This creates particularly difficult operating conditions for the bearings.

The problem of designing bearings for a vertical axis wind turbine shaft is presented, among others, in **[L. 6]**. A number of solutions for prosumer wind and hydropower plants have been created at the Department of Mining Mechanisation and Robotisation of the Silesian University of Technology. This article describes a design proposal for a vertical bearing of a wind turbine shaft.

OPERATING CONDITIONS, REQUIREMENTS AND ASSUMPTIONS FOR SHAFT BEARING OF WIND TURBINE WITH VERTICAL AXIS OF ROTATION

A particular feature of the operating conditions forvertical shaft bearings for a prosumer wind turbine is the high variability of the shaft rotational speed associated with the variable speed of the wind driving the turbine rotor of a plant. In contrast to the working conditions of industrial wind turbines' rotors installed on high towers, prosumer turbines are exposed to much greater variability in wind speeds occurring at lower heights. It is also very common for the rotors of prosumer vertical-axis power plants to come to a standstill, with the associated high frequency of start-ups. The bearing system in this situation must allow efficient operation over a large range of rotational speed variations and allow frequent starts with the lowest possible starting resistance, despite the permanently acting high thrust load. These requirements preclude the satisfactory use of typical plain bearings, which require a sufficiently high sliding velocity and, therefore, a sufficiently high operational speed of the shaft, to achieve the full load-bearing capacity of the lubricating film **[L. 7–10]**. The start-up of plain bearings under load is connected with high starting resistance, intensive abrasive wear of the bearing parts and the danger of seizure **[L. 11]**. Frequent start-ups in this situation generate a lot of heat associated with a fire hazard **[L. 12–13]**.

Rolling bearings with low starting resistance cannot be used over a higher speed range. This is due to the fact that the noise level of rolling bearings increases with the rotational speed, especially if there is operational damage in the form of chipping of the surface layer of bearing parts (pitting). With an increase in the rotational speed of rolling bearings, the loads from centrifugal forces acting on rolling elements strongly increase, which is also connected with an increase in operating noise **[L. 7]**. Increased continuous noise cannot be accepted in bearing systems operating in the immediate neighbourhood of people. The constant noise in such a situation is particularly troublesome. It is necessary to develop a shaft bearing system for a prosumer power plant in such a way that high noiselessness and as little energy loss as possible are maintained over the full speed range, with particular attention to the lowest possible start-up resistance to enable the power plant to operate even in low wind speeds. Shaft bearings in power plants, especially on utility buildings and towers, must be able to withstand the full range of temperature fluctuations, including freezing temperatures. The requirements described can only be achieved by using a special hybrid bearing design combining the beneficial properties of rolling and plain bearings and eliminating their limitations.

The general concept of operation of the shaft bearing system of a wind turbine with a vertical axis of rotation relates to aviation. Aircraft always take off and land using wheeled landing gear, while flights take place with the landing gear retracted, using the lift generated on the aerodynamic wing profiles when the flight speed reaches the required level. The hybrid bearing construction is based on rolling start-up and run-out support, which is automatically deactivated when the slip velocity in the plain bearing reaches a level that ensures the formation of a load-bearing lubricating film that produces a hydrodynamic lubrication effect in the main plain bearing **[L. 14]**.

CONSTRUCTION OF HYBRID BEARING OF WIND TURBINE SHAFT WITH VERTICAL AXIS OF ROTATION

The structural form of the turbine shaft bearing system, especially for prosumer use, is illustrated in **Figure 1**, and its general structure is shown in **Figure 2**.

A support sleeve 2 secured by a Seger ring 4 is fitted to the lower end of the vertical shaft 1 via a keyed connection 3. Control levers 5 in a number of three or more, and a pressure bearing spring 6, are seated in the support sleeve 2. A sliding sleeve 7 cooperates with the support spring 6, which with its lower part equipped with a friction coating rests on a ring 8 seated on a supporting thrust roller bearing 9. The roller bearing 9 is supported on a disc 10 by the backing 11 dampening the vibrations and noise. The disc 10 is supported by a ball support on a bracket 12, embedded in the bearing base 13. Holders 14 containing replaceable inertia weights 15 are screwed onto the control levers 5, which are evenly distributed around the circumference. The pressure springs 16 hold the packets of weights 15 in the extreme position. Polymer inserts 17 protect the housings 14 from spontaneous loosening during the operation of the hybrid bearing. The control levers 5 are pivotably mounted on the axles 18, located in the recesses of the support sleeve 2 (see section A-A). On the lower end of the support sleeve 2, the journal 19 of the plain bearing is seated via a threaded connection, reinforced with a tapered seat. The spherical journal 19 cooperates with an underframe 20, which is screwed onto a stationary ring 21 fixed relative to the base 13 by, for example, brazing. The threaded connection of the underframe 20 to the ring 21 is sealed with a rubber gasket 22. A sheet metal cover 23 sealed with a gasket 24 is placed over the underframe 20. A cover 23 forms a lubricating fluid tank 25 and is closed from above by a cover 26 with a rotatable seal 27, preferably of the labyrinth type. A harmonic ribbing system 28 to aid in cooling the lubricant tank is inserted onto the cover 23 (see section C-C). The cooling of the ribbing 28 is assisted by gravity airflow following the course of the dashed arrows shown in **Figure 1**.

The extreme deflections of the control levers 5 are adjusted by a screwed-in sleeve 29 operating simultaneously all the control levers 5, which are protected by a cover 30 during bearing operation. The damping lining 31 prevents noises from being generated and vibration from being transmitted to the building structure on which the bearing is placed. The holes 32 in the underframe 20 are used to insert a hook spanner when initially adjusting the position of the underframe relative to the ring 21. The lubrication grooves 19a on the spherical surface of the journal 19 are provided in a radial or helical direction. Shallow oblique bevels 19b are integrated with the lubrication grooves 19a, which promote the formation of a series of lubrication wedges during the operation of the plain bearing (so-called "Rayleigh thresholds") **[L. 15–16]** (see cross-section B-B).

The operating cycle of the hybrid bearing as a whole is as follows: at a standstill, the full thrust load on the bearing Q is transferred through the initial deflection of the spring 6 and via the sliding sleeve 7 to the supporting rolling bearing 9. The plain bearing is then fully relieved due to adequate clearance between the journal 19 and the underframe 20. In this situation, the start-up takes place with minimum resistance to motion of the rolling bearing 9 only.

During start-up, as the rotational speed of the shaft 1 increases, the lifting force of the sliding sleeve 7 gradually increases, causing a slight increase in the tension of the spring 6. This is due to the centrifugal force acting on the control lever assembly 5. The centrifugal force depends on the position of the centre of mass S of each set of control levers rotating on a radius Dw/2 and the instantaneous value of the angular velocity ω. When the centrifugal force resulting from the momentary increase in the rotational speed of the shaft reaches an adjustable value, the load on the rolling bearing is released smoothly and, at the same time, the load Q is transferred onto the plain bearing, in which a slip velocity has already occurred that is necessary for the formation of a lubricating film with the required load-bearing capacity. Both rolling and plain bearings operate simultaneously for a short load-switching period, with the load on the plain bearing growing continuously. When the start-up is complete, the rolling bearing 9 stops and only the plain bearing with fully developed hydrodynamic lubrication operates. Load removal from the supporting roller bearing can be observed by illuminating the contrasting marking 8a on the side of ring 8 with a strobe lamp. In operational practice, this disconnection can also be revealed by acoustic noise, as the operation of a rolling bearing is clearly distinguishable from the virtually noiseless operation of a plain bearing with liquid lubrication.

During the operation of the plain bearing, there is an intensive circulation of the lubricant 25, shown by the continuous arrows in **Fig. 1**. The lubricant circulation is intensified by the grooves 19a on the plain bearing journal, acting as the vanes of a centrifugal pump. The lubricant flowing through the gaps between journal 19 and underframe 20 takes up the heat generated in the bearing. This heat is then absorbed through the thin wall of the sheet metal cover 23, from where it is returned to the environment by convection and radiation, facilitated by the gravitational movement of air through the ribs 28. The cooled lubricant falls by gravity to the bottom of the cover 23 and through oblique holes in the underframe 20 returns to the plain bearing inlet, drawn in by the action of the lubrication grooves in the rotating journal 19.

If, for any reason during operation, the rotation speed of the shaft drops below the set value (e.g. when the wind speed drops), the automatic load-switching system acts completely automatically in the reverse direction. The decreasing centrifugal force causes the spring 6 to smoothly return to its initial position, which results in the successive transfer of load Q to the "rested" rolling bearing via the sliding sleeve 7. The plain bearing is gradually relieved until it is fully released. The final run-out of the hybrid bearing takes place exclusively with the supporting rolling bearing. The entire bearing system is fully ready for restart after stopping, even immediately, in the manner described earlier.

This course of all start-ups and run-outs of the hybrid bearing means that the plain bearing always operates exclusively under hydrodynamic lubrication conditions, and this protects them from the occurrence of abrasive wear and the threat of seizure **[L. 13, 17–21]**. Owing to this design, the hybrid bearing is characterised by a particularly long operating life since the rolling bearing supporting the start-up and run-out only operates for short intervals and is at a standstill for the rest

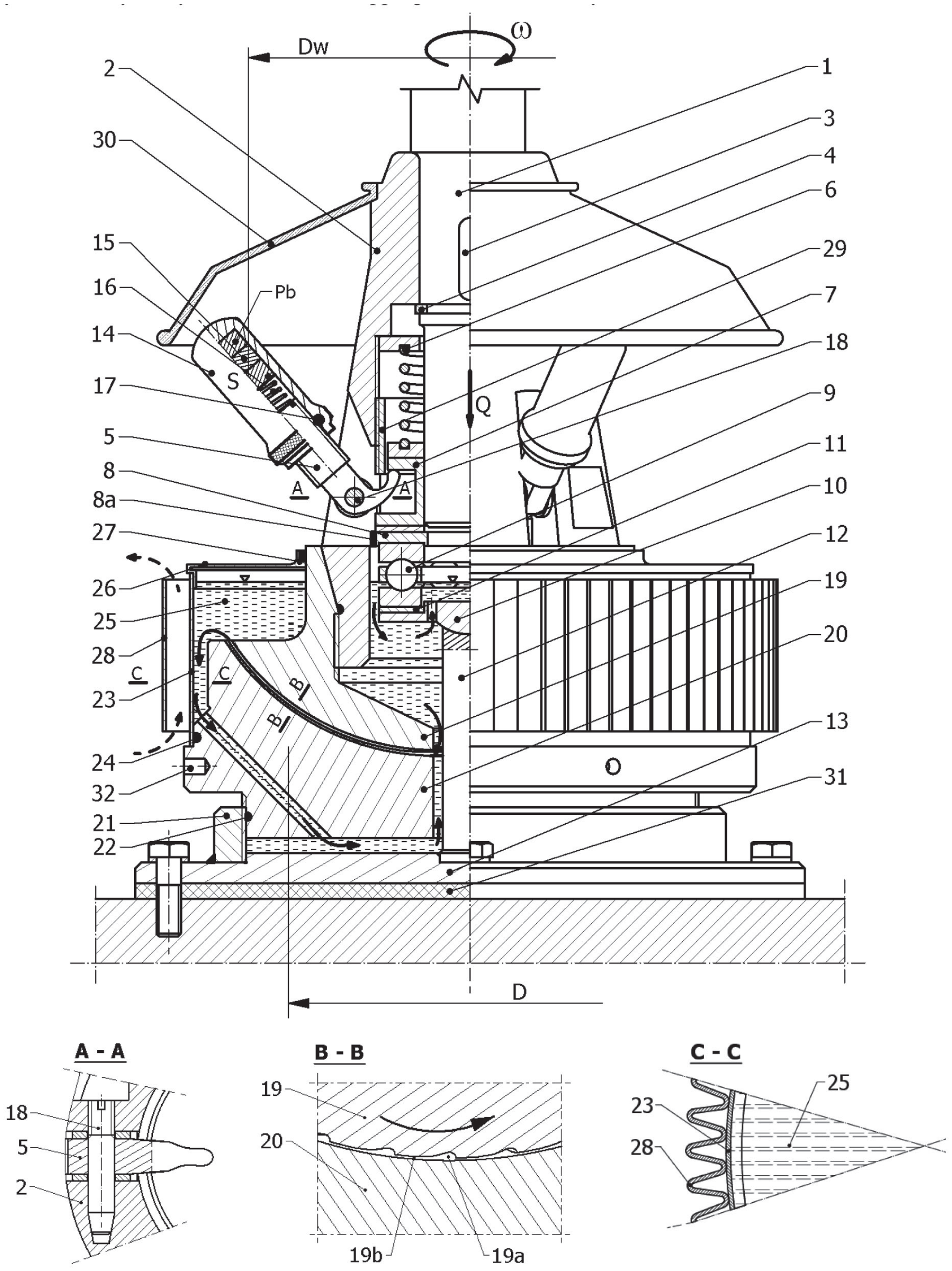

Fig. 1. A hybrid wind turbine shaft bearing node with automatic load switching, wherein: 1 – lower vertical shaft end, 2 – support sleeve, 3 – keyed connection, 4 – Seger ring, 5 – control lever, 6 – support spring, 7 – sliding sleeve, 8 – ring, 8a – contrast marking, 9 – rolling bearing, 10 – disc, 11 – vibration and noise damping pad, 12 – ball support on a bracket, 13 – bearing base, 14 – control lever housing, 15 – replaceable inertia packets of weights, 16 – compression spring 17 – polymer insert, 18 – control lever axle, 19 – spherical plain bearing journal, 19a – lubrication grooves, 19b – shallow oblique bevel, 20 – underframe, 21 – fixed ring, 22, 24 – rubber gasket, 23 – sheet metal cover, 25 – lubricating fluid, 26 – cover, 27 – rotating labyrinth type seal, 28 – harmonic ribbing system, 29 – screwed-in sleeve, 30 – control lever cover, 31 – damping lining, 32 – adjustment holes

Rys. 1. Hybrydowy węzeł łożyskowania wału siłowni wiatrowej z samoczynnym przełączaniem obciążenia, gdzie: 1 – dolna końcówka pionowego wału, 2 – tuleja wsporcza, 3 – połączenie wpustowe, 4 – pierścień Segera, 5 – dźwignia sterująca, 6 – sprężyna nośna, 7 – tuleja przesuwna, 8 – pierścień, 8a – kontrastowe oznaczenie, 9 – łożysko toczne, 10 – tarcza, 11 – podkład tłumiący drgania i hałasy, 12 – kulowe podparcie na wsporniku, 13 – podstawa łożyska, 14 – oprawa dźwigni sterującej, 15 – wymienne bezwładnościowe pakiety obciążników, 16 – sprężyna naciskowa, 17 – wkładka polimerowa, 18 – oś dźwigni sterującej, 19 – kulisty czop łożyska ślizgowego, 19a – rowki smarowe, 19b – płytkie, skośne ścięcia, 20 – ostoja, 21 – nieruchomy pierścień, 22, 24 – gumowa uszczelka, 23 – osłona blaszana, 25 – ciecz smarna, 26 – pokrywa, 27 – obrotowe uszczelnienie typu labiryntowego, 28 – harmonijkowy układ użebrowań, 29 – wkręcana tulejka, 30 – osłona dźwigni sterujących, 31 – wykładzina tłumiąca, 32 – otwory regulacyjne of the time, while the plain bearing, operating only with liquid lubrication, is practically not subject to wear.

The hybrid bearing has a very wide speed control range, at which the load is switched from the rolling bearing to the plain bearing and vice versa. Adjustment is achieved by selecting the number and weight of interchangeable weights 15. If required, weights can be made from materials of different densities, including lead or copper, for example. More precise adjustment is achieved by turning the housings 14, which changes the spinning radius Dw/2 of the centre of mass S. For the proper operation of the hybrid bearing, an initial adjustment should be carried out before it is put into continuous operation. It is best to carry out this adjustment before pouring a lubricant into the bearing. When at a standstill, turn the underframe 20 using a hook spanner so that the journal 19 comes into direct contact with the underframe 20. This will be manifested by a strongly increased resistance when attempting to rotate the shaft 1. Then, move the position of the underframe back by a value of e.g. 0.3–0.8 mm, depending on the bearing size. The angle of rotation of the hook spanner should then be used, knowing the underframe's thread pitch. This initial clearance value of the plain bearing can be easily adjusted during operation if necessary. After the initial bearing clearance has been established, the tank 23 should be filled with lubricant up to the level of the lower rolling bearing ring 9. The rotational speed adjustment, at which the load is to be switched, should be carried out in successive tests, starting from a fairly high rotational speed, i.e. with a low weight of the weights 15, and then proceeding in the direction of decreasing the switching speed by possibly adding weights and turning the holders 14 on all the control levers 5. Load shifting (in both directions) should be as smooth as possible, with no perceptible inhibition of movement, but only a visual or acoustic assessment of the moment of load shifting. After the final determination of the desired switching speed, the limitation of the maximum swing of the control levers 5 must be set by turning the sleeve 29. It is advantageous that the range of extreme deflection of the lever 5 is in the order of 1–2 mm. This is conducive to achieving a long fatigue life for the spring 6 and maintaining the constancy of its characteristics. It is advisable to determine the lowest rotational speed of load-switching that secures full hydrodynamic lubrication of the plain bearing with a certain reserve. This will result in a high operating life with the greatest possible quiet running of the power plant bearing system, as the operating range of a rolling bearing with a higher noise level will be limited, both in terms of the operating time and its maximum rotational speed. The high running quietness is particularly desirable in prosumer wind turbines. The reduced movement resistance of the hybrid bearing enables the power plant to operate even in low winds, allowing the wind energy to be used more fully.

The high cooling efficiency of the plain bearing and its operation solely with liquid lubrication enables fluids with a much lower viscosity to be used as lubricants, as it does not have to perform a lubricating function at start-up. The low viscosity of the lubricating fluid means reduced resistance to its movement in the bearing, and hence a higher energy efficiency of the bearing and a reduced heat generation.

An oil-in-water, water-in-oil emulsion or even water alone can be used as a lubricant **[L. 22–24]**. This is greatly facilitated by the possibility of obtaining reduced mean contact pressures in the plain bearing and achieving a high mean sliding speed by using as large a mean diameter D as possible (**Fig. 1**). The ability to interchange the journal and underframe with larger sizes while retaining the other main components of the hybrid bearing can be exploited. The use of water or emulsion as a lubricant requires the appropriate corrosion protection of the plain bearing components.

Water used as a lubricant in a plain bearing has a number of very favourable properties compared to typical bearing oils **[L. 25–29]**. It has, on average, twice the specific heat, a higher density and virtually no effect of temperature on properties, especially viscosity **[L. 30–31]**. It also boasts high physical and chemical stability and a lack of susceptibility to the ageing processes characteristic of oils **[L. 8]**. Water also has the particular advantage of being highly available, low in cost and non-flammable. The low viscosity of water relative to bearing oils can be compensated in a plain bearing by significantly reducing contact pressures and significantly increasing the average sliding speed in the bearing **[L. 16]**. The hybrid bearing design presented here can easily be achieved as previously described. The water and water-oil emulsion in the bearing described in the article can also be used at negative ambient temperatures. The layer of ice between the journal and the bush does not

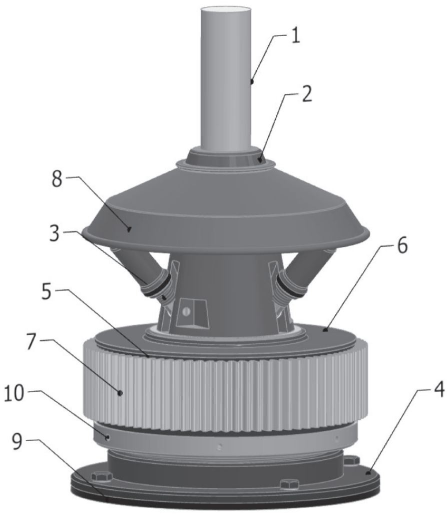

Fig. 2. General construction of a hybrid wind turbine shaft bearing node with automatic load switching, wherein: 1 – shaft, 2 – support sleeve, 3 – control lever, 4 – bearing base, 5 – sheet metal cover (lubricant tank), 6 – cover, 7 – harmonic ribbing system, 8 – control lever cover, 9 – damping lining, 10 – adjustment holes

Rys. 2. Budowa ogólna hybrydowego węzła łożyskowania wału siłowni wiatrowej z samoczynnym przełączaniem obciążenia, gdzie: 1 – wał, 2 – tuleja wsporcza, 3 – dźwignia sterująca, 4 – podstawa łożyska, 5 – osłona blaszana (zbiornik cieczy smarnej), 6 – pokrywa, 7 – harmonijkowy układ użebrowań, 8 – osłona dźwigni sterujących, 9 – wykładzina tłumiąca, 10 – otwory regulacyjne

significantly increase the resistance to motion (see skates, sledge) and quickly melts during operation. The high environmental advantages and complete non-flammability of the water-lubricated bearing are particularly desirable for use in shaft bearings in wind power stations with a vertical axis of rotation, where the bearings are installed, for example, in the attics of residential buildings, in utility buildings and other buildings.

The very high durability, high running quietness, low starting resistance and high energy efficiency of the bearings using the described hybrid bearing predestine them in particular for use in prosumer wind power plants. The spherical shape of the plain bearing comprising the hybrid bearing makes it possible to transmit the high thrust forces and lateral loads that can occur in the operation of wind power plants. Such shaping eliminates the uneven load distribution between the journal and the underframe, which may occur as a result of assembly errors or under the influence of a long power plant shaft in a typical configuration of its elements. The usually considerable length of the shaft means that, in addition to the main hybrid bearing described, at least one additional radial bearing must be provided for guidance and lateral stabilisation of the shaft. Such bearings do not carry significant loads, so simple radial plain bearings with self-lubricating bushes can be applied. Their positioning and embedding are best carried out during initial operation, taking into account the location of the wind turbine in the specific structural situation of the building in which it will be used. The turbine should be equipped with an effective brake and a locking device for immobilisation in emergencies and excessively strong winds. Apart from these situations, according to the presented concept, the bearing system is practically maintenance-free, which is a great advantage.

SUMMARY

Wind turbines with a vertical axis of rotation of the turbine rotor are particularly suitable for use as prosumer electricity sources in the field of so-called "green energy". They harness wind energy in the immediate neighbourhood of the energy consumer's residence, usually available in the form of winds with limited speed, blowing at low altitudes. This results in special requirements for high energy efficiency, quiet running, long service life and limited maintenance. These requirements apply particularly to the bearing system of power plant shafts exposed to high permanent thrust loads, frequent start-ups and rotational speed variations.

The hybrid bearing design presented in this paper meets these requirements by employing the rolling support for shaft start-up and run-out and a plain bearing operating exclusively under conditions of full hydrodynamic lubrication. The automatic rotational speed-dependent load-switching systems, lubrication and cooling systems applied in a hybrid bearing ensure a particularly long service life and highly quiet running while maintaining high energy efficiency over the full rotational speed range of shafts with turbine rotors. The hybrid bearing design has been adapted to the use of lubricating fluids with the lowest possible viscosity, including oil-water emulsions and even water itself. The use of water as a lubricant makes the bearings highly environmentally friendly and completely fire-safe. These features predestine the proposed solution for general use in prosumer wind turbines, and they can also be applied in other types of machines with a vertical rotation system.

REFERENCES

1. Kuchmacz J., Mika Ł.: Description of Development of Prosumer Energy Sector in Poland. Polityka Energetyczna, t. 21, 4, Polish Academy of Sciences. Mineral and Energy Economy Research Institute of the Polish Academy of Sciences 2018, pp. 5–20.
2. Radziewicz W.: Nowoczesne rozwiązania konstrukcyjne turbin wiatrowych małej mocy. Maszyny Elektryczne. Zeszyty problemowe, Vol. 1, 105, Łukasiewicz Research Network – Institute of Electrical Drives and Machines Komel 2015, pp. 143–48.
3. Szulc A., Tomaszewska B.: Preliminary assessment of the wind conditions as a potential for using wind micro-installation to improve air quality in Poland. E3S Web Conf. 86 00031, 2019.
4. Lubośny Z.: Elektrownie wiatrowe w systemie elektroenergetycznym. Wydawnictwa Naukowo-Techniczne. Warsaw 2006.
5. Nalepa K., et al.: Poradnik małej energetyki wiatrowej. Wojewódzki Fundusz Ochrony Środowiska i Gospodarki Wodnej. Intelligent Energy Europe 2011.
6. Szelka M., Szweda S., Szyguła M., Mikuła J., Mikuła S.: Węzeł łożyskowania siłowni wiatrowej o pionowej osi obrotu. Patent Application No. P. 440590 of 07.03.2022.
7. Dietrich M.: Podstawy konstrukcji maszyn. Vol. 2. Wydawnictwa Naukowo-Techniczne. Warsaw 1991.
8. Lawrowski Z.: Łożyska ślizgowe. Wydawnictwo Politechniki Wrocławskiej. Wroclaw 2001.
9. Mikula A. M., Gregory R. S.: A Comparison of Tilting Pad Thrust Bearing Lubricant Supply Methods. ASME. J. of Lubrication Tech. January 1983, 105(1), pp. 39–45.
10. Rotta G., Wasilczuk M..: Modeling Lubricant Flow Between Thrust-Bearing Pads. Tribology International 2008, vol. 41, No. Issues 9–10, pp. 908–13.
11. Olszewski O., Wasilczuk M.: Łożyska ślizgowe wzdłużne szczególnie dla maszyn o rozruchu pod obciążeniem. Tribologia 1993, No. 4/5.
12. Bhushan B.: Modern Tribology Handbook, CRC Press 2001.
13. Lawrowski Z.: Tribologia, tarcie, zużycie i smarowanie. PWN (Polish Scientific Publishers). Warsaw 1993.
14. Mikuła J., Mikuła S., Strzelecki S.: Szybkobieżne łożysko ślizgowe z tocznym wspomaganiem rozruchu (koncepcja łożyska kombinowanego). Przegląd Mechaniczny 2021, No. 4.
15. Wang X., Zhang Z., Zhang G.: Improving the performance of spring-supported thrust bearing by controlling its deformations. Tribology International 1999, Vol. 32, pp. 713–720.
16. Wasilczuk M., Dąbrowski W.: Konstrukcyjne sposoby zwiększania obciążalności hydrodynamicznych łożysk wzdłużnych. Tribologia 1997, No. 3.
17. Kiciński J.: Teoria i badania hydrodynamicznych poprzecznych łożysk ślizgowych. Ossolineum. 1994.
18. Dąbrowski L., Neyman K., Wasilczuk M.: Łożyska wzdłużne – współczesne problemy eksploatacyjne. Zagadnienia Eksploatacji Maszyn 2004, Vol. 3 (139).
19. Wasilczuk M.: Studium problemów badawczych, konstrukcyjnych oraz metod projektowania hydrodynamicznych łożysk wzdłużnych. Gdansk University of Technology Publishing House. Gdansk 2004.
20. Iliev H.: Failure analysis of hydro–generator thrust bearing, Wear 1999, Volumes 225–229, Part 2, pp. 913–917.
21. Wodtke M.: Obliczeniowa weryfikacja parametrów konstrukcyjnych podpory hydrostatycznej. Tribologia 2004, No. 191.
22. Stryczek S.: Napęd hydrostatyczny, elementy i układy. Wydawnictwa Naukowo-Techniczne 1984.
23. Olszewski A.: Studia nad czynnikami wpływającymi na obciążalność i charakterystyki tribologiczne poprzecznych hydrodynamicznych łożysk ślizgowych smarowanych wodą. Gdańsk University of Technology 2015.
24. Korbiel T., Blaut J., Uliński A.: Analiza parametrów smarnych łożyska hydrodynamicznego smarowanego wodą o wybranych parametrach technologicznych, Przegląd Mechaniczny 2015, No. 4, pp. 36–39.
25. Haonan Zhang, et al: Simulation Design and Numerical Analysis of Bearing Capacity of Water Lubricated Thrust Bearing. IOP Conf. Ser.: Earth Environ. Sci. 446 052081. 2020.

26. Zhanchao Wang, Ying Liu, Yuechang Wang: Influence of squeezing and interface slippage on the performance of water–lubricated tilting–pad thrust bearing during start up and shutdown. Lubrication Science 2018, 30 (4) pp.137–148.
27. Olszewski A.: Łożyska ślizgowe smarowane wodą. Eksploatacja systemów tribologicznych. Wydawnictwo Politechniki Świętokrzyskiej, Kielce 2013.
28. Olszewski A., Wodtke M., Łubiński J.: Konstrukcje hydrodynamicznych łożysk poprzecznych smarowanych wodą. Przegląd Mechaniczny 2015, No. 12, pp. 29–37.
29. Neyman A., Olszewski A., Wasilczuk M.: Łożyska ślizgowe smarowane wodą. Tribologia 2005, No. 4, pp. 205–219.
30. Vohr J. H.: Prediction of the Operating Temperature of Thrust Bearings. ASME Journal of Lubrication Technology 1981, Vol. 108, No. 1, pp. 97–106.
31. Dadouche A., Fillon M., Bligoud J.C : Experiments on thermal effects in a hydrodynamic thrust bearing. Tribology International 2000, Vol. 33, Issues 3–4, pp. 167–174.