New Products and Improved Reliability of Main Bearings for Wind Turbine Generators

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Wind turbine generators, which are becoming an increasingly more mainstream source of renewable energy, are becoming larger. Furthermore, bearings used in these wind turbines are required to be reliable. This section introduces **NTN**'s latest products and design approach for spherical roller bearings used in many onshore turbines and single-row tapered roller bearings that are used in offshore turbines more and more.

1. Introduction

Adoption of renewable energy is being promoted worldwide to address global warming, as exemplified by the Paris Agreement, an international accord for reducing greenhouse gas emissions. Last year, renewable energy, excluding hydropower, exceeded nuclear power in global share of power generated - wind power accounted for about 5 % of the total[1].

To broaden adoption of renewable energy, it will be important to reduce the LCOE (Levelized Cost of Energy) which is calculated by dividing costs of power generation, including construction, operation, and maintenance costs, by the projected amount of power generated during the operating period. Turbines have improved utilization as a result of increased tower heights, lengthening of blades, and improved blade shape. Off-shore wind power has been increasingly adopted in recent years. Since construction costs are higher than on-shore wind power, there is a need to develop ultra-large turbines, often exceeding 10 MW, extend service life, and improve maintenance efficiency.

In wind turbines, bearings are used at the support section for the rotor shaft (main shaft), gearbox, and generator as shown in **Fig. 1**. Additionally bearings are used to allow pitch control of each blade, yaw control of the machine head, and within the pitch and yaw reducers which drives them. This article describes efforts by **NTN** to improve reliability and achieve optimization of the main bearing used at the main shaft support section.

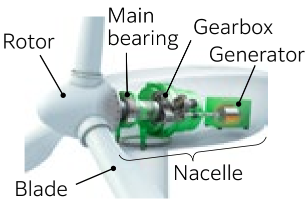

Fig. 1 Internal Wind Turbine construction

2. Composition of main bearing

The main bearing is the most important part for supporting the wind load received by the blades and transmitting driving power to the generator. The bearing type used varies depending on the composition of the drivetrain. As shown in **Fig. 2**, there are two basic categories: the gearbox type, and the 'direct drive' type with no gearbox.

Type ① in **Fig. 2** has traditionally been the most common choice for the gearbox type installed on-shore. In this type, the main shaft is typically supported by a single main bearing within a pillowblock housing and a bearing inside the gearbox. Spherical roller bearings tolerant of mounting error are used. Type ②, in which support is provided using two spherical roller bearings, is also used in many on-shore turbines. However, with type ②, sliding must be allowed at the outer ring outer diameter surface on the free side to cope with thermal expansion and contraction of the main shaft. To ensure reliability over the long term, there are also structures which use inward-facing (direct mount) double row tapered roller bearings in the fixed position, and cylindrical roller bearings capable of accommodating thermal expansion and contraction by sliding in the axial direction in the floating position.

With the direct drive type, on the other hand, reliability is better due to the reduced number of parts. A directly-linked generator enables power generation at a low rotational speed by making permanent magnets multipolar, however, this increases the size of the generator rotor. Therefore, the main shaft must have a large diameter and loading is supported by a compact double row tapered roller bearing with a large contact angle (Type ⑤).

In addition to the direct drive type, a multi-pole synchronous generator of the "gearbox + medium speed type" balances reliability and cost and is also used in off-shore turbines. Due to the increased size of

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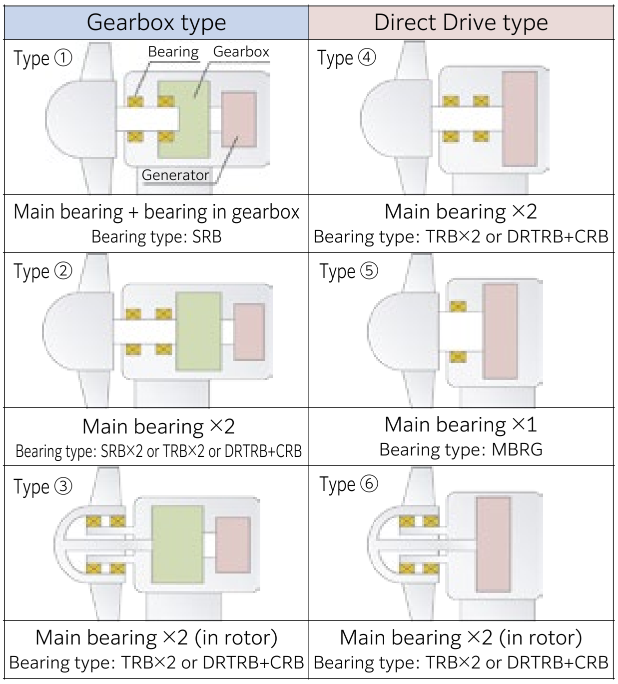
wind turbines, there is increased use of back-to-back single row tapered roller bearings instead of double row tapered roller bearings with a large contact angle which have a large impact on productivity and cost (type ②, ③). With this bearing type, it is possible to optimize service life and system rigidity through the use of preload. Bearing setting must be done by the wind turbine manufacturer, but at **NTN**, we support users through analysis to determine the setting range.



SRB: Spherical roller bearing　TRB: Tapered roller bearing
DRTRB: Double row tapered roller bearing (face-to-face)
MBRG (moment bearing): Double row tapered roller bearing (back-to-back)
CRB: Cylindrical roller bearing

Fig. 2 Relationship between drive train and bearing type

The following will introduce **NTN**'s efforts with a focus on spherical roller bearings, which are the mainstream choice for on-shore turbines, and single row tapered roller bearings, which are increasingly used in off-shore turbines.

3. Extending life of spherical roller bearings

The aforementioned spherical roller bearings are advantageous due to their tolerance for mounting error, and the ability to use independent housings for each bearing. However, there are cases where premature damage occurs due to operational wear of the raceway surface. **NTN** is helping to extend the life of these types of bearings and minimize turbine size by using unique technology which accounts for the application conditions particular to main bearings.

3.1 Asymmetrical design of different rows

The main bearing is subjected to a radial load acting vertically on the shaft due to the weight of the rotor and blade, and axial loading acting horizontally on the shaft due to the wind load. If we assume an upwind wind turbine, i.e., the mainstream type with the rotor receiving the wind located on the upwind side, then a larger load acts on the rear bearing row away from the blade than on the front bearing row near to the blade **(Fig. 3)**.

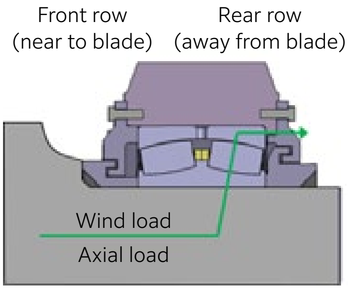


Fig. 3 Loading condition

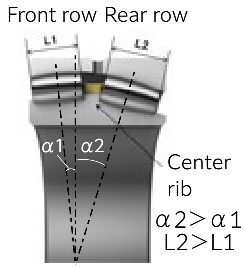


Fig. 4 Asymmetrical design

At **NTN**, we noticed these characteristics of the applied load, and in 2017 we issued a press release on an asymmetrical spherical roller bearing. This bearing has a unique design featuring different roller lengths and contact angles among the different rows[2)] **(Fig. 4)**. These changes increase calculated life by about 2.5 times, and enable reduction of inner diameter by about 10 % and weight by about 30 % in a bearing with life comparable to the conventional product. If this bearing is used in a wind turbine, bearing downsizing can be achieved, which can contribute to reducing size, weight, and cost of the entire wind turbine **(Fig. 5)**.

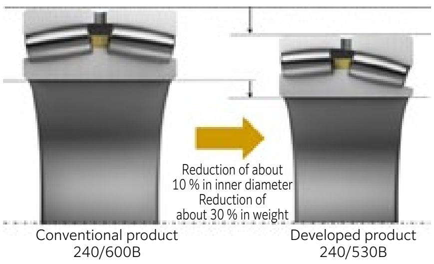


Fig. 5 Example of design for downsizing

3.2 DLC coating

(1) Structure

The rollers of spherical roller bearings are barrel shaped. Within the spherical roller bearing, differential slippage[*1] occurs, where the bearing rotates with slippage at the contact points between the roller contact surface and raceway surface. Also, rotation repeatedly stops and starts due to wind conditions, and the bearing is lubricated with grease. If poor lubrication (insufficient oil film) is experienced during operation, wear may occur at the raceway surface due to metal contact, starting from points with a high PV value (i.e., the product of the contact stress (P) and sliding velocity (V)) and progressing into a two-peaked form. As a result, stress is then concentrated at the lines of pure rolling contact where no wear occurs, and this may cause flaking and cracking of the raceway surface **(Fig. 6)**.

*1 Differential slippage: Slippage attributable to differences in speed in the rotation direction between the roller and raceway

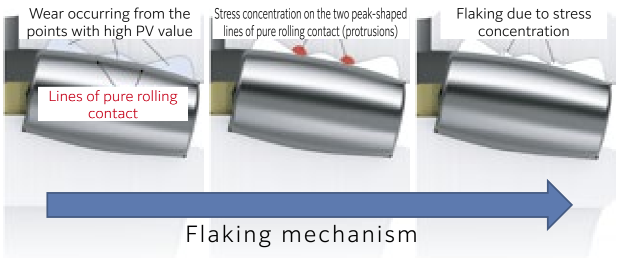


Fig. 6 Damage mechanism

The rotating inner ring experiences loading about the entire circumference of the raceway surface, but the outer ring is fixed in the housing, and thus the load zone is concentrated in a specific range, and damage occurs due to repetitive loading.

With the aforementioned asymmetrical design, the PV value can be reduced by about 30 %, so the design is effective to some degree in reducing wear. On the other hand, it is difficult to avoid metal contact in a state with insufficient oil film, and other approaches were needed to further improve reliability. Thus we developed a bearing with a DLC (diamond-like carbon) coating applied to the roller contact surface **(Fig. 7)**. The DLC coating used by **NTN** employs a three-layer structure: ① a metal sub-layer to increase adhesion to the base material, ② an intermediate layer to act as a hardness gradient between the metal sub-layer and the top layer, and ③ a high hardness top layer of DLC coating. The coating has outstanding adhesion and wear-resistance given the differential slippage particular to spherical roller bearings and lubrication conditions where oil film formation is inadequate **(Fig. 8)**.

Fig. 7 DLC coating spherical roller bearing

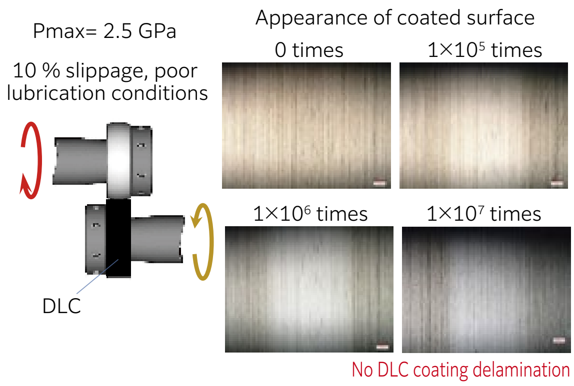


Fig. 8 DLC coating delamination test

(2) Verification of effectiveness

Verification testing was carried out to confirm the superiority of the DLC coating. Testing was done with two types of bearings: a small model bearing and a full scale test bearing.

① Evaluation using a small model bearing
(φ 120 × φ 180 × 60)

A combined radial and axial load was applied, similar to an actual turbine, and wear status of the outer ring load region was compared every 50 hours, under accelerated conditions where the outer ring raceway surface of a standard product flakes at 300 hours **(Fig. 9)**.

Fig. 9 Outer ring raceway after 300 hours

Fig. 10 shows the test results. The wear progression speed of the asymmetrical product was about 2/3 that of the standard product. On the other hand, about 5 μm of wear occurred initially with the DLC coating product, but after that wear did not progress and the results were extremely good.

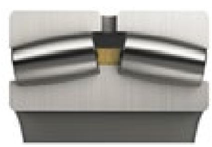
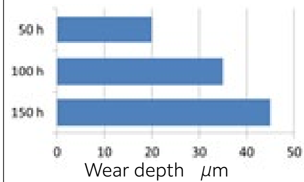
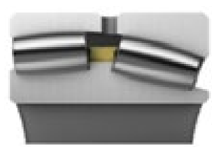
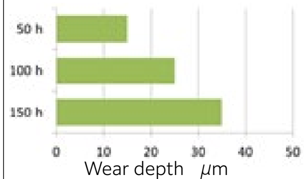
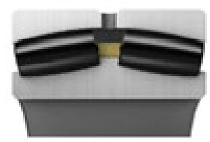
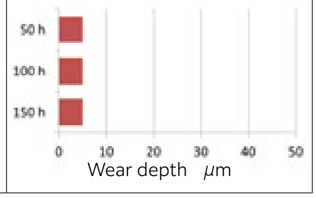
Test bearing	Changes in wear depth of outer ring load region
 Standard product	
 Asymmetrical product	
 DLC coating product	

Fig. 10 Test results with model size bearings

② Evaluation using actual-size bearing (φ 600 × φ 870 × 272)

To accelerate testing, as with the small model bearing, evaluation was done under conditions where the standard product flakes at 720 hours.

Fig. 11 shows the condition of the outer ring raceway surface load region after testing. Flaking is evident on the standard product, but not on the DLC coating product, where the results were extremely good with only 2 μm of wear.

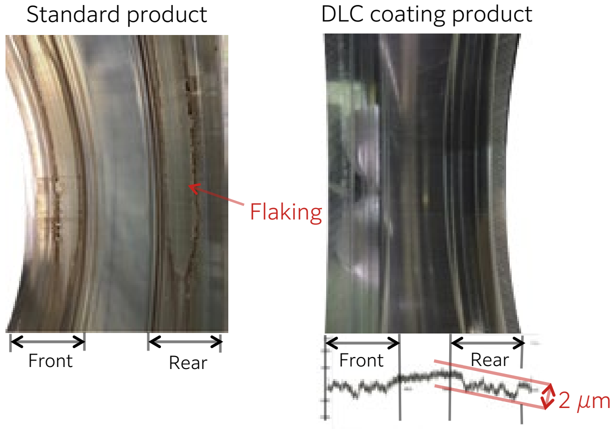


Fig. 11 Test results with full scale bearings

3.3 Proposed specifications of spherical roller bearings

In light of the above, **NTN** proposes the following for spherical roller bearings used as the main bearings in wind turbines **(Fig. 12)**.

① Standard design: This type employs asymmetrical rollers, and has a center rib on the inner ring. Structurally, rollers are supported at three points: the inner/outer ring raceway surfaces, and a center rib on the inner ring. This prevents skew*2 of the rollers, and suppresses slippage between the raceway and rollers.

② DLC coating: This type is based on the standard design, and is used when wear damage needs to be suppressed.

③ Asymmetrical design: This is used when there is a need to extend life (through flaking countermeasures) and reduce turbine size (bearing size reduction).

④ DLC coating + asymmetrical design: This type lowers initial cost by reducing overall size and weight of wind turbines, and can potentially improve reliability and reduce generation costs through more stable operation.

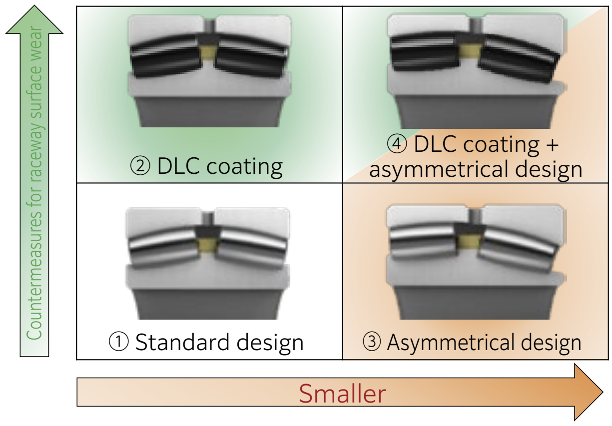


Fig. 12 Lineup of spherical roller bearings for wind turbine main shaft

*2 Skew: Roller inclination over its normal axis of rotation in roller bearings

4. Size reduction of tapered roller bearings

Here we introduce the characteristics and design approaches for size reduction of the back-to-back single row tapered roller bearings **(Fig. 13)** that are being increasingly used in off-shore turbines.

Fig. 13 Single row tapered roller bearing

4.1. Design parameters

Wind loads act on the blades and the weight of the rotor itself act on the main bearing as moment loads **(Fig. 14)**, thus maintaining a large distance between the load centers of the two main bearings in the system is key for reducing the resultant bearing load. By using single row tapered roller bearings in a back-to-back arrangement, the distance between load acting points can be kept large, which enables reduction of bearing size and weight.

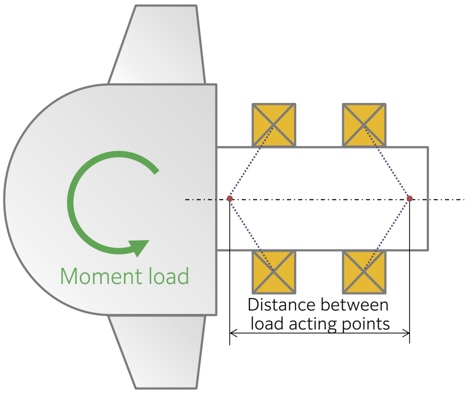


Fig. 14 Relationship between applied load and bearing span

In determining the contact angle and distance between load centers, optimal values must be considered in light of use conditions. Characteristics based on differences in contact angles are presented next.

4.2 Verifying effects due to differences in contact angle

(1) Effects on life

In Example 1, considered in **Fig. 15**, we confirmed the effects when the contact angle was varied only for the axially loaded row. As the contact angle increased, both the equivalent load and bearing capacity decreased, but the capacity decreased less, so life increased.

In Example 2, considered in **Fig. 16**, we verified the effects of the axially loaded row when the contact angle was varied only for the non-axially loaded row. In this case, the results showed that life decreased regardless of the fact that the distance between load centers increased due to the increased contact angle. This is because the induced axial load increased when the contact angle of the non-axially loaded row was increased. This shows that increasing the distance between load centers does not necessarily lead to longer life directly, and that the induced axial load must also be taken into account. That is, increasing the distance between load centers by maximizing the contact angle of the axially loaded row is related to longer life of both bearings.

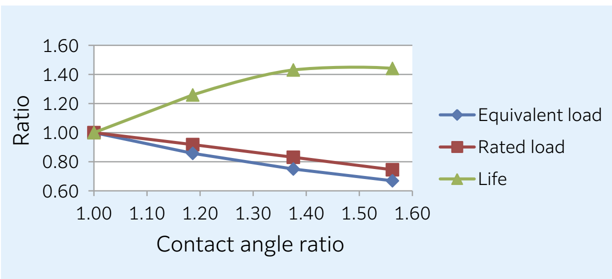


Fig. 15 Example 1 Relationship between contact angle and bearing life for axial load side row

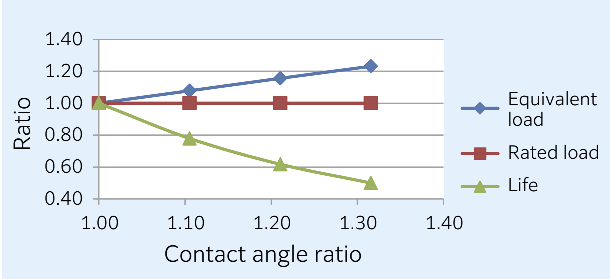


Fig. 16 Example 2 Effect on the axial load side row due to the change in contact angle of non-axial load side row

(2) Relationship of axial setting and life

When the axial setting is 0, as indicated in **Fig. 17**, the larger the contact angle, the longer the bearing life. However, the rate of decrease in life increases as the axial gap decreases (i.e., when preload is increased), and there is a reversal at more than 1,050 μm preload. This is because axial rigidity and resultant applied axial load increases with a larger contact angle.

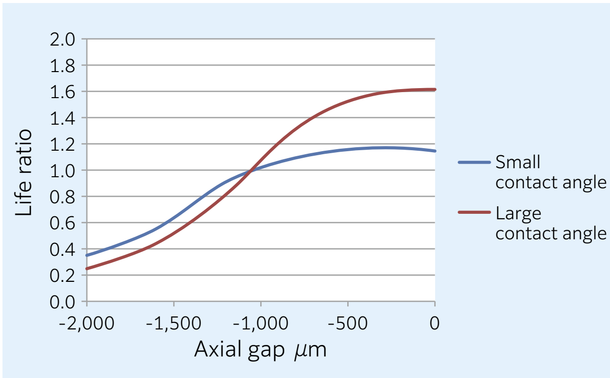


Fig. 17 Effect of axial clearance and bearing life for differing contact angles

(3) Effects of temperature variation on life

With back-to-back single row tapered roller bearings, radial expansion and contraction of the bearing, as well as axial elongation and contraction of the shaft and housing, both affect the axial setting. However, the effect of axial elongation/contraction of the shaft and housing is small, and the effect of axial expansion/contraction of the bearing is dominant. Variation in the axial setting was calculated by taking -1,050 μm where life reverses as a basis, as shown in **Fig. 17**, and assuming the inner ring operating +5 ℃ hotter than the outer ring **(Fig. 18)**. If the contact angle is small, then the rate of decrease in life becomes smaller, as shown in (2), but the amount of change in the axial setting increases, so caution is necessary.

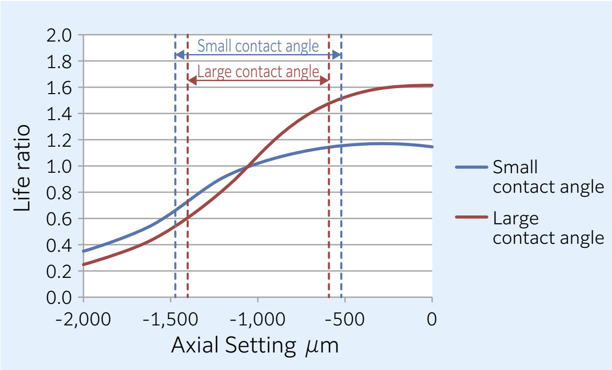


Fig. 18 Effect to bearing life for temperature change

(4) Relationship of aspect ratio and capacity to bearing cross section

As shown in Example 1 considered in **Fig. 15**, life changes with variation in the contact angle, but the aspect ratio*3 of the bearing cross section may have an effect. As shown in **Fig. 19**, with an aspect ratio of 1.1, that is a cross section that is larger in the radial direction, it is evident that the rate of decrease in bearing capacity when the contact angle is increased from α 1 to α 2 is smaller than the aspect ratio 0.9. This is because it is easier to achieve increased roller diameter and roller length within the smaller aspect ratio even when the contact angle is increased. On the other hand, if the contact angle is reduced, then decreasing the aspect ratio also makes it easier to achieve increased bearing capacity.

*3 Aspect ratio: Bearing cross section height / Bearing group width

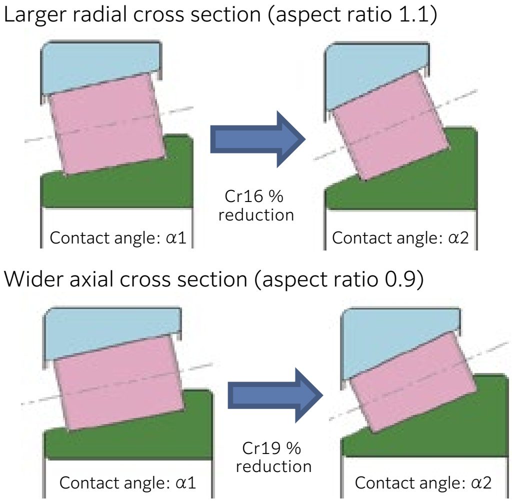


Fig. 19 Relationship between aspect ratio of cross section and load rating

4.3 Summary of effect verification

By increasing the contact angle, it is possible to reduce the radial reaction load, but there is also an increase in the induced axial load, and it is necessary to check effects on life and contact stress. Furthermore, main bearings are initially set into preload, but care must be given to the fact that the applied axial load increases under preload to the extent that axial rigidity increases. Another point for caution is that, when the contact angle is reduced, increased variation in axial setting may result in response to temperature changes.

Design with single row tapered roller bearings must be based on a good understanding of the above characteristics, but in actual practice, selection of the contact angle also varies depending on the permissible bearing size. Therefore, at **NTN**, we will utilize analysis tools and know-how we have acquired through our extensive experience to collaborate with wind turbine manufacturers from an early stage, to provide support to establish drivetrain designs.

5. Summary

This article has introduced the efforts of **NTN** to improve reliability and achieve optimization of main bearings used in wind turbines.

As the size of bearings continue to increase, we will respond by proposing new technologies and new products to help optimize designs and improve reliability, including manufacturing methods, and thereby help broaden adoption of renewable energy in collaboration with wind turbine designers.

References

1) P:Statistical Review of World Energy 2020.
2) Kazumasa Seko, Takashi Yamamoto, "Asymmetrical Spherical Roller Bearings" for Wind Turbine Main Shafts, NTN TECHNICAL REVIEW. No.86, (2018) 96-101.

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