New Technology of Bearings for Wind Turbine Generators and Market Trends of Wind Turbine Industry

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The Kyoto Protocol, adopted in 1997 globally, accelerated the introduction of power generation by renewable energy to prevent greenhouse gas emission from 2000. Furthermore, there have been growing concerns about both safety and reliability of nuclear power generation since the Great East Japan Earthquake caused a number of nuclear accidents in March 2011. Many countries around the world are consequently showing a great interest in renewable energy. Wind power, as the most practical renewable energy, has been spreading all over the world since 2000. Today, the cost reduction in wind power generation is the biggest key to boost the prevalence of the wind power generation. Rotor blades of wind turbine generators installed onshore are being upsized to be able to operate in weaker wind blowing areas, while higher power generating offshore turbines are being developed. As a result, rolling bearings installed into these turbines should be larger and more reliable.

***Key Words**: bearing, Kyoto Protocol, renewable energy, greenhouse gas, wind power generation, onshore, offshore*

1. Introduction

Power generation using renewable energies is giving great attention across the planet. In particular, the introduction of wind power generation, one of the main energy, has grown prevalent mainly in Europe since the year 2000. In recent years, China's introduction of wind turbine generators has also been notable, becoming number one in the world in 2009 for annual installation, and in 2011 for cumulative installation, demonstrating a significant increase in wind turbine generator growth. **Figure 1** shows the global trends for introduction of wind turbine generators[1]. This report introduces the latest technologies of bearings implemented to wind turbine generators and the market trends.

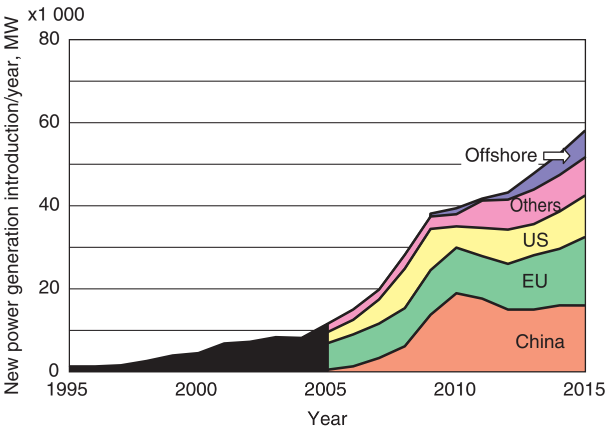


Fig. 1 Global trends for introduction of wind turbine generators

2. Configuration of Wind Turbine Generators

Figure 2 shows the configuration and components of a wind turbine generator[2]. The drive train, which consists of the main shaft, gearbox and generator, is housed into the nacelle. The blades connected to the wind turbine generator's hub catch wind. The wind drives the main shaft, in turn the gearbox increases rotational speed until power generation is possible. By rotating the generator, rotational energy is converted into electricity.

Currently, the mainstream model is between 1.5 and 2.3 MW (megawatts), which consists of a gearbox increasing speed by approximately 100-fold and an induction generator. The diameter of the blades is between 80 and 100 meters, and the tower height is around 100 meters.

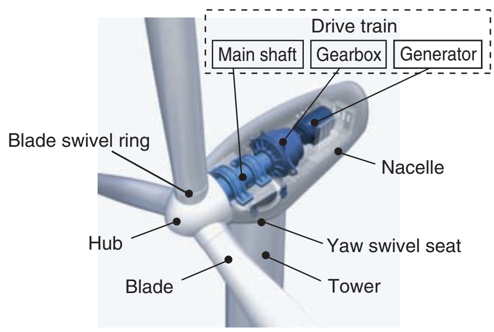


Fig. 2 Configuration of wind turbine generator

3. Characteristics of Wind turbine generators

3. 1 Wind turbine generator Classes

Wind turbine generators are installed across the world, where the wind turbine generators are standardized. According to the IEC61400-1ed.3[3] issued by the International Electrotechnical Commission (IEC), wind turbine generators are sorted into 9 classes (from IA and IB to IIIC) depending on wind speed and turbulence parameters. **Table 1**[3] shows the wind turbine generator class.

V_{ref} : The reference average wind speed over 10 minutes
V_{ave} : Annual average wind speed
A : The category for higher turbulence characteristics
B : The category for medium turbulence characteristics
C : The category for lower turbulence characteristics
I_{ref} : Expected value of turbulence intensity at 15 m/s

Table 1 Basic parameters for wind turbine classes

Wind turbine generator class		I	II	III	S
V_{ref} (m/s)		50	42.5	37.5	Value required by the designer and/or the customer
V_{ave} (m/s)		10	8.5	7.5	
I_{ref}	A	0.16			
	B	0.14			
	C	0.12			

However, a new class, 'S' has been defined for wind turbine generators installed in special conditions, such as Japan, where typhoons, earthquakes and so on are likely to occur. Moreover, there are expectations that standards will be formulated specifically to fulfill Japan's unique wind conditions in order to encourage the spread of wind turbine generators.

3. 2 Environment of Use

Wind turbine generators are installed in the open air and have to operate in various natural environments. As wind turbine generators are introduced to cold climates, where there is a need for survival at −40℃, the low-temperature brittleness and lubrication performance shall be took into consideration. In recent years, an increasing number of wind turbine generators are being installed offshore, where the environment differs completely to onshore so that the countermeasures against corrosion caused by seawater and so on are required.

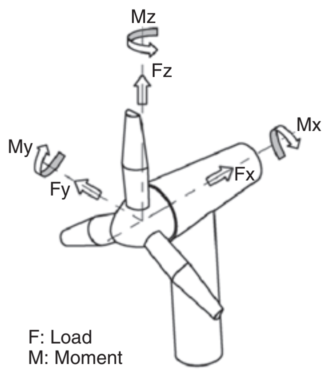


Fig. 3 Schematic directions of loads and moments

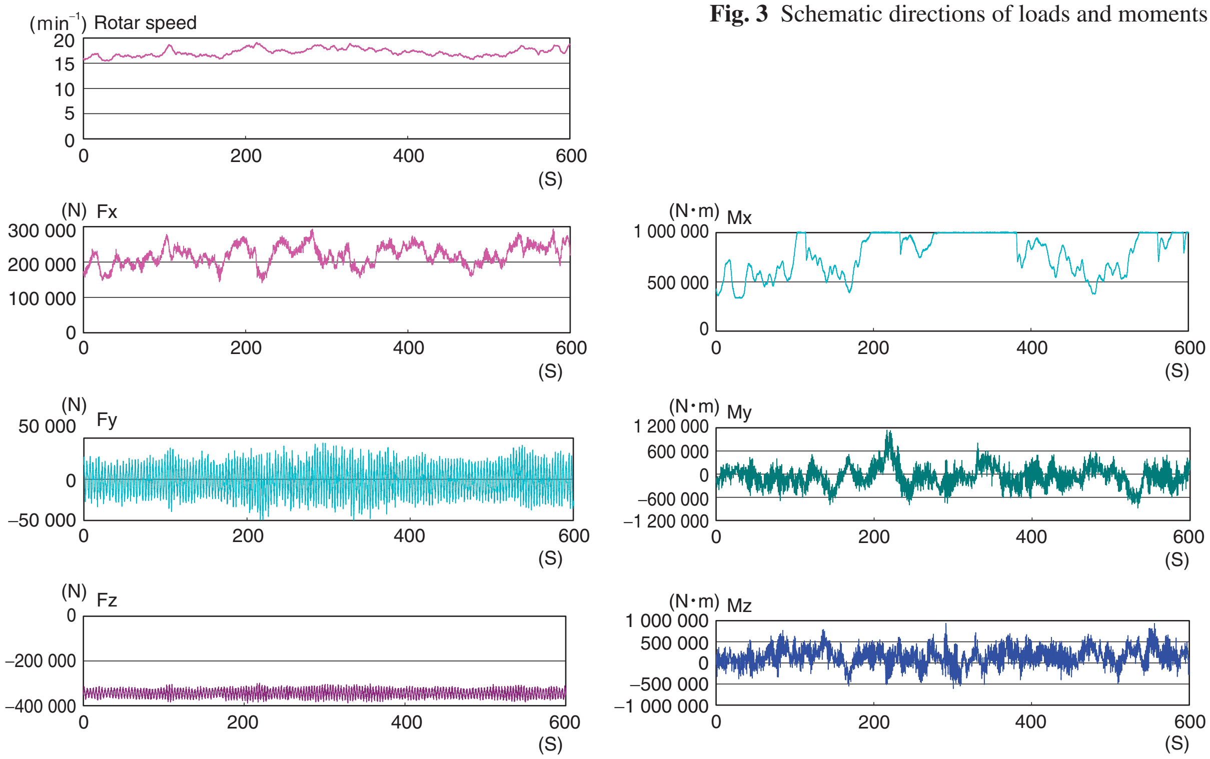


Fig. 4 One of distributions of main shaft rotational speed, loads and moments for 600 seconds

3. 3 Wind turbine generator Operating Conditions

In wind turbine generators, which harness natural energy, the load applied to the blades fluctuates at short cycles depending on wind conditions, crossing a wide range from light to heavy loads. It is also necessary to consider the minute vibration when the wind turbine generator stops and rotates at the extreme low-speed (around 0.1 min^{-1}) during idling. **Figure 3** shows the load and the moment directions[4] at the rotor centre, and **Fig. 4** is an example[2] of the loads and the moments. As wind conditions differ depending on the area where wind turbine generators are installed, their required performance is investigated in accordance with a combination of the various operating conditions called DLC (Design Load Case[3]) specified in IEC61400-1ed.3 and its frequency.

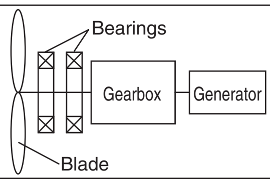
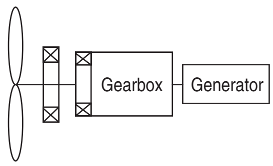
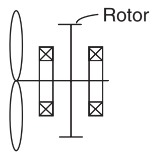
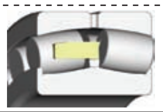
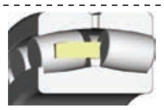
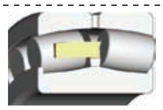
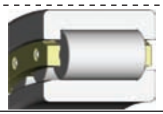
4. Wind Turbine Generators Drive Trains and Main Shaft Bearings

4. 1 2 MW Wind Turbine Generator Drive Trains and Main Shaft Bearings

Table 2 shows the configuration of drive trains and the characteristics of the main shaft bearings for 2 MW wind turbine generators, currently the most commercialized model.

According to JTEKT's estimate, 80% or more of 2 MW wind turbine generators are Type 1 and 2, consisting of gearboxes and 4 or 6 pole induction generators. On the other hand, approximately 20% of wind turbine generators are Type 3, which directly connect to a large multipole synchronous generators without gearboxes as

Table 2 Configuration of 2 MW wind turbine drive trains and the characteristics of the main shaft bearings

Wind turbine generator	Type	1		2		3	
	Rough structural drawing						
	Characteristics	· Configured from a main shaft, gearbox, generator · Wind load supported by two main shaft bearings (separate housing)		· Configured from a main shaft, gearbox, generator · Wind load supported by two bearings, the one for the main shaft and the other for the gearbox carrier (separate housing)		· Generator rotor supported by the main shaft bearings · Wind load supported by two main shaft bearings (integrated housing) · No gearbox	
	Generator type	Induction generator		Induction generator		Synchronous generator	
	Cost	○		◎		△	
	Reliability	○		○		◎	
	Efficiency	◎		◎		○	
Main shaft bearing	Location	Front	Rear	Front	Rear	Front	Rear
		Free side	Fixed side	Fixed side	· Supported by the gearbox carrier bearing · Bearing type differs between gearbox manufacturers	Fixed side	Free side
	Structural drawing	Spherical roller bearings 	Spherical roller bearings 	Spherical roller bearings 		Double row tapered roller bearings 	Cylindrical roller bearings 
	Number	2		1		2	
	Installation ability	◎	◎	◎	–	△	△
	Radial load performance	◎	◎	◎		◎	◎
	Axial load performance	○	○	○	–	◎	Not applicable
	Vibration resistance	○	○	○		◎ (if preloading)	○
	Allowable misalignment on inner ring/outer ring	◎	◎	◎	–	△	△
	Axial direction allowance	Not applicable	△	Not applicable	–	Not applicable	◎
Remarks		· Problem with reliability of gearbox · Problem of electric pitting of generator bearing		· Problem with reliability of gearbox · Problem of electric pitting of generator bearing		· High cost compared to induction generator · High reliability as there is no gearbox	
*Market share (2008)		37%		47%		16%	

◎: Excellent ○: Good △: Possible ×: Not possible *JTEKT estimate breakdowns of the gearboxes and the electric pitting of bearings mounted in the induction generators often occur. This configuration is called "direct drive". However, Type 3 has the disadvantage of a significant increas in the weight of the nacelle as the generator is heavier than the induction generator.

Various types of bearings are implemented to the main shaft. The main shaft bearing does not only bear the load applied to the blades but also plays the important role of transmitting rotational torque to the gearbox.

In the 2 MW class, spherical roller bearings are mainly applied as they have excellent self-aligning and load resistance properties. Moreover, in the direct drive configuration (Type 3) an integrated housing design is adopted to make it easier to control misalignment of the front and rear bearings. In recent years, wind turbine generators intend to consist of double row tapered roller bearings, which have excellent axial loading performance on the fixed side, and cylindrical roller bearings, which have excellent axial direction allowance on the free side.

4. 2 Drive Trains and Main Shaft Bearings for Wind Turbine Generators over 2 MW

There is an increase in the development and commercialization of large wind turbine generators over 2 MW. **Table 3** shows specifications of a typical wind turbine generator, and **Table 4** gives the drive train configuration and characteristics of main shaft bearings[2].

Many wind turbine generators over 2 MW have similar configuration to the 2 MW class, however as shown in **Table 4**, there is an unique configuration, where the main shaft is supported with one steep-angle (contact angle 45°) double row tapered roller bearing, making the wind turbine generator smaller. In such cases, the main shaft is lighter, however the bearing outside diameter is around 2.5 m, making it difficult to procure the bearing and peripheral components. Wind turbine generator manufacturers in China, where it is relatively easy to produce large components, are actively adopting this configuration. In the future, in order to improve reliability and speed up the weight reduction of wind turbine generators, a hybrid type combining the advantages of Types 1, 2 and 3 would become main stream. This type will consist a gearbox with a low speed-increase ratio, and a smaller synchronous generator than the one applied to direct drive configuration.

4. 3 Requirements of Main Shaft Bearings

Bearing selection is based on the standards[4] of international audit and inspection institutions, GL (Germanischer Lloyd) and DNV (Det Norske Veritas AS). These institutions have established standards for the static safety factor and service life of bearings. In addition to the conventional L_{10} life (Basic rating life calculation: ISO281-2007[5]), there is a demand to investigate L_{10}m life (Modified rating life calculation: ISO281-2007) and L_{10}mr life (Modified reference rating life calculation: ISO/TS16281-2008[6]), which secures a service life of 20 years (175 000 hours), in consideration of the following

(1) Lubricant viscosity and contamination during operation
(2) Internal bearing design
(3) Operating clearance
(4) Bearing, shaft, housing rigidity
(5) Roller load distribution
(6) Contact stress distribution in the axial direction considering the shape of rollers and raceway

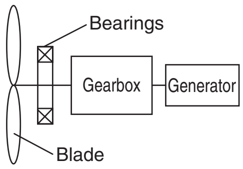
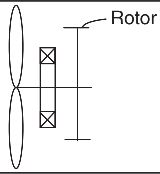
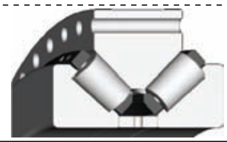
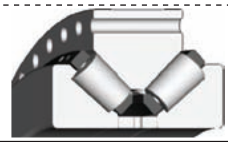
Moreover, as well as the above requirements, bearings must also satisfy the below factors.

- Compact and rigid bearings considering rigidity of peripheral components (weight reduction of drive train)
- Cost competitiveness
- Availability
- Excellent maintainability

Table 3 Specifications for over 2 MW wind turbine generators

Generation capacity (MW)	Blade diameter (m)	Transmission type	Generator type
2.3	82	Direct	Synchronous
	113	Gearbox	Inductive
2.4	92	Gearbox	Inductive
2.5	100	Gearbox	Inductive
2.75	103	Gearbox	Inductive
3.0	101	Direct	Synchronous
	109	Gearbox	Synchronous
	90/112	Gearbox	Inductive
3.4	104	Gearbox	Inductive
3.6	120	Gearbox	Inductive
4.1	113	Direct	Synchronous
4.5	128	Gearbox	Synchronous
5.0	116	Gearbox	Synchronous
	126	Gearbox	Inductive
6.0	126	Gearbox	Inductive
	150	Direct	Synchronous
	154	Direct	Synchronous

Table 4 Configuration of over 2 MW wind turbine generator drive trains and the characteristics of the main shaft bearings

	Type	4	5
Wind turbine generator	Rough structural drawing		
	Characteristics	・Configured from a main shaft, gearbox, generator ・Wind load supported by one main shaft bearing (larger bearing)	・Generator rotor supported by the main shaft bearings ・Wind load supported by one main shaft bearing (larger bearing)
	Generator type	Induction generator	Synchronous generator
	Cost	○	△
	Reliability	△	○
	Efficiency	◎	○
Main shaft bearing	Structural drawing	Steep-angle double row tapered roller bearing 	Steep-angle double row tapered roller bearing 
	Number	1	1
	Installation ability	△	△
	Radial load performance	◎	◎
	Axial load performance	◎	◎
	Vibration resistance	◎ (If preload is applied)	◎ (If preload is applied)
	Allowable misalignment on inner ring/outer ring	△	△
	Axial direction allowance	Not needed	Not needed
Remarks		・It may be difficult to procure bearings and peripheral components due to a larger bearing diameter ・Possible to make more compact in the axial direction ・Problem of reliability of gearbox ・Problem of electric pitting of generator bearing	・It may be difficult to procure bearings and peripheral components due to a larger bearing diameter ・Possible to make drive trains more compact in the axial direction ・High cost compared to induction generator ・High reliability due to no gearbox mounted

◎: Excellent ○: Good △: Possible ×: Not possible

4. 4 Case Study

Conventionally, wind turbine generators were of a sturdy design, therefore it wasn't necessary to consider rigidity of the shaft and housing. However, in recent years, hollow shafts and thinner housing are applied to reduce weight of wind turbine generators, and it is no longer possible to sufficiently secure rigidity of these components. As a result, JTEKT introduced a shaft analysis program and FEM analysis to study the optimal bearing specifications considering rigidity of the shaft and housing in addition to internal bearing design, clearance and raceway crowning. **Figure 5** and **6** show some examples of the roller load distributions. As **Fig. 5** shows continuous load distribution is obtained when the housing is rigid enough. On the contrary, uneven load distribution is obtained seen in **Fig. 6** when the housing is not rigid. As a result, bearing design have to be taken into consideration as there is a possibility that weight reduction of wind turbine generators causes insufficient rigidity of peripheral components.

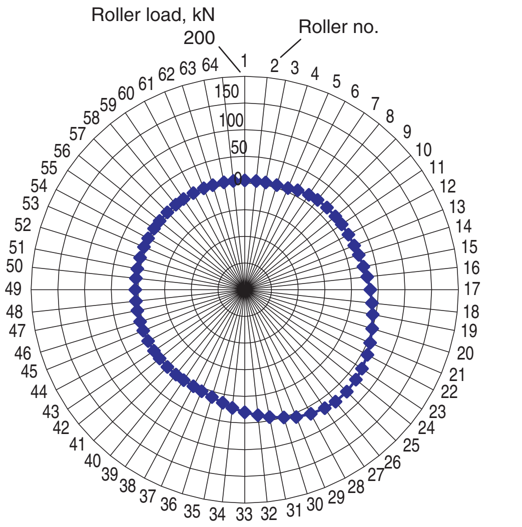


Fig. 5 Example of load distribution on roller in case of high-rigidity housing

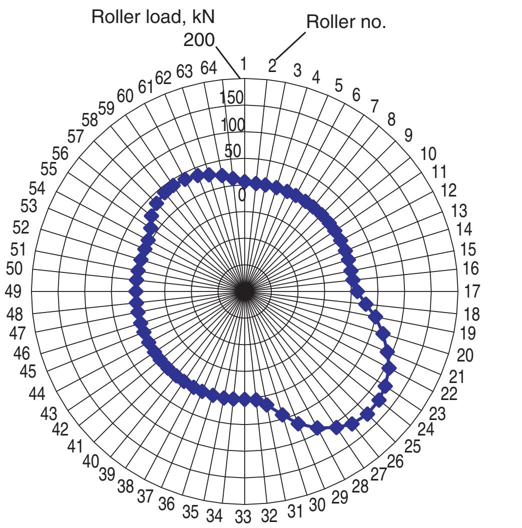


Fig. 6 Example of load distribution on roller in case of low-rigidity housing

5. Gearbox Bearings

The gearboxes consist of a carrier, planet gears, a ring gear, a low-speed shaft (sun gear) and parallel shafts. Most wind turbine generator on the market have a 1-stage planet gear and a 2-stage parallel shaft. **Figure 7** gives an example of the configuration of a 2 MW gearbox. Recently, in order to make gearboxes more compact, an increasing number of gearboxes have one multi-stage planet gear or the planet gear connected to a 1-stage parallel shaft.

The gearbox transmits the rotational torque from the main shaft to the generator, and increases the speed through engagement of the gear until power generation is possible. The rotational speed of the output shaft is usually between 1 300 and 1 600 min^{-1}, which depends on types, pole numbers and frequency of the generator. As the planet gear is subjected to high torque, it is necessary to investigate the rigidity. In order to improve the rigidity, the planet gear has been recently integrated with the bearing outer ring raceway (**Fig. 8**). Moreover, the rotational speed and rotational torque of wind turbine generator gearboxes change depending on wind conditions, which also varies second by second. In turn, the load applied to the bearing and the bearing rotational speed also fluctuates. Bearings mounted on high speed shafts are particularly prone to low loads and high speed rotations, and smearing occurs due to the sliding between the roller and the raceways. To countermeasure the sliding, the bearing internal design is optimized, and surface treatment is introduced. As for the main countermeasure, special surface treatment is applied to cylindrical roller bearings mounted in gearboxes for wind turbine generators in the 2 MW class or above. Furthermore, many wind turbine generator gearboxes are not anchored to the main frame. They are only fixed in the rotational direction with torque arm. As a result, there are an increasing number of breakdowns caused by vibration as the gearboxes operate in a unique condition. As wind turbine generator gearboxes are used in special operating environments, it is important to conduct pratical rotation tests to confirm bearing performance, rather than just investigate bearing design. In addition, lubricating method, lubricant types and contamination control are important as the lubrication system also lubricates the gear unit.

Bearing selection should be referred to ISO81400-4. **Figure 9** and **Table 5** show a typical gearbox bearing layout and the bearing types used in gearboxes[7] respectively. In the same way as main shaft bearings,

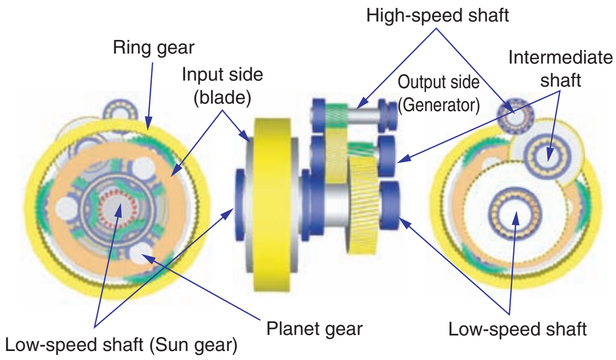


Fig. 7 2 MW class gearbox configuration

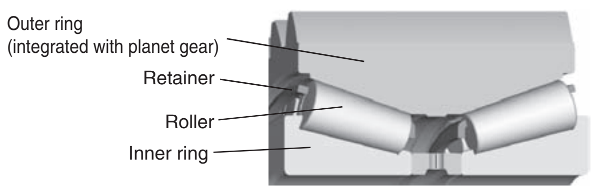


Fig. 8 Integrated bearing for planet gear

there is a requirement to study service life paying consideration to internal bearing elements, the shaft, and lubrication. Moreover, depending on the positions, the maximum contact stress between the roller and raceways, and required service life[7] are specified (**Table 6**).

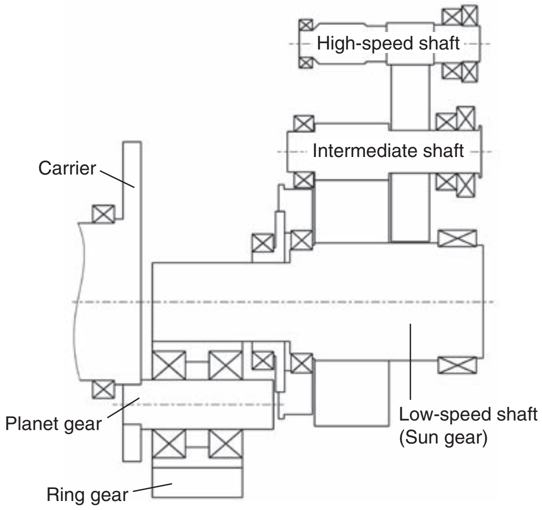


Fig. 9 Bearing layout for gearbox

Table 5 Bearing types used in gearbox

Positions	Bearing model			
High-speed shaft	CRB	TRB	SRB	TRB×2
	TRB+CRB		CRB+4 point BB	
Intermediate shaft	CRB		SRB	
	TRB×2		CRB+4 point BB	
Low-speed shaft (Sun gear)	CRB	SRB	TRB×2	
	2 row TRB			
Planet gear	CRB×2	SRB×2	TRB×2	
Carrier	CRB	TRB	SRB	BB

CRB: Cylindrical roller bearing TRB: Single row tapered roller bearing
SRB: Spherical roller bearing BB: Single row deep groove ball bearing
4 point BB: 4 point contact ball bearing
2 row TRB: Double row tapered roller bearing

Table 6 Maximum contact stress and required calculated life

Positions	L_{10} (hours)	L_{10mr} (hours)	Static safety factor: Max. operational load	Static safety factor: Max. static	Max. contact stress (MPa)
High-speed shaft	30 000	Specified by wind turbine generator manufacturers	3.0	2.0	1 300
High-speed intermediate shaft	40 000				1 650
Low-speed intermediate shaft	80 000				1 650
Planet gear	100 000				1 650
Low-speed shaft	100 000				1 450

6. Bearings for Induction Generators

In recent years, doubly fed induction generators are introduced widely to commercialized wind turbine generators in order to efficiently convert rotational energy to electrical energy from low-wind speeds. **Figure 10** shows a simple diagram of the configuration of the generators. As for the bearings applied to induction generator, sparks occur in the extremely thin oil film of the rolling contact area, and the raceway may locally melt if electrical current passes through a bearing. In other words, damage is caused by electric pitting (**Fig. 11**), which is one of the main causes of breakdowns.

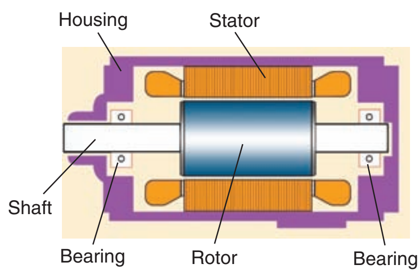


Fig. 10 Configuration of inductive generator

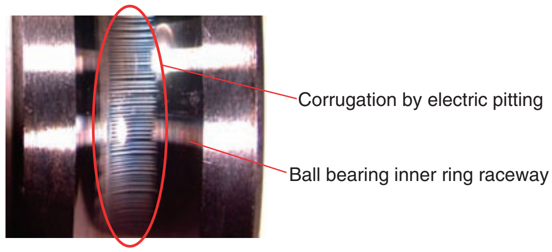


Fig 11 Example of electric pitting on inner ring raceway of ball bearing

Bearings have to acquire an insulation performance in order to prevent electric pitting. One countermeasures is to apply insulated hybrid ceramic bearings[8] consisting of rolling elements made from ceramic (silicon nitride) because of excellent insulation. Ceramic balls with diameters of approximately. 50mm are used as rolling elements in the bearings of generators for 2 MW wind turbine generators. **Figure 12** shows a 3D model of an insulated hybrid ceramic bearing. In comparison with the insulation film on the outer ring outside diameter (ceramic sprayed coating, resin coating) and insulation on the housing, this bearing has the following advantages.

- Long- term and stable insulation performance
- Easy installation to generators
- Improvement on grease life due to low temperature rise

Table 7 shows a comparison of characteristics between ceramics and bearing steel[9], while **Fig. 13** shows the temperature rise[9] of an insulated hybrid ceramic bearing.

As conventional bearings sometimes cause electric

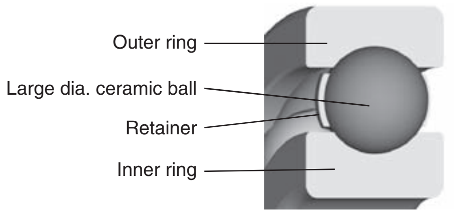


Fig. 12 3D model of insulated hybrid ceramic bearing

Table 7 Comparison of characteristics between ceramics and bearing steel

Item	Ceramics (Si_3N_4)	Bearing steel (SUJ2)	Ceramics advantage
Heat resistance (℃)	800	180	Maintains high load ability under high temperatures
Density (g/cm^3)	3.2	7.8	Low temperature rise
Linear heat expansion coefficient (1/℃)	3.2×10^{-6}	12.5×10^{-6}	Small dimension change
Vickers hardness (HV)	1 500	750	
Longitudinal elastic modulus (GPa)	320	208	High rigidity
Poisson ratio	0.29	0.3	
Conductivity	Insulant	Conductive	Electric pitting resistant
How material is joined	Common joint	Metal joint	Seizure resistant

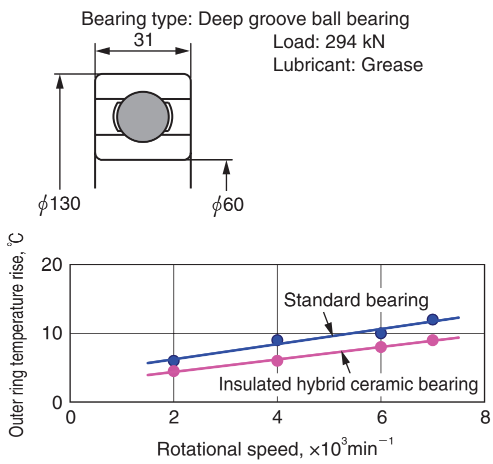


Fig. 13 Temperature rise characteristic of insulated hybrid ceramic bearing

pitting, they need to be replaced. When bearings are replaced, not only replacement work but also time to access the nacelle shall be considered. As a result, long downtime of wind turbine generators leads to massive loss of electricity generation. Introduction of insulated hybrid ceramic bearings enables long grease life to extend the maintenance period as well as to prevent from downtime of wind turbine generators caused by failure of generators. This contributes to a significant reduction in maintenance costs and improvement in operation efficiency.

7. Market Trends of Wind Power Generation

Power generation utilizing wind power has grown rapidly mainly in Europe since the year 2000. In order to improve power generation efficiency, wind turbine generators have been bigger (higher power generation capacity). **Figure 14** and **15** show the change in wind turbine generator size and the change in average power generation per wind turbine generator respectively. Moreover, from 2007, the number of wind turbine generators introduced to all over the world, particularly in China, has increased rapidly. In recent years, countries around the world establishes national policies to increase the ratio of power generation by renewable energies. Europe has set a target of reaching 20% of all power consumption generated by wind power in the year 2020. In the US, the technical feasibility study on 20% of all power consumption coming from wind power in the year 2030[10] has been currently done. In Japan, the ratio of power generated by wind power is still low compared with other countries, However in July 2012, FIT (Feed-in Tariff) was adopted so that installation of wind turbine generators is projected to grow. As a result, high power generation efficiency is indispensable in order to reduce both installation and development costs as the profitability of wind power business is important. In the future, specification of wind turbine generators would be different as they are installed to offshore as well as onshore.

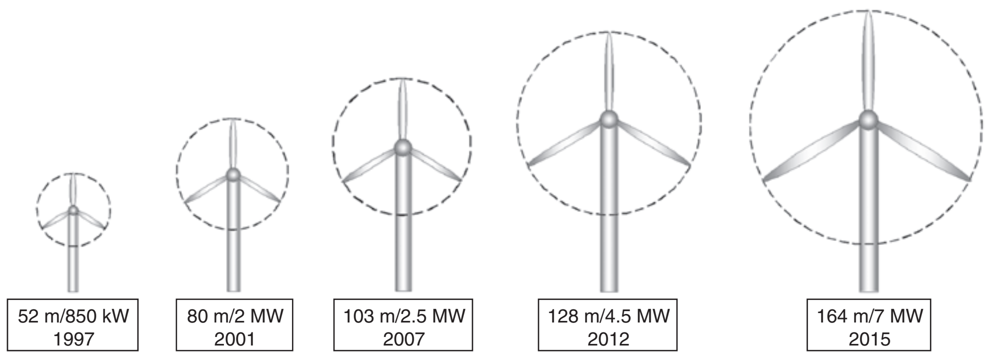


Fig. 14 Change in wind turbine generator size

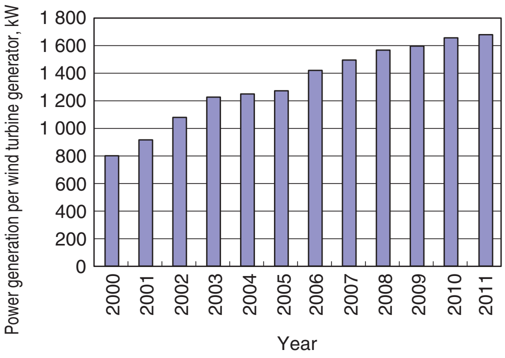


Fig. 15 Change in average power generation per wind turbine generator

7. 1 Onshore Wind turbine generators

Currently, most wind turbine generators are located onshore. Wind turbine generators have been larger (high power generation capacity), which have led to reduction in the number of installation since the wind power generation market grew in 2000. As a result, the cost of installation and transportation has increased significantly and there is a demand to make the wind turbine generators lighter and smaller. Furthermore, in recent years, good wind condition areas have been already occupied. Therefore, wind turbine generators have to be installed to areas where the wind speed is quite low and unstable. The blade diameter need to be larger in order to be capable of generating power from low wind speeds. In addition, there are demands on higher power generating efficiency, i.e. extended power generation time and, improved reliability leading to less maintenance period, less breakdowns and less repairs.

7. 2 Offshore Wind turbine generators

In recent years, large size wind farms have been built in shallow ocean in Europe, and the operations have commenced. The sea surface is flat so that turbulence does not occur often. Moreover, power generation period is longer due to stable wind conditions. The locations where wind turbine generators are installed can be accessed by boat, making it easy to transport large wind turbine generators. As a result, power generation efficiency is significantly improved due to the wind turbine generators with higher power generating capacity for a long time operation. However, there is a limit to how large wind turbine generators can be produced. Wind turbine generators need to be lighter by using new material and new drive train configurations (such as multiple generators driven by hydraulic transmission).

8. Conclusion

In these times, when the safety and reliability of nuclear power are doubted, the expansion of power generation utilizing wind power is no doubt. There are high expectations of wind power generation however only 10 years or so have passed since wind turbine generators began being commercialized and it cannot be said that they are sufficiently reliable. Moreover, wind turbine generator manufacturers are being abolished and/or merged all over the world, and it is evident that the industry is not yet established. However, if the Feed-in Tariff system spreads across the world, profitability will improve and it is believed action towards improving power generation efficiency will accelerate. JTEKT expect wind turbine generators will be lighter, smaller and with higher reliability through introducing new technologies and will contribute to the promotion of renewable energies by developing and providing the optimal bearings for wind turbine generators.

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