Preventing lightning damage in bearings by using mechanical preloading

Frank Leferink\textsuperscript{a, b, *}

\textsuperscript{a} University of Twente, Enschede, The Netherlands
\textsuperscript{b} THALES, Hengelo, The Netherlands

\textbf{A R T I C L E   I N F O}

\textbf{Article history:}
Received 9 May 2016
Received in revised form 30 July 2016
Accepted 3 October 2016
Available online 13 October 2016

\textbf{Keywords:}
Lightning
Arcing
Bearing
Boundary film lubrication

\textbf{A B S T R A C T}

High positioned systems such as wind turbines or radar system onboard a ship can be easily struck by lightning. The lightning current has to be conducted via defined paths to prevent damage. A key element to protect is the bearing system between the rotating and stationary part. Providing a bypass current path via additional means such as a slip ring is the conventional way of protecting bearing. The arcing due to high voltage difference between rollers and raceway is however the main cause of damage to the bearing system. It is commonly assumed that, if the wind turbine blades, or the radar, is rotating, the lubrication between the rolling elements and the raceway is a non-electrical conducting hydrodynamic lubrication layer, and thus high voltages can be developed. But if the bearing is sufficiently preloaded it is still providing a conductive path via boundary lubrication. No arcing occurs, and no damage. The concept of pre-loading the bearing system has been evaluated using many experiments on stationary and rotating bearings, and after performing endurance testing.

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1. Introduction

Wind turbines can be easily struck by lightning [1–7]. The most common damage is the electronic control system, while the most visible damage is the lightning damage to the composite blades. The bearing system is also a vulnerable part [8–11], although less investigated. The risk of radar equipment being struck by lightning is much higher in the littoral, i.e. waters near the coast, than in the blue water areas, far away from the coast [12]. Naval vessels were operating in the blue water but this is changing rapidly to the littoral. Radar systems are often located at a high position and are therefore also vulnerable to be struck by lightning. Also for rotating radar systems the bearing system is the key component between the rotating and stationary parts of a radar system. No public data was found on lightning damage to radar bearings, but the problem can be compared with that of bearings on wind turbines [12]. The main-shaft bearing is one of the most involved parts [8], and lightning damages to these bearings can result in high costs of maintenance. In the main standard IEC 61400-24 [1] only very generic information can be found, such as that the bearing should be protected. In Ref. [13] lightning tests on an electric vehicle are described showing that the lightning current path flows between the metal alloy of the wheel and ground. No further investigation on the bearing is reported. In Refs. [2–4,8] it is suggested that the damage of the main-shaft bearing is caused by flashovers within the bearing lubricant, or arcing, resulting in pitting. The possibly following high current after the arc could result in overheating and welding, but this latter phenomenon is not described in literature. In a conventional system, slip rings are conducting the lightning around the bearing, in order to prevent arcing. This is also the conventional approach protecting arcing in radar system bearings. The slip ring consists of a series of carbon brush elements divided over the circumference of the radar antenna drive creating an electrical conductive path for the lightning current. The disadvantage of these brush elements is the wear, resulting in very regular maintenance, for instance once per year. Furthermore the wear is causing dust, thus pollution. A slip ring around the main shaft is also the generic means to protect the bearing of wind turbines against lubricant flashovers, since the bearing is a very critical component to exchange. Because of this protection, practical experience with lightning damage to wind turbine bearings is scarce, wind turbine bearings are not normally checked after lightning strikes [2,3]. Few investigations of the damaging effect of lightning current on bearings have been carried out. In Ref. [11], the tests were exaggerated by reducing the number of rolling elements, to force the current through only 1 or 2 such elements. But it was
also concluded that the damages produced by an arc can be bigger than the current conduction damage. In the following sections the stationary bearing, boundary lubrication and rotating bearing, and lightning experiments on a rotating preloaded bearing solutions are discussed, showing the advantages of mechanical preloading of bearing to prevent damage due to lightning currents.

2. Stationary bearing

A new trend in architecture during the last few years is the use of retractable roofs in stadiums. These roof structures have no fixed connections to ground; instead they have thousands of moving contact points. Traditionally, for a building or a fixed-roof stadium, lightning rods are grounded to the roof steel, the roof steel connected to columns, and the columns connected to a ground grid. But for a retractable roof it is likely that the current will find its way to ground via bearings. This problem is described in Ref. [14]. Lightning current tests have been performed on a greased bearing in stationary condition, and it was found that no damage occurred to rolling elements and raceways. The retractable roof has been used in many areas where lightning has hit the structure without damaging the structure. This situation is comparable to a stationary radar, i.e. a radar which is normally rotating but is in a non-active mode. The weight of the radar in a parked position is pressing through the lubricant and a direct contact between rolling elements and the raceway is made. Then no arcing is possible, and no pitting results. Comparable conclusions have been drawn in Ref. [11] where lightning currents were conducted through bearings. The identical tests to a rotating and a stationary bearing only resulted in damage to the rotating bearing. It was concluded that the cause of damage is arcing between rolling elements and raceways at the breakdown points through the insulating hydrodynamic lubrication layer present in the rotating bearing. This was also concluded in Ref. [15], and confirms the assumption that the arcing resulting in pitting is the cause of damage, and not the current which might cause locally heating. Of course, in case nearly all rolling elements are removed, such as in Ref. [11], then only one roller has to conduct the current resulting in a very high local current density, and inevitably damage.

In Refs. [9,10] models for the bearing impedance have been developed, based on extensive measurements of a 1:20 reduced scale model of typical main shaft wind turbine bearings. To replicate the mechanical load conditions, also scaled mechanical forces, tilt–moment and rotation speed that appears in real scale main shaft bearings were used. Fig. 1 shows the measured impedances of the reduced scale bearing model, for parked, idling, partial load and full (wind) load. In the parked-standing mode, the bearing impedance shows a low impedance (ohmic) behavior that can be justified considering that the bearing elements are in metallic contact due to the null rotation speed that does not allow for the formation of the lubricant film. But in the idling, partial and full wind load conditions, the bearing can be modelled by a capacitance suggesting that there is film lubrication between the roller and the raceway. This is in line with the assumption in Ref. [5], which assumes a film of 50 μm thickness at the operational speed of a wind turbine (20–30 RPM).

3. Boundary lubrication

If a radar antenna is rotating a hydrodynamic layer of lubricant is developed in the bearing which will result in an insulating layer. If a lightning strikes the antenna, a high voltage is developed, and flashover will occur, causing a spark, which will ultimately result in pitting on the race and rollers even at relatively low current levels. To prevent damage, carbon brushes in a slip ring are often used to provide a low impedance current path. Preloaded bearings have been used many times to reduce the variations in movements, to attain the required built-in stiffness and running accuracy. Experiments with an electrostatic discharge gun on bearings showed that stationary bearings were conducting (as expected), rotating bearings were not conducting due to the oil film (as expected), but that rotating preloaded bearings were also conducting. This last effect is against the conventional knowledge and unexpected. However, the actual friction regimes for sliding lubricated surfaces have been broadly categorized into solid/boundary, mixed, or fluid friction, on the basis of the Stribeck curve [16–18]. In general, unbreakable lubricating films are required to prevent intimate contact between mating surfaces, which are produced by fluid film lubrication. In practice, however, the transition from fluid film lubrication to boundary lubrication occurs with increasing load or decreasing relative velocity, which leads to an increase in the coefficient of friction. Stribeck, and others, studied the variation of friction between two liquid lubricated surfaces as a function of a dimensionless lubrication parameter $nN/P$, where $n$ is the dynamic viscosity (Ns/m²), $N$ the sliding speed (m/s) and $P$ the load projected on to the geometrical surface which is usually load per unit length of bearing in N/m. An example is shown in Fig. 2. In the film lubrication regime the rolling elements and raceway are completely isolated via a thin layer of lubrication oil. In the boundary lubrication regime the film
thickness formed is significantly smaller and the load will be carried by the asperities, rather than by the lubricant.

The Strubeck curve provides a qualitative explanation of the transition but its quantitative evaluation methods have not been established yet. In Refs. [19,20] the complex impedance of a bearing system was measured, with the objective to calculate the film thickness and breakdown ratio. It was concluded that in the full fluid film lubrication regime, the film separates the two surfaces, and the impedance is very high and capacitive, like as shown in Refs. [9,10]. When the oil film starts to break down, i.e. is approaching boundary lubrication the impedance shows a low value in the order of less than 1 Ω. This result confirms our experiments performed on preloaded bearing, where it was impossible to create a spark gap because the preloading prevented full fluid film lubrication.

4. Resistance and lightning tests on bearing

The analysis and experiments described before suggest that preloaded bearings can conduct lightning currents without damage, and carbon brush elements are thus not needed. Resistance measurements and lightning current experiments have been carried out on normal and preloaded bearings to determine the effect of preloading.

The resistance between the two bearing raceways, with the rolling elements in between, was measured on a normal bearing using a milli-ohmmeter. The resistance was less than 1 mΩ for the static bearing, i.e. not rotating. This low impedance is achieved as a result of the direct contact between rolling elements and the race-way. When the bearing was rotating the resistance increased to more than 1000 Ω due to the film lubrication. The same test was performed on a mechanical preloaded bearing, as used for a radar system. Radar systems are using preloaded bearings to prevent wiggling and assure accurate tracking of objects. This preloaded bearing showed a resistance of less than 1 mΩ, for static and rotating conditions.

Lightning current tests, including the fast A pulse, the B pulse, and the high-energy C pulse, have been performed on normal roller bearings and preloaded roller bearings [21]. The lightning current generator is described in Ref. [22] and consists of a series of three pulses as described in Refs. [23,24]:

- A-pulse test setup for high current, consisting of a cascade capacitor bank, for short stroke electrical currents of 100 kA,
- B-pulse artificial line intermediate current test setup, capacitor-coil circuit, for currents of 2 kA,
- C-pulse continuing current test setup, 3-phase diode bridge circuit for DC currents of, in this test, 300 A.

The parameters for the tests are listed in Table 1. These are measured values for the tests on the bearing and the differences between the various experiments was within ±5%.

To perform a complete lightning test, the test setup is subsequently connected to each of the test setups and loaded with the maximum output.

4.1. Conventional bearing

A single lightning current test was performed on the first, normal, bearing. Only the A-pulse was used for the static bearing. No changes in rotation and resistance was observed. Then the normal bearing was rotating at normal speed, in film lubrication condition, and the lightning A-pulse test was repeated. Severe damage to the bearing was observed. Mechanical vibration increased and acoustic

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**Table 1**

<table>
<thead>
<tr>
<th>Pulse name</th>
<th>Peak current</th>
<th>Rise time</th>
<th>Time to half value</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>100 kA</td>
<td>9 µs</td>
<td>240 µs</td>
<td>700 µs</td>
</tr>
<tr>
<td>B</td>
<td>2 kA</td>
<td>200 µs</td>
<td>500 µs</td>
<td>3 ms</td>
</tr>
<tr>
<td>C</td>
<td>300 A</td>
<td>–</td>
<td>10 ms</td>
<td>200 ms</td>
</tr>
</tbody>
</table>

**Fig. 2.** Strubeck curve.

**Fig. 3.** Damaged rolling elements.
noise increased. After dismantling the normal bearing, the damage could be observed on the rolling element, as shown in Fig. 3. The damaged inner and outer raceway is shown in Fig. 4.

4.2. Preloaded bearing

High voltage tests have been performed to test the effectiveness of spark gaps mounted external to a radar system. Using a mechanical preloaded bearing it was not possible to generate a spark, because the bearing was creating a continuous conductive path. Although the concept of boundary lubrication is known, this result was not expected because the common assumption was that even at low speed there is film lubrication, creating an isolated layer. The concept of using a sufficiently preloaded bearing has been filed in a patent [25]. A special test setup was built to test a typical preloaded bearing configuration under normal operating conditions, rotating at approximately 25 RPM, as shown in Fig. 5. To simulate the currents typical for a lightning stroke, the setup was subjected to an A, B and C lightning pulse as mentioned in Table 1. The axial preload on the bearing-system was the same as the preloading with the radar system installed. Measurements of the bearing resistance before and after each lightning current test showed values below 1 mΩ, typical between 300 and 700 μΩ.

To monitor the condition of the bearing system, axial, radial and tangential accelerations have been measured before and after each lightning pulse test. This is a very well known technique to estimate if there is some deviation, e.g. pitting, in the rolling element and/or raceway. The vibrations have been measured with a sample frequency of 2 kHz and a record length of 10 s. From this raw data and FFT spectrum, the RMS value of the vibration (acceleration) was calculated, as shown in Fig. 6.

The differences between the subsequent measurements are of the same order of magnitude as the standard deviation of the set of measurements, so no change in vibration before and after the lightning test was observed.

To test the remaining operational life of the bearing system, an endurance test was also performed. Assuming that wear is equivalent to the total number of revolutions, the bearing system was set to rotate at a much higher speed than the operational speed in order to compress the total test time. The bearing temperature was monitored to assure normal operating conditions. The endurance test was stopped after 4 weeks at high rotational speed, representing many years of normal operation. The root mean square (RMS) values of the measured vibrations during the endurance test are shown in Fig. 7 and Table 2.

The differences between the subsequent measurements are of the same order of magnitude as the standard deviation of the set of measurement results. There are no differences in the shape of the spectra that indicate any deterioration of the bearing system.

Since the results of the vibration measurements indicate no deviations and that bearing system is not damaged, only the upper bearing of the test setup was disassembled following the endurance
5. Conclusion

The rolling element and raceway of a bearing system can be damaged by lightning. The primary cause is pitting caused by the arcing between the rolling elements and raceway at the breakdown points through the insulating lubrication layer present in a rotating bearing. If a bearing is stationary and loaded with some mass, then this weight is sufficient to press through the lubricant such that a direct contact between rolling elements and the raceway is made. No damage has been observed by many researchers, and the presumed welding is not found to be a dominant factor, if many rolling elements are, in parallel, in contact with the raceway.

Experiments with an electrostatic discharge gun on bearings showed that stationary bearings were conducting, and rotating unloaded bearings were not conducting due to the oil film, as
expected. However, rotating preloaded bearings were also conducting, which is against the conventional ideas that there is always a lubricating film present. The Stribeck curve shows that the transition from solid/boundary lubrication to fluid film lubrication occurs, depending on the dynamic viscosity and sliding speed and inverse to the load. Radar systems are using preloaded bearings to prevent wiggling and assure accurate tracking of objects. Various resistance measurements and lightning current tests have been carried out to determine the effect of preloaded bearings. The boundary lubrication is present if the bearing is sufficiently preloaded, which assures a continuous electrical contact between rolling elements and raceway and resistance measurements show values less than 1 mΩ. The lightning experiments performed show no increase of vibration, which is a measure of possible pitting. Endurance tests have been performed to ensure that even small pitting was not present. After the endurance test the bearing was dismantled and inspected visually. No damage was found, while a comparable normal bearing, without preloading, show considerable damage. The lack of damage for the preloaded bearing proves the validity of the preloading concept, to protect a bearing system against the risk of lightning damage.

Further research could be performed on the influence of lightning current amplitudes, including the extreme currents found in some regions in the world, on possible damage. Also the rela-

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**Fig. 7.** Results of vibration measurements during the endurance test with increased rotational speed. Note: the graphs have been shifted slightly to give a 3D impression. The scales should be read as if every line starts on the bottom-left corner.
tion between the various parameters in the Stribeck curve and the resulting resistance is an interesting topic for further research.

References