Method for the investigation of the EDM breakdown voltage of grease and oil on rolling bearings

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Abstract – Rolling bearing currents cause damage both to the bearing and to the lubricant contained therein. To prevent such damage, the influence of the lubricant in the bearing is becoming increasingly important. By analysing the discharge currents and the breakdown voltage in rolling bearings with lubricants of different composition, knowledge of the electrical behaviour of the system (bearing and lubrication) can be gained. In the context of this paper, a method for characterizing the breakdown voltage at the rolling bearing and results of investigated greases and oils are presented.

Keywords – EDM, breakdown voltage, bearing currents

1. Introduction

The use of frequency inverters to control variable-speed inverter-fed electric motors and generators causes damage to the rolling bearings as a result of bearing currents [1-6]. This problem has become even more significant in recent years with the increasing use of inverter-controlled electric motors in the automotive industry. As known current-related damages, the crater formation in the bearing raceway, the fluting across the raceway and the oxidation of the lubricant in the contact zone between the rolling element and raceway can be observed [7-10]. They can be seen in Figure 1. Investigations in recent years have shown that the lubricant used in the rolling contact and its electrical properties have a major influence on these damages caused by current passage. Depending on the composition and the electrical and rheological properties of the lubricant, different electrical effects can be observed in the bearing [8-10]. Currently there are no standards or prescribed test methods for the characterization of the electrical lubricant properties: relative permittivity, specific electrical conductivity and breakdown field strength for rolling bearing lubrication under realistic rolling bearing conditions of high pressure, high temperature and shearing [8]. There are standards for the investigation of the electrical lubricant properties only for transformer oils [11-13]. Investigations regarding the electrical lubricant properties were carried out in [14-21], and the breakdown properties of lubricants were examined in [21-24].

2. Aim of the paper

In the context of this paper, investigations of the damaging current passage in rolling bearings subjected to voltage for lubricating greases and oils of different composition are presented. The lubricants differ in their rheological and electrical properties. The focus is on the discharge currents, also called “Electric Discharge Machining” currents (EDM-currents). Interesting in this context is the occurrence of EDM-currents as a function of the conductivity of the lubricant used. In addition, this paper presents a method for the determination of the breakdown voltage of the lubricant in the rolling bearing contact under conditions of practical relevance.

Figure 1: Damages caused by bearing currents and bearing voltage: a) fluting, b) crater formation, c), d), e) grease degradation
3. Basics

3.1. EDM-breakdowns and EDM-currents

Depending on the insulating capacity of the lubricating film in the rolling bearing and the system capacities, bearing voltages occur. Figure 2 shows oscillograph measurements of bearing currents and bearing voltages.

An EDM-current occurs as soon as the voltage across the bearing exceeds the insulating capacity of the lubricating film. The sudden discharge occurs in the form of an arc between the bearing rings and the rolling elements. When conventional rolling bearing greases or oils are used, the insulating behaviour of the lubricating film depends on the lubricating film thickness and the breakdown field strength of the lubricant. The lubricant used in the bearing thus has a crucial influence on the occurrence of EDM-currents. The use of conductive lubricants is expected to prevent voltage build-up across the lubricating gap and thus prevent EDM flows [8], [19], [20]. Figure 2 shows typical electrical events during the application of voltage to a rolling bearing.

Figure 2 a) shows that the voltage can be built up completely over the lubricating film. The insulating properties of the lubricating film are not exceeded, in this way no EDM-breakdowns occur. Only non-critical recharging currents flow. A complete voltage build-up is only possible if the bearing runs in full lubrication condition.

Figure 2 b) shows the voltage and current characteristics when EDM-currents occur. If the insulating property of the lubricating film is exceeded, the voltage drops abruptly and a discharge current flows. The bearing runs in full lubrication condition. A reduction in the height of the lubricating film (e.g. due to a reduction in speed) or an increase in the bearing voltage lead to the fact that the breakdown field strength of the lubricating film is reached earlier, so that the probability of an EDM-breakdown increases.

If the bearing runs in mixed friction condition, metallic contact occurs between the rolling elements and the bearing rings. As a result, no voltage can be built up across the lubrication gap. Figure 2 c) shows this condition. Only voltage pulses and ohmic currents can be observed. With high bearing voltages, the event shown in Figure 2 c) also occurs at full lubrication in the bearing. By using conductive lubricants, it is also expected that no voltage will build up across the lubrication gap [7], [8], [19], [20]. The breakdown voltage of the lubricant can be determined by the generation of EDM-breakdowns in the bearing.

3.2. Investigated lubricants

In order to investigate the effects of insulating and conductive lubricating greases and oils on bearing voltage, lubricating greases with different base oils, thickeners and additives were investigated. G1 (grease 1) and O1 (oil 1) are two insulating lubricants. O1 is the base oil of grease G1. G2 has the same composition as G1. In addition, 10 % copper powder was added to increase the conductivity. O2 is an oil with medium conductivity. O3 and G3 are company products for which the composition is not known. O3 is the additive base oil of G3. It is known that O3 and G3 are conductive, and the conductivity is increased with the help of ionic liquids. The basic lubricant data of the investigated greases and oils can be found in Table 1.

Figure 2: Oscillograph measurements of bearing currents and bearing voltages: a) no EDM-breakdowns, recharging currents, b) EDM-breakdowns, c) no EDM-breakdowns, ohmic-currents
Table 1: Investigated lubricants

<table>
<thead>
<tr>
<th>Grease</th>
<th>Base oil viscosity at 40°C [mm²/s]</th>
<th>Base oil viscosity at 100°C [mm²/s]</th>
<th>Base oil</th>
<th>Thickener</th>
<th>Additive</th>
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</thead>
<tbody>
<tr>
<td>G1</td>
<td>105</td>
<td>11</td>
<td>mineral oil</td>
<td>lithium</td>
<td>no</td>
</tr>
<tr>
<td>G2</td>
<td>105</td>
<td>11</td>
<td>mineral oil</td>
<td>lithium</td>
<td>10% copper</td>
</tr>
<tr>
<td>G3</td>
<td>108</td>
<td>14</td>
<td>product</td>
<td>product</td>
<td>ionic liquid</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Oil</th>
<th>Base oil viscosity at 40°C [mm²/s]</th>
<th>Base oil viscosity at 100°C [mm²/s]</th>
<th>Base oil</th>
<th>Additive</th>
</tr>
</thead>
<tbody>
<tr>
<td>O1</td>
<td>105</td>
<td>11</td>
<td>mineral oil</td>
<td>-</td>
</tr>
<tr>
<td>O2</td>
<td>100</td>
<td>20</td>
<td>polyglycol</td>
<td>-</td>
</tr>
<tr>
<td>O3</td>
<td>108</td>
<td>14</td>
<td>product</td>
<td>-</td>
</tr>
</tbody>
</table>

3.3. Used test benches and test procedure

For the investigation of rolling bearing voltage and currents, several test rigs were developed and set up at the Institute of machine elements, gears and transmissions (MEGT) at the Technical University of Kaiserslautern, which allow the realistic reproduction of the electrical conditions in the rolling bearing of inverter-fed electric motors. The special feature of the experiments is that, in comparison to the real electric motor, the electrical and mechanical operating conditions can be varied independently of each other. The converter used was developed especially for these applications, more detailed information is given in [7] and [8].

The investigations for this study were carried out on an axial bearing test bench called “GESA - Device for extended lubricant analysis”. The GESA test cell can be seen in Figure 3. The test setup was developed and set up as part of the research project FVA 650 II “Methodology for the practical characterization of electrical lubricant properties to improve the computational prediction of bearing currents” at the Research Association for Drive Technology (FVA). GESA consists of a vertically arranged shaft equipped with a deep groove ball thrust bearing type 51208 (15 rolling elements) and it is driven by an electric motor. The test stand is characterised by quiet and low-vibration running, which ensures stable formation of a lubricating film in the rolling bearing. This is a requirement for characterizing the electrical properties of lubricants [10], [21].

Voltage and current flows at the rolling bearing can be measured under controlled and reproducible conditions (speed, load and temperature). The measurement and the control of the current flow and temperature are realized by a self-developed slip ring. Both the rotating shaft and the housing can be cooled with the help of water cooling. The impedance and the capacity of the lubricated bearing can be determined with this measuring setup, as well.

The test sequence for each of the six tested lubricants is the same and it is shown in Figure 4. In the first phase, the lubricant is pre-conditioned and the bearing runs in under constant load and speed for a period of 16 hours without applying voltage. In phase 2, a test voltage is applied to the bearing. The applied test voltage is varied from 1 V to 60 V under constant load, speed and a fixed switching frequency of the inverter. In the subsequent phases 3 and 4, the bearing temperature is increased from approx. 10 °C to 100 °C at constant load and speed. A constant test voltage is applied to the bearing in these phases (phase 3 with 5 V; phase 4 with 20 V). The bearing current and the bearing voltage are measured in regular temperature steps. The detailed test conditions of the individual phases can be found in Table 2.
Table 2: Test conditions for the GESA tests in 4 phases

<table>
<thead>
<tr>
<th>Phase</th>
<th>Speed $n$ / rpm</th>
<th>Load $F$ / N</th>
<th>Test voltage $U$ / V</th>
<th>Switching frequency $f$ / kHz</th>
<th>Temperature $\theta$ / °C</th>
<th>Duration $t$ / h</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1000</td>
<td>240</td>
<td>0</td>
<td>0</td>
<td>steady-state ca. 40</td>
<td>16</td>
</tr>
<tr>
<td>2</td>
<td>1000</td>
<td>200</td>
<td>1 - 60</td>
<td>10</td>
<td>steady-state ca. 40</td>
<td>0.5</td>
</tr>
<tr>
<td>3</td>
<td>1000</td>
<td>200</td>
<td>5</td>
<td>10</td>
<td>10-100</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>1000</td>
<td>200</td>
<td>20</td>
<td>10</td>
<td>10-100</td>
<td>2</td>
</tr>
</tbody>
</table>

4. Results of the investigations

At the beginning of the investigations, no information on the electrical properties of the lubricants was available. For this reason, the lubricants were measured on a cylinder capacitor. The results are shown in Figure 5.

A cylinder capacitor called EPSILON+ was used to determine the specific conductivity and relative permittivity of all lubricants as a function of the lubricant temperature. The results for the conductivity are shown in Figure 5 a) and for the permittivity in Figure 5 b). It is expected that the conductive lubricants G2, G3 and O3 should have the highest specific conductivities. However, the capacitor measurements show that O3 has the highest conductivity among the six lubricants. G2 shows a relatively low conductivity near to the result of G1, although copper particles have been mixed in G2. This can be explained by the fact that additives and particles dissolved in the grease only lead to a conductivity of the grease at small distance between the electrodes, as they occur in rolling contact, for example. In the cylinder condenser (distance 1 mm), these additives are encapsulated by the insulating base oil. For determining the electrical properties of rolling bearing lubricants, the measurements on the cylinder capacitor can therefore only be used to a limited extent.

4.1. Results from phase 1 of the GESA investigations

Phase 1 of the investigations is required for the preconditioning of the lubricants and for the running-in of the bearings. This step homogenizes the grease, allowing the subsequent tests to be carried out with the rheological and electrical properties of the grease as constant as possible [25]. The run-in of the bearing causes smoothing on the bearing raceways and on the rolling element surfaces. This is necessary because otherwise roughness peaks may come into contact at an early stage and a stable lubricating film build-up is not possible. Therefore measurements of the bearing impedance and the bearing currents and voltages have a lower informative value before this phase. At this stage, the viscosity ratio $\kappa$ is greater than 5 for all lubricants and tests.

Figure 6 a) and b) shows the impedance and phase angle measurements for system characterization. They are performed after preconditioning. The measurements are performed at a steady-state temperature of the bearings of approx. 40 °C, a speed of 1000 rpm and a load of 200 N. The system is characterized by a high degree of stability. A lower impedance of the conductive lubricants over a frequency spectrum can be expected compared to the insulating greases. The measured phase angle should remain at about 0° for the conductive greases over a frequency spectrum. It can be seen, that the impedance and phase angle are approximately the same for all investigated lubricants. As the frequency increases, the impedance decreases and the phase angle shifts in the direction of -90 °. The impedance measurement shows, that in this operating condition (bearing steady-state temperature) an insulating lubricating film separates the surfaces in the bearing for all investigated lubricants. This film can break through under an electrical charge.

Based on the impedance measurement, G1 is the best insulator. O3 should have the highest conductivity due to the low impedance values at low frequencies. Figure 5 a) shows that O3 has the highest conductivity. O1
and G1 are the lubricants that can insulate. G3 also has high conductivity, like O3. However, this cannot be detected by the impedance measurement. The copper particles from G2 have no significant influence on the bearing impedance. Probably the copper particles were pressed out of the raceway after the 16 h run. The bearing with G2 has a lower impedance than the bearing with G1. This can be an indication of the existing conductivity through copper particles.

Figure 6: Measurements of a) bearing impedance and b) phase angle after 16 hours preconditioning at approx. 40 °C at a speed of 1000 rpm, a load of 200 N

4.2. Results from phase 2 of the GESA investigations

In phase 2 of the GESA investigations, a test voltage is applied to this system. The inverter switching frequency is 10 kHz. The further conditions can be found in Table 2. The aim of the investigation is to determine the breakdown voltage of the lubricating film for all lubricants. For this purpose, the test voltage is gradually increased (1 V - 10 V with 0.1 V steps; 10 V - 60 V with 5 V steps). For the examined lubricants, a voltage range can be determined in which EDM-currents occur. Figure 7 shows the results from phase 2 of the investigation. For all lubricants, there is a complete build-up of voltage over the lubricating film in the low voltage range. EDM-currents also occur with all lubricants. The conductive lubricants G3 and O2 show improvements with regard to their electrical behaviour in the bearing. When the voltage is increased, no voltage is built up above the lubricating gap in any of the six lubricants tested. In this case ohmic currents flow. This effect already occurs with conductive lubricants G3 and O2 at lower voltages compared to G1, G2 and O3. G3 behaves best with regard to the electrical behaviour in the bearing. A complete voltage build-up is only possible up to approx. 12 V. EDM-currents of up to about 25 V then occur.

Figure 7: Results from phase 2 of the GESA tests. Measurements of EDM-voltage at voltage variation (1 - 60 V). Determination of electrical-tribological limits at approx. 40 °C at a speed of 1000 rpm, a load of 200 N and an inverter switching frequency of 10 kHz.

4.3. Results from phase 3 and 4 of the GESA investigations

In phase 2, the voltage build-up over the lubricating film was investigated as a function of the applied voltage level. In phases 3 and 4, the voltage build-up in the bearing as a function of the bearing temperature is examined more closely. The bearing is first cooled down to approx. 10 °C for this purpose. After reaching temperature of 10 °C, the operating conditions specified in Table 2 are set on the GESA. Increasing the bearing temperature results in a reduction of the base oil viscosity and thus also in a reduction of the lubricating film thickness. The investigations are completed after reaching 100 °C bearing temperature. During the increase in bearing temperature, bearing voltage and bearing current are measured in regular temperature steps (every 0.5 K). After evaluation of the recorded data, the temperature range in which EDM-currents occur can be specified. The ranges in which a complete voltage build-up is possible or ohmic currents flow are also defined. When EDM-currents occur, the number of detected currents per second and the level of the flowing EDM-current and the EDM-voltage are determined. The results from phase 2 have shown that the level of the applied bearing voltage has an influence on whether EDM-currents or ohmic-currents flow. Therefore, the investigations presented in this chapter are performed at both a low applied test voltage of 5 V (phase 3) and a higher applied test voltage of 20 V (phase 4). Figure 8 a) shows the average number of measured EDMs as a function of bearing temperature.
at an applied test voltage of 5 V and 20 V (see Figure 8 b)).

![Graph 1](image1)

**Figure 8**: Results of phase 3 and 4 of the GESA investigations on the average EDM number per second as a function of bearing temperature (10 °C – 100 °C) at a speed of 1000 rpm, a load of 200 N and an inverter switching frequency of 10 kHz a) Results for an applied test voltage of 5 V b) Results for an applied voltage of 20 V.

It can be clearly seen that at an applied test voltage of 5 V, the temperature range in which EDM-breakdowns occur is very large for all investigated lubricants. In the case of greases G1, G2, G3 and oils O1, O2, O3 EDM-breakdowns can be observed. This means that EDM-breakdowns can also occur with conductive lubricants. The temperature range, in which EDM-breakdowns take place, is wide.

At an applied test voltage of 20 V (Figure 8 b) there are differences to Figure 8 a). EDM-breakdowns increasingly occur for lubricants G1, G3 and O3 at lower bearing temperatures, where the lubricating film thickness is higher. Low number of EDM-breakdowns can be observed for G2, O1 and O2 at temperature about 10 °C.

The temperature range of the EDM-discharge currents is significantly lower. As the temperature rises, ohmic currents predominantly occur. With the conductive lubricants G2 and O2, EDM-discharge currents could only be detected sporadically at low bearing temperatures about 10 °C. With grease and oil only few voltage builds up across the lubricating film and EDM-breakdowns can be observed. Predominantly ohmic currents are detected.

In addition to the temperature ranges in which bearing currents occur, the frequency distribution of the EDM-currents and voltages are also helpful for further assessment. Figure 9 and Figure 10 therefore shows the maximum, minimum and mean EDM-voltages occurring at an applied test voltage of 5 V and 20 V for all investigated lubricants. The values are resulted as a mean value from all current and voltage measurements of phases 3 and 4. In addition, the frequency distribution of the average EDM-voltages is shown in Figure 11 and Figure 12. Figure 11 shows the frequency distribution at an applied voltage of 5 V and Figure 12 shows the frequency distribution at an applied voltage of 20 V for all investigated lubricants.

![Graph 2](image2)

**Figure 9**: Average values of the EDM-voltage averaged over all 900 measured values at GESA in phase 3 on the axial grooved ball bearing 51208 at an axial load of 200 N, speed of 1000 rpm, temperature variation from 10 °C to 100 °C, measurement of voltage after temperature change in 0.5 K steps, with applied voltage of 5 V and switching frequency of 10 kHz.

When considering the results from phase 3 of the GESA investigation (applied test voltage 5 V), differences between the conductive greases and the insulating greases can be seen. The mean EDM-voltages for all greases are just over 2 V. Depending on the conductivity, the mean, maximum and minimum EDM-breakdown voltage for conductive lubricants is lower. Based on the frequency distributions of the voltages occurring in phase 3 (Figure 11), there are no large deviations between conductive and insulating lubricants. EDM-breakdowns can occur with all lubricants, independent of their insulating or conductive properties.
The results from phase 4 of the tests (applied test voltage 20 V) clearly show the influence of the conductive lubricant with cooper particles on the occurrence of EDM-breakdowns. The mean and the maximum EDM-voltage measured for the greases G2 are significantly lower than for the other lubricants (Figure 10). Clear differences can also be seen between the frequency distribution of the measured mean EDM-voltage at 5 V (Figure 11) and at 20 V (Figure 12).

Conclusions from phase 3 and 4 of the investigation:

- The breakdown voltage, measured at the bearing, fluctuates strongly. This can be explained by the dynamics of the rotating bearing.

- In the case of insulating and conductive lubricants, EDM-breakdowns may occur. In the case of conductive lubricants, the breakdown occurs at a lower voltage.

- The influence of conductive lubricants at a low applied test voltage (5 V) is low. The mean and maximum EDM-voltage of conductive lubricants is lower compared to insulating lubricants, but the differences are low.

- The influence of conductive lubricants at a high applied test voltage (20 V) are clearly recognizable. Voltage build-up in the bearing is predominantly prevented, thus ohmic currents flow.

Figure 10: Average values of the EDM-voltage averaged over all 900 measured values at GESA in phase 3 on the axial grooved ball bearing 51208 at an axial load of 200 N, speed of 1000 rpm, temperature variation from 10 °C to 100 °C, measurement of voltage with temperature change in 0.5 K steps, with applied voltage of 20 V and switching frequency of 10 kHz.

Figure 11: Results of phase 3 of the GESA test at constant speed of 1000 rpm, load of 200 N and inverter switching frequency of 10 kHz. Frequency distribution of the average EDM-voltage at applied voltage of 5 V.
5. Conclusions
In the context of this article, results from investigations of conductive and insulating lubricants in rolling contact under test voltage application were examined. The focus was on the occurrence of EDM-currents and the electrical conditions in the rolling bearing. The axial bearing test rig “GESA” developed at the MEGT was used for this purpose. The tests on a cylindrical capacitor to determine the specific conductivity of the greases can only be used to a limited extent, as the distance between the capacitor electrodes is greater than the lubricating film thickness in rolling bearing contacts. When measuring the bearing impedance at bearing steady-state temperature, no significant differences between the conductive and insulating lubricants are discernible. If conductive lubricants are used, a lower bearing impedance can be measured. When applying voltage to the bearing, it was shown that with a lower test voltage at the bearing a complete voltage build-up across the lubricating film is possible for all tested greases and oils. EDM-currents can also be detected for all greases and oils. As the applied test voltage increases, clear differences in the electrical behaviour of the conductive greases compared to the other greases can be detected. Tests with an applied test voltage of 20 V show that the conductive greases already prevent a build-up of voltage at higher lubricating films in the case of higher and lower bearing temperatures. Mostly ohmic currents flow, which are comparable to currents occurring in mixed friction operation conditions. The results, presented in this paper, show that the use of conductive lubricants has an influence on the electrical conditions in the rolling contact.
It must also be examined which electric effects have influence regarding the bearing damages presented in the introduction. For this purpose, it is recommended to carry out long-term tests with conductive grease in the rolling contact. This also allows to investigate the long-term effect of the conductivity.
In the context of this paper, a method for the investigation and comparison of the EDM-breakdown voltage of lubricants for rolling bearings was presented. The method can be used to investigate insulating and conductive greases and oils. The lubricants were tested on thrust ball bearing 51208 under test conditions close to the conditions of electrical motors and gears. EDM-breakdowns were generated in the bearing by the application of test voltage. After automated detection of these EDM-breakdowns, the breakdown voltage was analysed and compared. With the developed method greases and oils were investigated and evaluated.

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References


References