Modelling of impulse currents in mechanical rolling element bearings

Hendrik Kolbe and Annette Muetze
Electric Drives and Machines Institute, Graz University of Technology, Graz, Austria, and

Kay Hameyer
Institute of Electrical Machines, RWTH Aachen University, Aachen, Germany

Abstract

Purpose – The purpose of this paper is to contribute toward the modelling of the microscopic interaction between high-frequency discharge bearing currents and rolling element bearings in the contact zone. It also aims to develop a reduced model that can serve as a starting point for further developments.

Design/methodology/approach – The complexity of an ideal comprehensive model is identified and analysed. Based thereon, a reduced model is developed.

Findings – The true system is highly complex and cannot be solved in a single-step approach. The proposed reduced model allows the explanation of the melting of the bearing surfaces under the influence of the high-frequency currents. It also provides a starting point for the development of an extended model.

Research limitations/implications – The model excludes the dynamic rolling movement of the bearing. The development of the frosting and fluting observed on the bearing running surfaces can only be explained in parts.

Practical implications – The melting of the bearing race surface can be modelled and thereby explained. The proposed model forms a good basis for further work toward an extended model to explain the high-frequency bearing current bearing damage mechanism.

Originality/value – The paper offers a method to model the microscopic interaction between high-frequency discharge bearing currents and rolling element bearings in the contact zone. This phenomenon has not yet been modelled to this extent. Such a model – and the understanding brought forth from it – allows the reduction in the cost for safe operation of modern variable speed drive systems.

Keywords Electrical machines, Numerical models, Multi-physical problem, Machine tools, Numerical control, Modelling

Paper type Research paper

1. Motivation

Modern drive technology has brought a wide variety of inverter operated machines. Depending on the application and hence the design, the drives can have excellent control and variable speed performance, and can potentially offer significant energy savings when compared to conventional systems. As is frequently the case, developments that lead to such significant improvements on some aspects, also have their drawbacks. One of the parasitic phenomena that the change of drive technology has given rise to are high-frequency (HF) inverter induced bearing currents (IIBCs) that can significantly

COMPEL: The International Journal for Computation and Mathematics in Electrical and Electronic Engineering
Vol. 31 No. 6, 2012
pp. 1575-1589

0332-1649
DOI 10.1108/03321641211267001

damage the bearings. These currents originate from the HF common-mode voltage of the inverter and are fundamentally different in nature than the low-frequency bearing currents that have been known for decades (Kohaut, 1948; Boyd and Kaufman, 1959; Ammann *et al.*, 1988). Today, the underlying principles of IIBCs are mostly well understood. Appropriate modelling tools have been developed and mitigation techniques identified (Chen *et al.*, 1996; Busse *et al.*, 1997a; Link, 1999; Boyanton and Hodges, 2002; Muetze, 2004; Schiferl and Melfi, 2004). However, there has been no satisfactory explanation of the current flow and damage mechanism inside the bearing. This gap of knowledge may lead to the sizing of mitigation techniques mainly based on engineering experience and likely including a costly oversizing, given the ultimate cost of drive failures.

Explanations given for the damage mechanism of low-frequency bearing currents have shown to be not satisfactory (Muetze *et al.*, 2006). Confirming this statement, the difference between the damages induced to bearings by low- and HF bearing currents has been proven experimentally (Zika *et al.*, 2009). In contrast to the low-frequency bearing currents, HF IIBCs do not flow continuously, but as HF current pulses. The lack of a satisfactory answer about the degree of current load a bearing might possibly be able to withstand results in costly failures of modern variable-speed drive systems on the one, and costly application of oversized mitigation techniques on the other side.

Understanding the damage mechanism inside the bearing is closely related to the understanding of the interaction between the bearing material and the HF current at a microscopic level. The modelling of this interface and the mechanisms that take place results in a highly complex multi-physical problem. Because of this complexity, the problem needs to be broken down into smaller underlying questions that can be solved in individual steps. In this context, the development of appropriate modelling techniques that apply existing techniques in a novel way and support experimental approaches are a great asset. No comprehensive study of this complexity and the numerous aspects that would need to be considered in an ideal, comprehensive model has been undertaken so far. To complicate matters further, for many of the system parameters that are expected to be of influence reliable data are lacking. This contribution tries to fill this gap by:

- Systematically identifying and analysing the different aspects that would need to be considered in an ideal, comprehensive model.
- Developing a reduced model through application of existing techniques in a novel way.
- Presenting a first set of results that allows to explain the melting of the bearing surfaces under the influence of the HF currents.

Thereby, it shall serve as a starting point for development of an extended model to further understand the bearing damage mechanism and ultimately reduce the associated cost of operation of modern variable-speed drives.

2. Modelling challenge

The system, which consists of the bearing running surface, rolling element, and current, is a highly complex and multi-physical system: considering first only static behaviour, an ideal comprehensive model would already comprise (at least):

(1) the deformation of the solid bodies in the contact zone;
(2) the lubrication film developed therein;
(3) the current path;
(4) the conduction mechanism inside the bearing; and
(5) how this affects the bearing:
    - locally (e.g. local heating); and
    - globally (e.g. increased wear).

These aims would require a mechanical analysis coupled with an electrothermal investigation. To complicate matters further, ideally, the movement of the different rolling elements and the formation of the lubricating film would be described by a dynamic approach. Such a model has not been developed before and there are still significant gaps of knowledge on the contribution of the different listed aspects towards the observed overall damage mechanism.

Given the current limited knowledge on the parameters that might be important and their interaction, such a model would be too complex to be solved in a single step and without prior identification of underlying individual smaller problems. Therefore, the problem needs to be broken down into smaller subproblems for which individual submodels can be developed. Today, the existing bearing submodels only describe the mechanical aspects. However, in order to properly model and understand the bearing damage mechanism due to IIBCs, submodels that include other aspects, such as for example the energy dissipated during the electric breakdown of the lubricant and the electrothermal interaction at the interface, are highly needed. From this need, the objective of the modelling approach presented in this paper derives.

We present a method to model the microscopic interaction between the IIBCs and the rolling element bearings in the contact zone, using commercially existing software. To this aim, we first identify the various aspects that might require consideration and that would be part of an all-inclusive comprehensive model. Based thereon, a reduced model is proposed. As part of this selection process, focus is placed on discharge bearing currents. The choices made regarding the selection of the parameters as well as the assignment of values to the different parameters are justified by the identified physical relationships. Furthermore, a first set of results is obtained. It already leads to an improved understanding of the phenomena taking place in the local contact zone and allows to explain the melting of the bearing surfaces under the influence of the HF discharge currents at microscopic level. This model and the systematic analysis shall serve as a starting point for the development of an extended model to further understand the bearing damage mechanism and ultimately reduce the associated cost of operation of modern variable-speed drives.

3. Discussion of various contributing factors

3.1 Hertzian contact theory

Under the mechanical load of the motor, the bearings are subject to deformation, notably in the contact zone of the rolling elements and the race and where these are carrying most of the mechanical load. The local current flow in the contact zone and hence the interaction between this current and the bearing material will depend on the local geometry. Therefore, the extent to which such deformation has to be considered in the analysis of the damage mechanism has to be researched. Hertz has proposed an analytic method to predict the contact area – expressed by the contact length $2a$ – and pressure – quantified by the maximum contact pressure p_0 – between two bodies due to deformation (Hertz, 1881; Brändlein *et al.*, 1998; Williams, 1994). Prerequisites are homogeneous, isotropic materials and mere elastic behavior, and that the contact area is even and small compared with the radii of the bodies.

In the context of IIBCs, the notion of the "apparent bearing current density" J_b has been introduced, that is the quotient of the peak amplitude of the bearing current and the Hertzian contact area due to the (elastic) deformation under the contact pressure. Generally, where a threshold is required, it is assumed that apparent current densities below 0.1 A/mm^2 will not put the bearing at risk. This value is mainly based on experience and lacks a complete scientific understanding. Recently, experimental results attributing the occurrence of fluting (considered as putting the bearing at risk) as opposed to a grey race to reduced load have been presented (Tischmacher and Gattermann, 2010) (radial force), (Magdun *et al.*, 2010) (axial force). It has also been shown that the bearing ages proportionally with the product of apparent current density, switching frequency, and time of operation (Muetze *et al.*, 2006). This indicates that both the magnitude and the number of discharges contribute to the bearing degradation. Summarising, the Hertzian contact area is likely to play an important role in the understanding of the damage mechanism. However, the way it requires consideration in an analysis of the latter still needs to be researched.

3.2 Elasto-hydrodynamic lubrication

Bearings need to be provided with adequate lubrication to prevent unacceptable friction and to allow only negligible wear. The interaction between solids and liquids is a computationally intensive and difficult task. The underlying reasons for the formation of the lubricating film differ significantly from hydrostatic effects, requiring the theory of fluid dynamics having been taken into account, which would eventually lead to a dynamic model. The lubrication regime is referred to as "elasto-hydrodynamic lubrication". It has three main contributing effects:

(1) formation of a hydrodynamic film;

(2) modification of the film geometry by the elastic deformation of the bodies; and

(3) high increase (several decades) of the viscosity of the lubricant under pressure.

The fact that viscous liquid can separate two sliding surfaces by hydrodynamic pressure is proved analytically by the Reynolds equation. However, the viscosity of the lubricant increases under the pressure of the contact (described by the so-called "Roelands" or "Barus" equation). Important contributions toward the modelling of this phenomena – and that are widely used in mechanical engineering today – have been made by Grubin (Williams, 1994; Hamrock and Dowson 1981).

An electric breakdown is evidently likely to occur where the film is minimal, at the film thickness h_0. This fact will be taken advantage of in the simplified model presented below. To complicate matters, the lubricating film is compressible, which introduces another factor of variability into an ideal model.

3.3 Surface roughness

The rolling element and bearing race surface have a certain surface roughness that can have the same order of magnitude as the lubricating film thickness. It is generally understood that the asperities are flattened within the first minutes and hours of operation so that elasto-hydrodynamic lubrication can be established. Nevertheless, some form of surface roughness will exist that has to be kept in mind as the current conduction mechanism is understood. For completion it shall be mentioned that the mechanism by which asperities are prevented from contacting each other is called micro-elasto-hydrodynamic lubrication. This rather difficult phenomenon is still a research topic, and a standard model for this lubrication regime has not been developed yet (Stachowiak and Batchelor, 2005).

3.4 Thermal effects

The thermal effects related to the phenomena eventually concern different parameters and elements of the model. The respective importance of these toward the damage mechanism has not been fully understood yet. On the one hand, the bearing temperature is determined by the losses of the machine (mainly copper and core loss) and the ambient temperature. The different surface areas and available cooling channels lead to a temperature difference between the inner and outer ring which, according to Brändlein *et al.* (1998), does not exceed 20 K. On the other hand, local effects in the contact zone, where the friction energy is transferred into heat, can lead to significant local temperature rises. When the lubrication is sufficient, the short local temperature rises are small, but thin lubricating films can cause temperature differences of up to 60 K between the centre (where heat is generated at the greatest rate) and the outer bounds of the elasto-hydrodynamic film (Stachowiak and Batchelor, 2005). This can significantly alter the viscosity of the lubricant and hence the thickness of the lubricating film. Any current flow through the bearing will cause additional heating. The high local temperature rises that can even lead to lubricant failure are in the focus of the proposed first generation model, as will be justified below.

4. Proposed simplified model

4.1 Overview and justification

The above paragraph has shown that a local description of the effects inside the bearings is far more complicated than the global understanding of the effects that is already available. To complicate matters further:

- Some of the phenomena that would need to be included in a comprehensive model are not fully understood yet, such as the micro-elasto-hydrodynamic lubrication or the exact breakdown mechanism of the lubricating film.
- Reliable data on the parameters that might be considered are often lacking.

The analysis provided in the preceding sections has shown the significant importance of the temperature on all the other parameters and factors of influence. Given the very different times of duration of the phenomena listed in the previous section, a static mechanical analysis in which the local transient electrothermal aspects are analysed has to precede a transient mechanical analysis: with the rotational speed and diameters of the rolling elements and of the running surfaces of bearings typically suffering from discharge bearing currents, the relative speed between a rolling element and the running surface is in the order of several meters per second (approximately 5 m/s for the example case bearing of Section 5). The relative distance travelled by the rolling element during the time of discharge of approximately 1 ns (see below, Section 4.3), is therefore in the order of a few nanometers (approximately 5 nm for the example case bearing). This is almost two orders of magnitude larger than the width of the discharge channel of the current pulse (77 times in case of the example discussed in Section 5).

In the proposed first generation model, the complexity of the system is reduced to a 2D static mechanical model in which:

- The dynamic rolling movement is neglected.
- The local transient electrothermal aspects are analysed.
- Many of the remaining other aspects (such as the influence of the load) are considered implicitly.

The contact – and notably the elasto-hydrodynamic lubrication film – is therefore represented as follows:

- Under the high pressure of the load, and at the microscopic level, the mechanical properties of the elasto-hydrodynamic film resemble those of a solid body, i.e. the film separates the two bodies from each other.
- The electric and thermal properties of the film are derived from literature presented in neighbouring fields (Larsson and Andersson, 2000; Chiou *et al.*, 1999).
- The surface roughness is not modelled explicitly. Its dimensions are in the order of several μm (Stachowiak and Batchelor, 2005) what it is close to an order of magnitude larger than the local breakdown phenomenon as modelled. It is considered implicitly by the assumption of the breakdown taking place at the minimum film thickness.
- The Hertzian contact area is not modelled explicitly. Focus is placed on the representation of the much (at least three orders of magnitude, see Section 6.1) smaller minimum thickness of the lubricating film, where the electric field strength reaches its maximum and the breakdown is most likely to occur.
- All external surfaces of the model are considered to be thermally insulating. This is derived from the assumption that no global temperature rise occurs during the short current pulse. This assumption has been verified in preliminary computations. It can also be understood from the thermal mass of the bearing material when compared to the heat source (Figures 2 and 3(a)).

Focus is placed on the size of the observed craters and measured voltages across the bearings that is converted into bearing current densities, as described below (Section 4.3).

As a result, an order of magnitude of the local temperature rise on the microscopic level is obtained. The proposed reduced model thereby allows to explain the melting of the bearing surfaces under the influence of the HF currents. It also provides a starting point for the development of an extended model and helps to identify aspects where further research is needed.

4.2 Bearing ball and race representation

The motors that suffer from bearing damage due to IIBCs are typically equipped with ball bearings. Extending the geometry into the third dimension would add additional complexity to the problem. A 2D static mechanical model that assumes constant behavior into the third dimension is used as a starting point. Because of the similarity of the cross sectional area, a cylindrical rolling bearing can be chosen as example case instead of a ball bearing.

Only one roller and the bearing race are modelled, and the load is applied as a point load (Figure 1). Analysis of damaged bearings has shown traces of current flow throughout the whole contact zone, i.e. over approximately a 60-90° pitch of the circumference. However, the simplification of the single roller model is justified by the current understanding that a breakdown would most probably occur in the contact area with the highest pressure distribution, i.e. the smallest film thickness.

The electrothermal analysis is preceded by a static mechanical analysis as a proof that the contact has been defined correctly for the purpose of the model, i.e. confirming the orders of magnitudes of the Hertzian contact area and the pressure at the contact zone that will influence the properties of the lubricant. Then, the two bodies are moved apart and a third body simulating the film is placed in between (Figure 2).

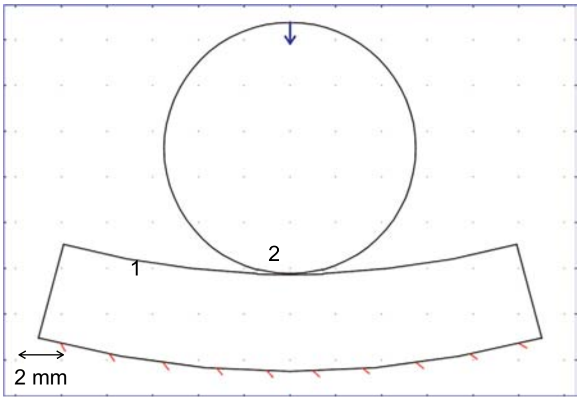


Figure 1.
Model with fixed race and applied point load

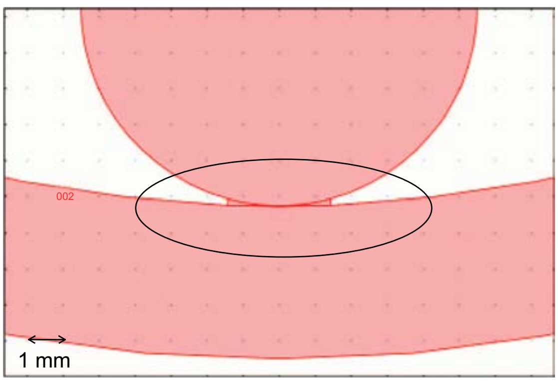


Figure 2.
Model with lubricant for electrothermal analysis

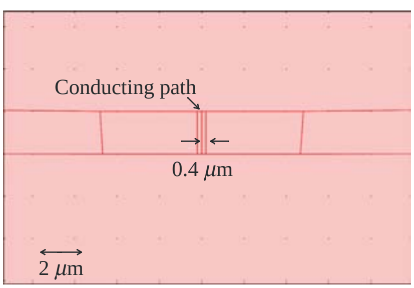
4.3 Lubrication film and breakdown path

The minimum thickness of the lubrication that occurs only over a short width is considered the most important aspect for the breakdown. Drawing from this understanding, only this part of the contact zone is modelled. The meshing parameters are adjusted through the introduction of sub-domains. The two smallest of these sub-domains, in the middle of the model, are assigned electrically conducting properties (Figure 3).

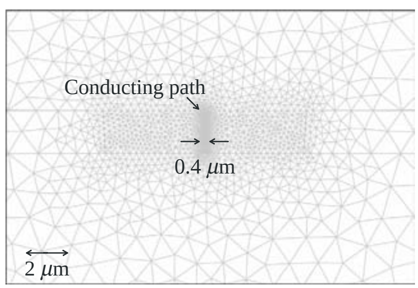
The current channel is given the same depth as its width and a current pulse is introduced with the help of a voltage source. This current pulse is taken as the simplified representation of a discharge bearing current that occurs when the common-mode voltage that has built up across the bearing through capacitive coupling breaks down. The current flow of the discharge current of 1 ns is modelled using two smoothed Heaviside functions (with a rise time of 0.2 ns, hence the current flow is actually 1.2 ns). This discharge time has been extrapolated from measured discharge currents, considering influence of the measurement technique on the latter. As outlined above, it has not yet been possible to directly measure the breakdown and the mechanism itself has not been fully understood. The current pulse serves thus as heat source in the transient thermal model that is implemented using a commercial software, and some of the aspects of a more extensive model are considered implicitly through the choice of the values of the parameters.

5. Example case bearing

A NUP209E.TVP2 cylinder rolling bearing is taken as an example case. It has equivalent dimensions to the 6209 ball bearings that are typically used with small machines of a few kilowatts rated power. The radii of the 15 rollers are 5.5 mm and the diameters of the inner and outer race surfaces are 54.5 and 76.5 mm, respectively. The rollers are 12 mm in length, the Young's modulus of the roller and race material is 200×10^9 Pa, and the Poisson's ratio of the material is 0.33. The minimum thickness of the lubrication film is set to 2 μm (derived from literature such as (Busse *et al.* 1997b, Prashad 1987 and Stachowiak and Batchelor 2005)) implemented with ten sub-domains. The current channel has an area of $0.4 \times 0.4\ \mu m^2$ (derived from literature on measured crater diameters (Muetze *et al.*, 2006)). The material properties of the metal bodies and the lubricant are summarised in Table I. With the lack of reliable data on certain parameters of influence, average values were chosen for the temperature range for



(a) Sub-domains within the lubricating film



(b) Mesh

Figure 3.
Close-up view of the model of the conducting path in the lubricating film

which information was available. Note that analysis of the influence of the temperature variation during the current impulse exceeds the limits of this first generation model. The results obtained emphasize the need for further research on modelling techniques that allow to further study the recursive effect of the temperature on the local phenomena.

6. Results

6.1 Static mechanical analysis

As described in Section 4.2, the electrothermal analysis is preceded by a static mechanical analysis. In this preliminary study, the Hertzian contact area A_H and pressure p_0 are determined both analytically and numerically, taking a load of 500 Nm for the single roller. Both results are in agreement, with $A_H = 1.32\,mm^2$ (contact width 0.11 mm) and $p_0 = 481$ and 520 MPa for the analytic and numerical solution (Figure 4). The results also confirm that the Hertzian contact area is much larger than the minimum thickness of the lubrication film and justify its implicit consideration in the proposed first generation model (Figure 3).

In addition, the von Mises stress is evaluated (Figure 5), which is an equivalent tensile stress computed from the stress tensor. Its maximum value is 294 MPa, which is only about 20 per cent of the yield strength of a typical bearing steel (AISI 52100, 1,400 MPa (Guo and Liu, 2002)). The assumption that no plastic deformation occurs is therefore justified.

		Metal bodies	Lubricant
Thermal conductivity	(W/(m K))	44.5	0.2
Specific heat capacity	(J/(kg K))	475	2,000
Density	(kg/m^3)	7,850	860
Electrical conductivity	(S/m)	4×10^6	1×10^{-11} (Breakdown: 1×10^7)

Table I. Material properties of the metal bodies and the lubricant

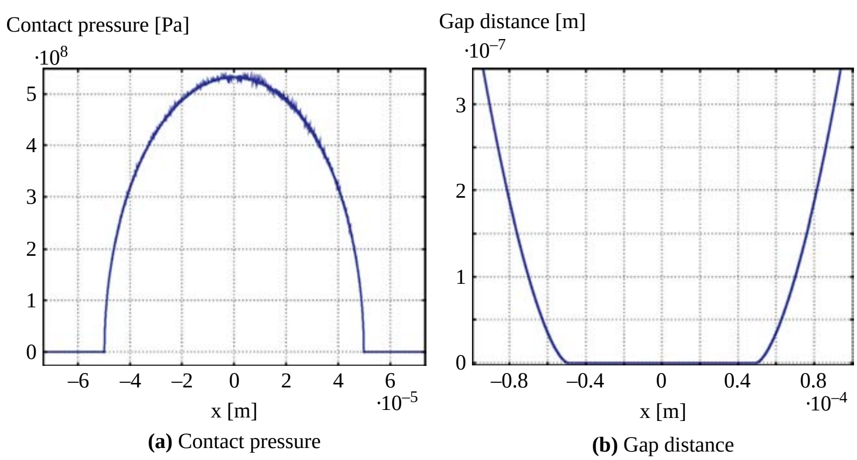
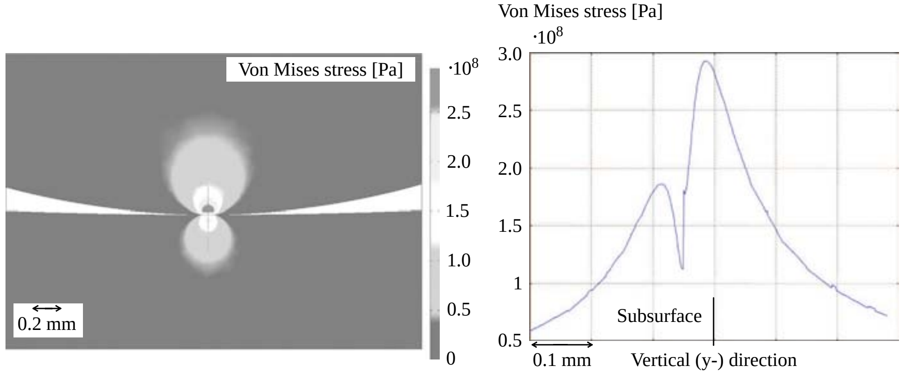


Figure 4. Finite element solutions for elastic deformation in the contact zone



(a) Close up view, line indicates cross sectional plot **(b)** Cross sectional plot

Figure 5.
Finite element solutions for von Mises stress in the contact zone

Note that the simulation also confirms that classical fatigue is initiated below the surface first (Brändlein *et al.*, 1998), where the maximum von Mises stress occurs.

6.2 Electro-thermal model

With the contact defined correctly, the two bodies are moved apart and a third body simulating the film is placed in between to further develop the electro-thermal model (Section 4.2). The initial temperature is set to 80°C, what is a typical temperature for bearings under normal operating conditions. The current flow of the discharge current is modelled as described above (Section 4.3). The applied voltage is 8 V, hence the maximum electric field strength is $8\,\mathrm{V}/0.2\,\mu\mathrm{m} = 40 \times 10^6\,\mathrm{V/m} = 40\,\mathrm{kV/mm}$. This is above the commonly cited strength of the lubricant under HF conditions of 15 kV/mm (Busse *et al.*, 1997b), and hence in line with operating conditions that would likely lead to a breakdown of the lubrication film and discharge bearing current. The field strength evidently decreases significantly with the increase of the lubricating film thickness away from the centre and is nonexistent within the metal bodies (Figure 6).

With the chosen values of the different parameters, the local average current density is $1.56\,\mathrm{A}/(0.16 \times 10^{-6})\,\mathrm{mm}^2 = 9.777 \times 10^6\,\mathrm{A/mm}^2$. This corresponds to an apparent current density of $1.21\,\mathrm{A/mm}^2$. This is well within the range of values commonly

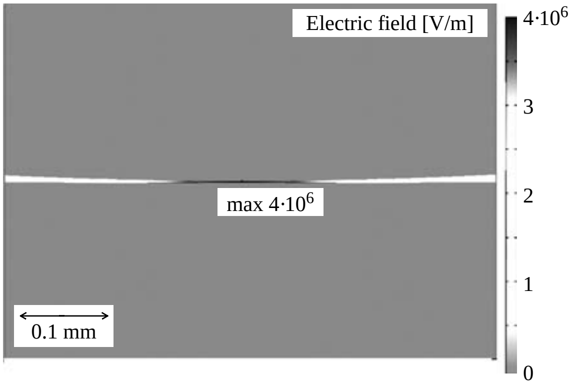


Figure 6.
Numerically computed electric field prior to breakdown (close-up view)

considered dangerous to the bearing. As a result, results of the first generation model that indicate damage to the bearing are in line with observations made in the field and the aspects and points defined as crucial to the mechanism will be at the starting point of the next generation model.

Figures 7 and 8 show the temperature at different points within the contact zone and how they evolve over time (Figure 7: close-up view of the breakdown path with the labels of the points then evaluated in Figure 8). Additional results showing the temperature distribution in the contact zone (upper half) and its evolution over time are given in the Appendix (Figure A1(a)-(f)). Three regions can be distinguished:

(1) First, hot spots develop at the edges of the conducting channel, where the current density is highest. As the current pulse occurs, the heat builds up almost instantaneously. Already after only 0.2 ns of current flow, these have reached temperatures of 2,900 K, and 1,000 K within the conducting path.

(2) Then, the heat builds up further within the conducting path, since the thermal conductivity of the lubricant is very low compared to the one of the metal bodies. Some points experience temperature rises of a few hundred Kelvin, but very high temperature rises over 4,000 K occur as well, all within 1 ns.

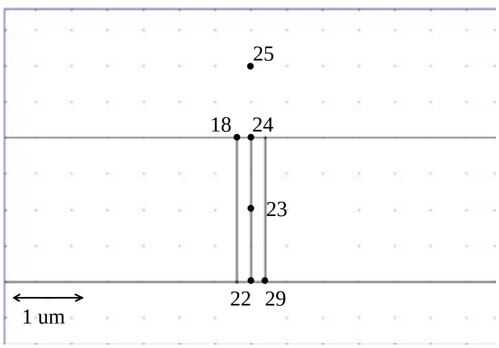
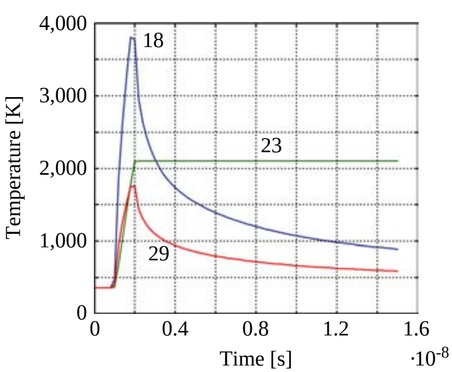
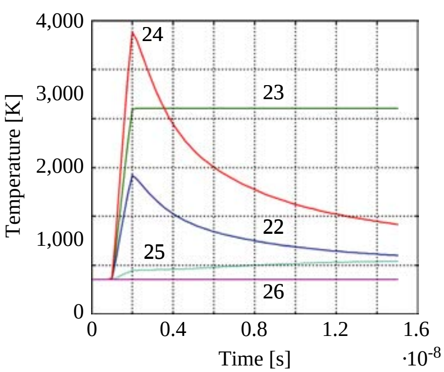


Figure 7. Labels of points shown in Figure 8



(a) At different diagonally distributed points in breakdown path



(b) Within conducting channel (pts 22, 23, and 24), and 1 μm (pt 25) and 10 μm (pt 26) underneath the metal surface

Figure 8. Temperature distribution over time within breakdown path (film) and underneath the metal surface, finite element solution

(3) This is followed by a slower cooling down time. Because of the relatively low thermal conductivity and high specific heat capacity, the film cools down very slowly.

The stored energy in the bearing before breakdown is estimated from $W = 1/2\, C_b V^2 \approx (1/2)\ 0.2 \times 10^9\ \mathrm{F} \times 8^2 \mathrm{V}^2 = 8\ \mathrm{nJ}$, with the bearing capacitance $C_b \approx 250\ \mathrm{pF}$ approximated from (Busse *et al.* 1997b). The energy required for melting and for vaporisation of the material of a crater with 0.5 μm diameter would be $W_{mel} = 2.2 \times 10^{10} \times (0.25\ \mu\mathrm{m})^3 = 0.34\ \mathrm{nJ}$ and $W_{vap} = 14.3 \times 10^{10} \times (0.25\ \mu\mathrm{m})^3 = 2.23\ \mathrm{nJ}$, which is smaller than the energy stored in the bearing capacitance before the breakdown.

Regarding the bearing damage mechanism, three statements can be made:

(1) The peak temperatures in the breakdown path at the interface between the lubricating film and the solid bodies reach or exceed – sometimes significantly – the melting point of the bearing material, which depends on the alloy and is in the order of 1,700-1,800 K.

(2) The temperature in the bearing material increases during a relatively long time after the breakdown has occurred, making it more susceptible to local deformation under the dynamic rolling movement.

(3) The energy stored in the bearing before breakdown is larger than the one required to vaporize the material of a crater of 0.5 μm diameter, providing enough energy to melt the material around the crater and below the surface, making it susceptible to deformation of the material structure, and to lead to a change of the chemical composition of the grease that has been proven experimentally in (Muetze *et al.* 2006).

7. Further work

The simplified model has illustrated the large heat developed in local hot spots by a discharge current that flows through a small conducting path. It has also been used to analyse the heat distribution over time within the path and the surrounding area. More work is required to better understand the interaction of this heat with the bearing material what will eventually give further insight into the bearing damage mechanism. Advanced understanding of the current breakdown and conduction mechanisms that are possibly initiated from local field emission effects will improve the modelling of the local current distribution. Analysis of the influence of additional aspects, such as the change of the material properties under the influence of the heat, pressure, and ideally the dynamic rolling movement will also provide better understanding of the bearing material current interaction. This will also include research on the state of the lubricant during the electrical breakdown, under high pressure and high temperature, and how this changes the lubrication mechanisms. Such analysis requires both the development of appropriate advanced modelling tools and models and of experimental approaches that allow to selectively verify the different aspects within reasonable costs.

8. Conclusions

While appropriate modelling tools have been developed to predict the occurrence of IIBCs, there has been no satisfactory answer about the level of current load and its characteristics a bearing might possibly be able to withstand. Given the high cost involved with occurring bearing failure or application of oversized mitigation techniques, there is a high need to better understand the interaction between the HF bearing currents and surfaces of the rolling element bearings at the microscopic level.

This system is highly complex and multidisciplinary, comprising electro-thermal, mechanical and fluid-structural aspects. Some of the phenomena that would need to be included in a comprehensive model are not fully understood yet. Furthermore, reliable data on the parameters that might be considered are often lacking. The different aspects that would need to be considered in an ideal, comprehensive model were systematically identified and their roles analysed. Based thereon, a simplified electro-thermal model was identified as the starting point for the development of a model to analyse the damage mechanism. This approach was chosen because of the significant importance of the temperature on all the other parameters and factors of influence.

Such a model was implemented and a transient electro-thermal analysis of the current pulse and local heat effect carried out. It allows to explain the melting of the bearing surfaces under the influence of the HF discharge currents and provides a starting point for further work. Since the ultimate aim of such work is to correlate the current flow and the induced damages, it will be essential to link the electro-thermal analysis with a mechanical analysis, keeping in mind that the lubricant is a very difficult part to model, and that the properties of the different materials of the contact zone are both temperature- and load-dependent.

References

Ammann, C., Reichert, K., Joho, R. and Posedel, Z. (1988), "Shaft voltages in generators with static excitation systems – problems and solutions", *IEEE Trans. En. Conv.*, Vol. 3 No. 2, pp. 409-19.

Boyanton, H.E. and Hodges, G. (2002), "Bearing fluting", *IEEE Ind. Appl. Mag.*, Vol. 8 No. 5, pp. 53-7.

Boyd, J. and Kaufman, H.N. (1959), "The causes and the control of electrical currents in bearings", *J. Soc. Lubr. Eng.*, Vol. 15, pp. 28-34.

Brändlein, J., Eschmann, P., Hasbargen, L. and Weigand, K. (1998), *Die Wälzlagerpraxis*, Vereinte Fachverlage GmbH, Mainz.

Busse, D., Erdman, J., Kerkman, R. and Schlegel, D. (1997a), "Bearing currents and their relationship to PWM drives", *IEEE Trans. Power. Electron.*, Vol. 12 No. 2, pp. 243-52.

Busse, D., Erdman, J., Kerkman, R., Schlegel, D. and Skibinski, G. (1997b), "The effects of PWM voltage source inverters on the mechanical performance of rolling bearings", *IEEE Trans. Ind. Appl.*, Vol. 33 No. 2, pp. 567-76.

Chen, S., Lipo, T.A. and Fitzgerald, D. (1996), "Modeling of bearing currents in inverter drives", *IEEE Trans. Ind. Appl.*, Vol. 32 No. 6, pp. 1365-70.

Chiou, Y.-C., Lee, R.-T. and Lin, C.-M. (1999), "Formation criterion and mechanism of electrical pitting on the lubricated surface under AC electric field", *Wear*, Vol. 236 Nos 1/2, pp. 62-72.

Guo, Y.B. and Liu, C.R. (2002), "Mechanical properties of hardened AISI 52100 steel in hard machining processes", *J. Manuf. Sci. and Eng.*, Vol. 124 No. 1, pp. 1-9.

Hamrock, B.J. and Dowson, D. (1981), *Ball Bearing Lubrication: Elastohydrodynamics of Elliptical Contacts*, Wiley, New York, NY.

Hertz, H. (1881), "Über die Berührung fester elastischer Körper", *J. für die reine und angewandte Mathematik*, Vol. 92, pp. 156-71.

Kohaut, A. (1948), "Riffelbildung in Wälzlagern infolge elektrischer Korrosion", *Z. Angew. Phys.*, Vol. 1 No. 5, pp. 197-211.

Larsson, R. and Andersson, O. (2000), "Lubricant thermal conductivity and heat capacity under high pressure", *J. Engineering Tribology*, Vol. 214 No. 4, pp. 337-42.

Link, P. (1999), "Minimizing electric bearing currents in ASD systems", *IEEE Ind. Appl. Mag.*, Vol. 5 No. 4, pp. 55-66.

Magdun, O., Gemeinder, Y. and Binder, A. (2010), "Investigation of influence of bearing load and bearing temperature on EDM bearing currents", *Proc. 2nd IEEE Energy Conv. Conf. & Exhib. (ECCE)*, pp. 2733-8.

Muetze, A. (2004), "Bearing currents in inverter-fed AC motors", PhD thesis, University of Technology Darmstadt, Shaker Verlag, Aachen.

Muetze, A., Binder, A., Vogel, H. and Hering, J. (2006), "What can bearings bear?", *IEEE Ind. Appl. Mag.*, Vol. 12 No. 6, pp. 57-64.

Prashad, H. (1987), "Effect of operating parameters on the threshold voltages and impedance response of non-insulated rolling element bearings under the action of electrical fields", *Wear*, Vol. 117 No. 2, pp. 223-40.

Schiferl, R.F. and Melfi, M.J. (2004), "Bearing current remediation options", *IEEE Ind. Appl. Mag.*, Vol. 10 No. 4, pp. 40-50.

Stachowiak, G.W. and Batchelor, A.W. (2005), *Engineering Tribology*, Elsevier, Amsterdam.

Tischmacher, H. and Gattermann, S. (2010), "Bearing currents in converter operation", *Proc. 14th Int. Conf. El. Machines* (*ICEM*), 6p.

Williams, J.A. (1994), *Engineering Tribology*, Oxford University Press, Oxford.

Zika, T., Gebeshuber, I.C., Buschbeck, F., Preisinger, G. and Gröschl, M. (2009), "Surface analysis on rolling bearings after exposure to defined electric stress", *Proc. IMechE., Part J: J. Engineering Tribology*, Vol. 223 No. 6, pp. 787-97.

Appendix

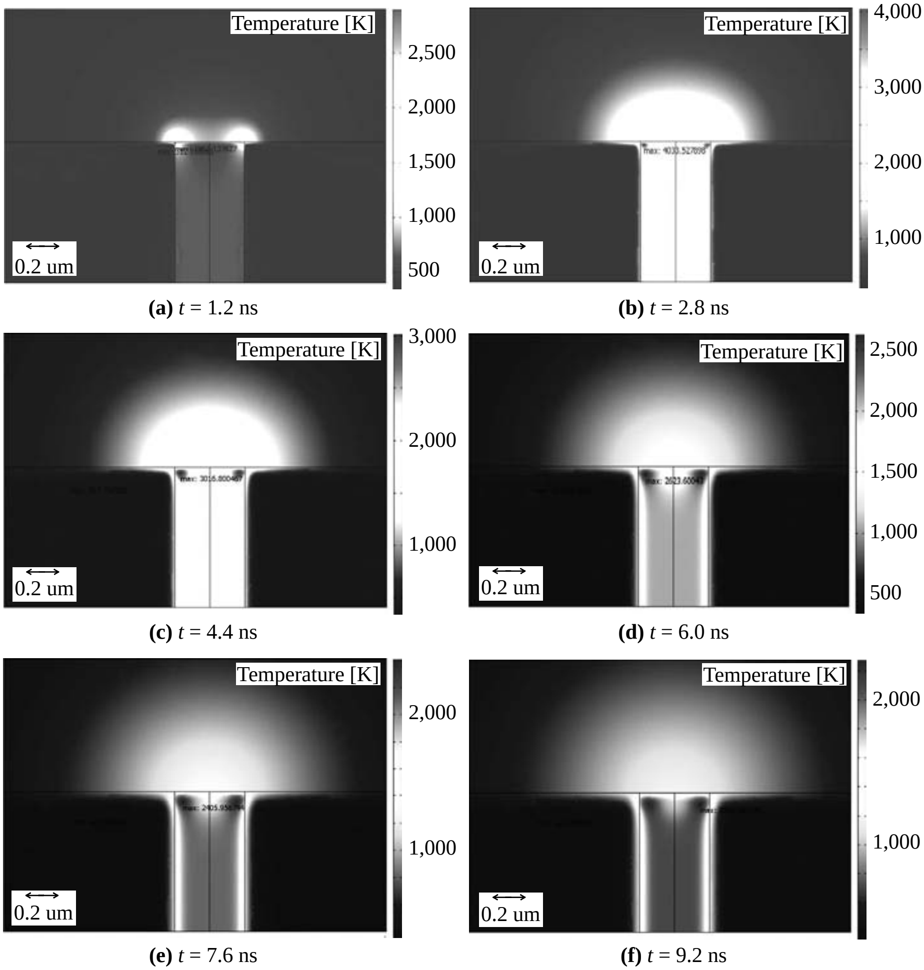


Figure A1. Temperature distribution at different times following the current pulse

Corresponding author
Annette Muetze can be contacted at: muetze@tugraz.at