Application guide bearing currents

TECHNISCHE UNIVERSITÄT DARMSTADT

Institut für Elektrische Energiewandlung

Darmstadt, 28.09.2021 Version 2.3

Institut für Elektrische Energiewandlung, Technische Universität Darmstadt (Publisher)

Institutsleiter: Prof. Dr.-Ing. habil. Dr. h.c. Andreas Binder

Landgraf-Georg-Str. 4

64283 Darmstadt

Germany

Authors: Dr.-Ing. Yves Gemeinder; Dr.-Ing. Martin Weicker

The present work was created as part of the output of an industrial consortium with focus on bearing currents at the Institute for Electrical Energy Conversion, TU Darmstadt.

Gemeinder, Yves; Weicker, Martin: Application guide bearing currents
Darmstadt, Technische Universität Darmstadt
Year of publication on TUprints: 2021
URN: urn:nbn:de:tuda-tuprints-193938
URI: https://tuprints.ulb.tu-darmstadt.de/id/eprint/19393

Content

List of Symbols

A_{Hertz}	*Hertz*'ian area	m^2
C	capacitance	F
C_{b}	bearing capacitance	F
C_{iso}	capacitance of insulating layers of the end-shields	F
G'	conductance of the cable per-length	$1/(\Omega{\cdot}\mathrm{m})$
i_{b}	bearing current	A
i_{rg}	rotor-to-ground current	A
i_{sg}	stator-to-ground current	A
i_{CM}	common-mode current	A
$\hat{J}_{\mathrm{b}}$	Peak apparent bearing current density	$\mathrm{A/m}^2$
L	inductance	H
n	rotor rounds per minute	rpm
R	Electric resistance	Ω
R_{bypass}	electric bypass resistance	Ω
$\hat{S}_{\mathrm{b}}$	Peak apparent bearing power	V·A
u_{b}	bearing voltage	V
u_{CM}	common-mode voltage	V
U_{dc}	inverter DC link voltage	V
u_{Ug}, u_{Vg}, u_{Wg}	Phase-to-ground voltages of phase U, phase V, phase W	V
$\hat{\sigma}_{\mathrm{b}}$	Peak apparent bearing power per total *Hertz*'ian contact area	$(\mathrm{V{\cdot}A})/(\mathrm{m}^2)$
ω	angular frequency	1/s

Subscripts

CM	common-mode
DE	drive end
DM	differential mode
f	frame
NDE	non-drive end
r	rotor
sw	stator winding
syn	synthetic

A. Introduction

A.1.1 Aim of this application guide

This application guide is intended to provide an overview of electrical bearing current effects in rolling bearings, related to bearing damage, concerning the questions:

- Which typical failures occur due to bearing currents?
- What are electrical bearing currents?
- How do electrical bearing currents occur?
- What are the main influencing parameters on electrical bearing currents?
- How can electrical bearing currents be measured or at least detected?
- Which remedial actions can be used to reduce electrical bearing currents?

This application guide is based on the research results of the industrial consortium with focus on bearing currents at the *Institute for Electrical Energy Conversion* at the *TU Darmstadt*. This application guide is based as well on the following published Ph.D. theses of the *Institute for Electrical Energy Conversion* [1], [2], [3] of the *TU Darmstadt* and of *Leibniz University Hannover* [4], [5], [6], Germany. Further selected results from three Ph.D. theses of *TU Wien* [7], [8], [9], *Vienna*, *Austria*, and two other universities [10], [11] are used together with other published literature sources for the research concerning electrical bearing currents and for this application guide. This application guide is focussed primarily to be used by application engineers and drive operators to give a first-hand overview on electrical bearing current effects. Further details are available in the cited literature. Thus this application guide cannot answer each question concerning electrical bearing currents, especially with theoretical background.

The first contact of an engineer with electrical bearing currents is often due to a damage of at least one bearing in a drive system in one of the drive elements, e.g. the electrical motor, the gear or the encoder. Investigating the causes of the bearing failure in an inverter-operated drive system, often at the first glance it seems to be caused by electrical bearing currents! But often this is <u>not</u> true (Figure 1), and then the drive operator is asking for qualified help. This application guide may such a first aid.

A.1.2 Not all bearing problems are due to bearing currents

While mechanical bearings of inverter-fed drive systems may fail due to inverter-induced electrical bearing currents, other causes of failure are often present, too, e.g. lubricant contamination by dust or debris, mechanical under- or overloading (Figure 2), mechanical or thermal bearing damage (Chapter B) etc. Therefore, before discussing bearing failures due to electrical bearing currents, any other possible failure causes should be excluded. In some rare cases two different failures may even occur at the same time. Thus the electrical bearing current effects do not need to be always the dominating cause for failure.

In case of bearing damages by electrical bearing currents the effects are not solely caused by the electrical machine or the feeding inverter alone, but the whole system setup of the drivetrain must be considered, when looking for the source of bearing current flow. This system setup consists of the motor cables, the feeding inverter and its type of output voltage pulse pattern, the electrical motor type and size, the type of mechanical bearing in the motor, gear and encoder and their kind of lubrication, as well the operation conditions, e.g. variable speed operation, continuous or not continuous operation, big acceleration or deceleration, vibrations, etc. Each drive train component may influence the generation and type of electrical bearing current, making it difficult to give a general statement on the cause-and-effect chain of electrical bearing currents.

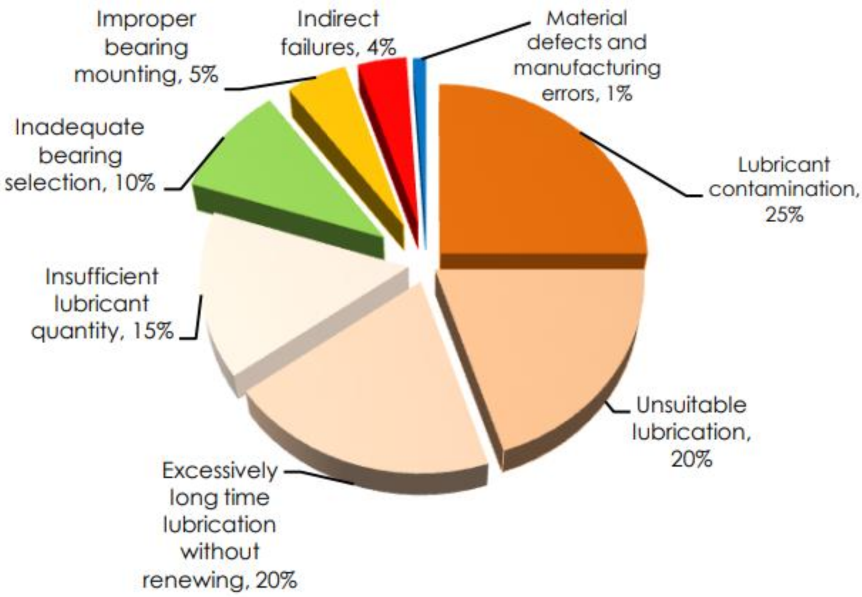


Figure 1: Distribution of common bearing failure causes [12]

Many publications, discussing bearing currents, are available, but a general method to distinguish bearing failures, caused by electrical bearing currents, is not given in these publications. The engineer is often faced with a quantity of detailed information, which has to be analysed thoroughly. For this purpose this application guide proposes an approach to analyse inverter-operated drive systems, concerning electrical bearing current effects in roller bearings. Sleeve bearings are less sensitive to bearing current damages due to the bigger contact surface and hence smaller bearing current density. Moreover their use is often restricted to large machines, which are not so often fed by inverters, and – if so - are fed with inverters of lower switching frequency and with less d*u*/d*t* in the inverter voltage output pattern. Hence the probability of bearing current occurrence is smaller.

Following approach for clarifying the influence of bearing currents is recommended:

Before starting in case of a bearing damage with measurements on bearing currents, all other related issues must be identified, because, according to Figure 1, bearing failure due to inverter-induced bearing currents may be less than 4% of all bearing failures. First of all, possible mechanical failure causes (bearing & lubricant issues, kind of mechanical installation, …) must be excluded, which count for more than 96% of all bearing failures. These mechanical parameters are boundary conditions for the bearing system anyway, and have therefore to be taken into account at any rate also for bearing currents failures.

A single electrical bearing current occurrence as a short current spike (except extreme current densities such as during a strong flash-over) does not destroy the bearing at once. To destroy a bearing, a continuous electric bearing current must occur such as a repetitive sparking at inverter switching frequency with an apparent bearing current density higher than 0.1 A/mm^2. The bearing current occurrence probability rate is proportional with the inverter switching frequency, because at each switching instant a change of electrical voltage at the bearing occurs. The damage mechanism for typical electrical bearing damage according Figure 5 and Figure 6 may be complicated and is not always easily straight-forward explained. In some cases it was found, that mechanical vibrations are also part of the damage process.

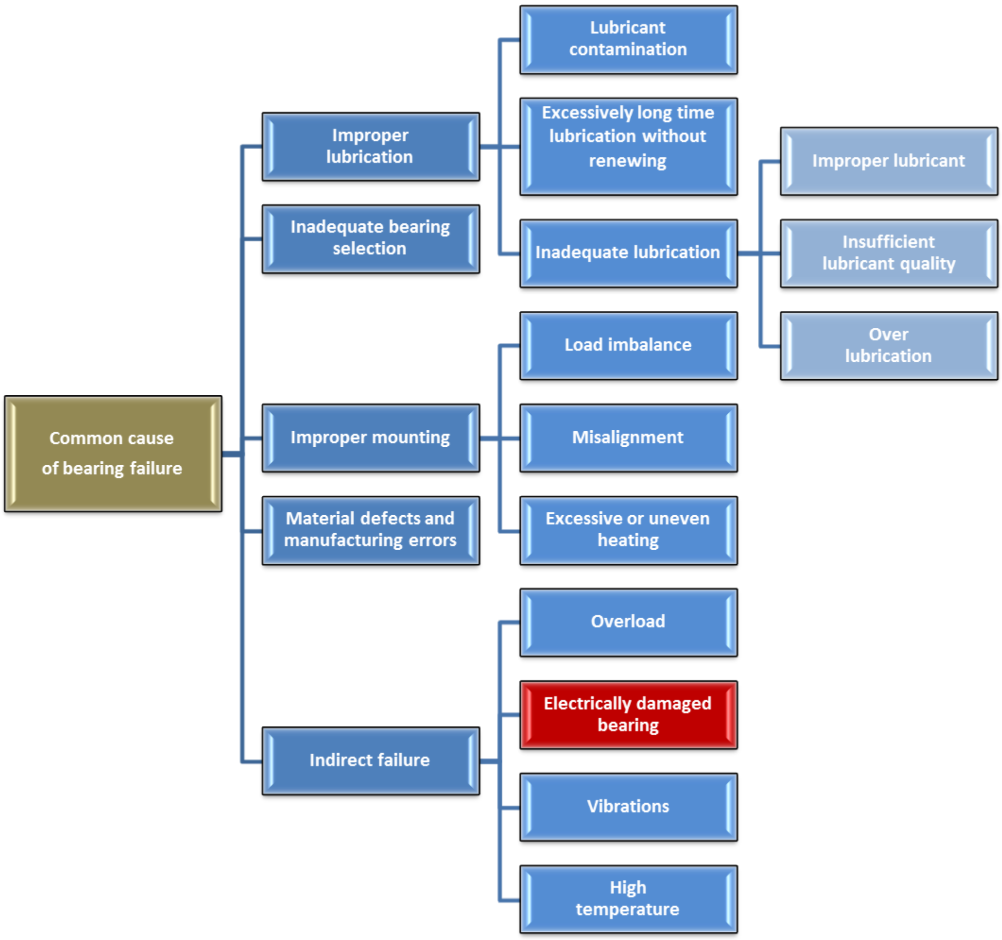


Figure 2: Common bearing failures [12]

A.1.3 Recommended approach of analysis

When can we state a bearing failure? For some operators already a noisy bearing is called a “damaged bearing” and hence a bearing failure. But often this is only an early sign that a bearing damage will occur. Usually a roller bearing failure is stated when by frequency analysis of the measured bearing vibration signal a dominating vibration amplitude at roller element bypass frequency is detected! But independent from the bearing failure definition, the procedure of analysis is always the same.

This application guide provides necessary information required for such analysis described in the following chapters:

a) What are bearing currents?
b) What are typical damage patterns due to electrical bearing currents?
c) What kind of faults or improper design of the electric and mechanical system may lead to bearing currents damages?
d) What kind of remedial actions may be recommended?
e) How can electrical bearing currents be measured?

I) <u>Checking a roller bearing concerning a possible bearing failure:</u>

When the system is still running and no modification at the drive system had been done, a mechanical vibration measurement with an envelope analysis concerning the frequency spectrum of the vibration signal should be done. Most of the bearing manufacturers supply a software tool to calculate the roller element bypass frequencies for their bearings. If a dominating vibration amplitude at such a bypass frequency is detected, please proceed according to Chapter B.

II) <u>For the case that electrical bearing currents may be the cause of failure:</u>

a) <u>For the case the bearing is already dissembled (concerning bearing current type see Chapter D) (If bearing is still assembled, go to part b)</u>

By analysing the damaged dissembled roller bearing and the lubricant (see Chapter B) along with the drive system topology information, first hints may be extracted which kind of bearing current has occurred. For these hints, the minimum required data are:

i. Drive system:

- ✓ Type of industrial application of the drive system?
- ✓ Bearing type? Bearing is affected at drive end or non-drive end side?
- ✓ Type of used lubricant i.e.: conductive lubricant: yes/no?
- ✓ Switching frequency of the feeding inverter?
- ✓ Machine and inverter type (see nameplates)
- ✓ Inverter output filter used? Such as e.g. common-mode ring cores, sine filter, d*u*/d*t*-filter, ...?
- ✓ Type of used motor cable, i.e. unshielded or shielded? Shield connection type to the grounding system?
- ✓ Type of the feeding grid at the inverter input terminals type: IT or TN?
- ✓ Is a gearbox used? If so, is the motor coupling el. insulated: yes/ no?
- ✓ Which kind of auxiliary devices exist such as grounding brushes, tacho generator, encoder, vibration sensors, ...?

ii. Operating data:

- ✓ Speed (fixed value or variable speed)? High acceleration/deceleration?
- ✓ Temperature of the bearings or of nearby motor parts?
- ✓ Kind of duty cycle? Used speed-torque profile?

iii. Operating documents and additional information:

- ✓ Maintenance book
- ✓ Observations of maintenance workers

Additional data of drive lay-out:

- ✓ Electrical machine arrangement: One-axis or multi-axis drives?
- ✓ Inverter operation with a) Direct torque control, b) Pulse width modulation, c) Hysteresis control?
- ✓ Used inverter topology i.e. 2-Level-inverter, 3-Level-inverter, Si-IGBT or Si-MOSFET or SiC-MOSFET elements?
- ✓ Infeed part of the inverter from the grid via “Active front end” (AFE) or “Diode rectifier front end” (DFE)?

As a result a hint may be given that a certain type of electrical bearing current has occurred or not. Maybe in addition a system assembling problem may be suspected.

b) Local inspection of the damaged system and measurements:

   i. Verification of grounding and EMC failures (see Chapter E)

      - ✓ Check the connections of the grounding cable and check the requirements of the components supplier concerning all cable installations!

   ii. Measurements (see Chapter C)

      - ✓ Common-mode current
      - ✓ Common-mode voltage
      - ✓ Parasitic leakage currents
      - ✓ Bearing voltage
      - ✓ Bearing and ambient temperature
      - ✓ Additional vibration and positioning measurements

c) Evaluation of bearing current type (see Chapter D):

   Comment: This can as well be done in parallel with part b)

d) Deriving counter-measures:

   i. For that further information is required on

      - ✓ Radial and axial mechanical bearing load force
      - ✓ Definition of available remedial resources versus permitted technical and economic conditions
      - ✓ Clarifying the drive system circuit diagrams

   ii. Choosing the remedial action based on the evaluated information and measurements

   iii. Installation of remedial counter-measures and measurements on their effectiveness

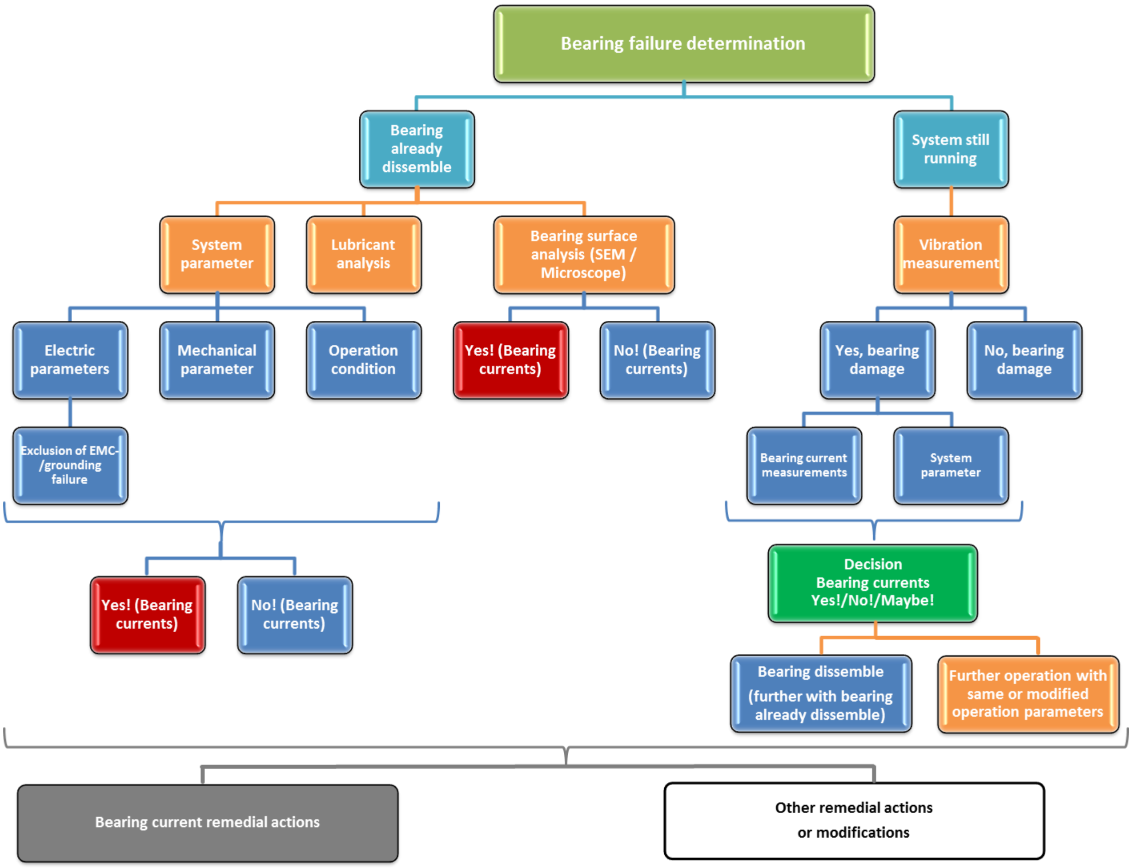


Figure 3: Diagnostic flow chart

B. Classification and Determination of Bearing Damage

Figure 4 gives an overview of the bearing "health" assessment. For a still assembled and operating drive system an immediate disassembly of the motor is not recommended, if there is only "gentle" audible noise coming from the bearing. First vibration measurements are recommended. So when the system is still running and it is not clear if a bearing damage exists, a diagnostic should start by the mechanical assessment of the bearings with vibration measurement techniques such as measured vibration acceleration, measured signal crest factor and envelope frequency analysis of the vibration acceleration signal at the bearing end shield of the machine. A roller bearing failure is given, when in the envelope frequency analysis of the measured bearing vibration signal a distinct, considerably high vibration amplitude at roller element bypass frequency of the bearing is detected. This could be caused by a damaged inner or outer bearing race surface or surface damage of one or several rolling elements and as well as a damage of the cage. In case of already disassembled bearings, different assessment methods are available. The lubricant colour and consistency and the bearing surfaces can be checked. By disassembling the bearing some general rules should be regarded according to the published bearing failure catalogues (e.g. [18], [19], [22], [23]):

1. Analyse the ambient conditions of the total drive system and make a protocol by photograph pictures!
2. The colour and lubricant distribution in the bearing should be protocolled by photographs [18].
3. Be aware, that due to the dissembling by pressing on the outer bearing ring additional bearing failures can be created.
4. Try not to pollute the lubricant while disassembling the bearing.
5. Use aluminium foil (no plastic) to conserve the bearing for further investigation e.g. at a diagnostic institute (or ask your diagnostic institute for proper foils)!

The first rating concerning the lubricant (according to 2.) can be done just by personal evaluation. For more detailed research, possibilities are available (Figure 9), which are described in the Chapter "Lubricant diagnostics" (Chapter B.1.3).

The investigation of the bearing surfaces (Chapter B.1.1) can be done by an optical inspection, further with a surface-reflecting light microscope analysis or with high resolution by a Scanning Electron Microscope (SEM). The optical inspection of the surfaces together with the given damage patterns in the above noted failure catalogues [18], [19], [22], [23], also regarding further special bearing problems (such as mentioned in Chapter B.1.5), allow a first hint concerning the damage issues. The degree of bearing damage (Chapter B.1.1) describes, how strong the bearing surface has been altered e.g. due to bearing currents.

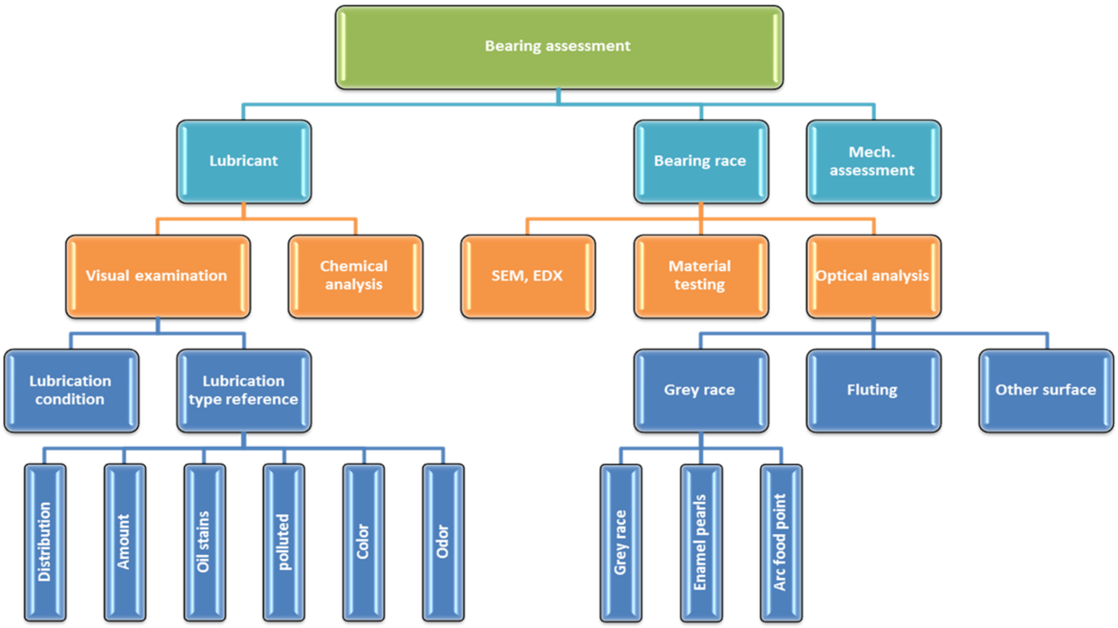


Figure 4: Bearing assessment structure

Table 1 gives an overview which attributes can be investigated and assessed by the bearing diagnostics and which surface damage pattern corresponds to which cause of damage. The diagnostic methods according to Figure 4 allow a decision between “classical” purely mechanical causes for bearing failures and damages due to electrical bearing currents.

Table 1 gives the overview, which criteria you finally take into account to prepare a diagnostic. The bearing current types are explained in detail in Chapter D.

Table 1: Comparison of typical attributes concerning bearing current types and the comparison with similar failure causes referenced in Figure 8.

Typical attributes	Similar failures causes	Current type
Surface: - Grey race (grade 0,1,2) - SRM sponge texture Lubricant: - Higher iron content - Other parameter near to normal ageing Technical operation parameter: - Low bearing loads, near to the bearing minimum loading	- Indentations of foreign bodies - Slippage tracks (- Micro pitting due to fatigue of lubricant	EDM bearing current (Chapter D.1.2)
Surface: - Grey race (grade 0 … 4) - Slug on the surface Lubricant: - Strong ageing - Bleed out - “Resinified” Technical operation condition: - Grounding failures - Shaft height >200mm no insulating bearing on one side mounted	- Temperature influences - False “brinelling”	Rotor-to-ground current (Chapter D.1.3) Circulating bearing current (Chapter D.1.4)
Surface: - Destroyed bearing surface depending on run time (grade 5)	- White etching cracks (short time) - Surface fatigue	Bearing current influence

B.1.1 Optical bearing surface analysis and bearing damage grades

There are different optical analysis methods to scan the bearing surface, which differ in the resolution grade:

a) Eyes
b) Reflecting microscope
c) Scanning electron micrograph SEM

Several further methods exist to analyse the material changes of the bearing surfaces, but they are typically cost intensive. Other methods to determine the surface characteristics e.g. roughness, are not further discussed here, because it is typically not necessary for the bearing damage diagnostics. Especially, the SEM is a more detailed diagnostic method and gives enough clear hints to determine the bearing failure. All above mentioned investigation methods are supplied by the bearing manufactures or at an independent research institute. Typical bearing failures due to electrical bearing currents are given in Figure 5 and Figure 6. For their explanation bearing current types are named, which are given in Chapter D.

A) Figure 5a)…c) shows typical bearing surfaces due to EDM bearing currents (Chapter D.1.2). Especially the SEM shows in case of EDM bearing currents a sponge texture of the material surface (Figure 5 b). The chemical lubricant analysis typically shows an increase of iron particles.

B) In the case of circulating bearing currents (Chapter D.1.4) and rotor-to-ground bearing currents (Chapter D.1.3) with the usually much higher current density the lubricant oil is separated from the grease (called “bleeding”). The lubricant is strongly “aged” by separating COOH-radicals from the lubricant molecules. By the carbon C from these COOH-radicals the lubricant is black-coloured and “resinified” (Figure 5 e) due to the loss of oily content (bleeding).

C) The bearing surface shows a “grey” race (Figure 5 a) in an early stage of bearing current flow due to small craters of small arcing, which are overrun by the roller elements, leading to the greyish surface. In a later stage fluting (Figure 5 d) may occur. The SEM pictures show small slugs (Figure 5 f) on the material surface, and the roughness of the surface is increased strongly.

D) In case of big EDM bearing currents peaks big craters of the short arcs occur (Figure 6 a).

E) If fluting (Figure 5 d, Figure 6 b) occurs on the bearing surface, this increased surface roughness causes “loud” bearings. In such a case the machine has to be stopped to avoid increased friction heat, which causes intensive oil loss, which gives further friction heat, until e.g. the cage will break and the bearing will block.

F) Bearings are manufactured usually from ferritic steel. So the magnetic field of the bearing current flow at big bearing currents magnetizes also the bearing steel parts. Due to the iron remanence the dissembled bearing parts show a magnetic behaviour, especially when they are cut into two pieces (Figure 7).

G) An overview on the aging and destroying development process is given in Figure 8, where in the first stage a “grey” race according to C) is visible.

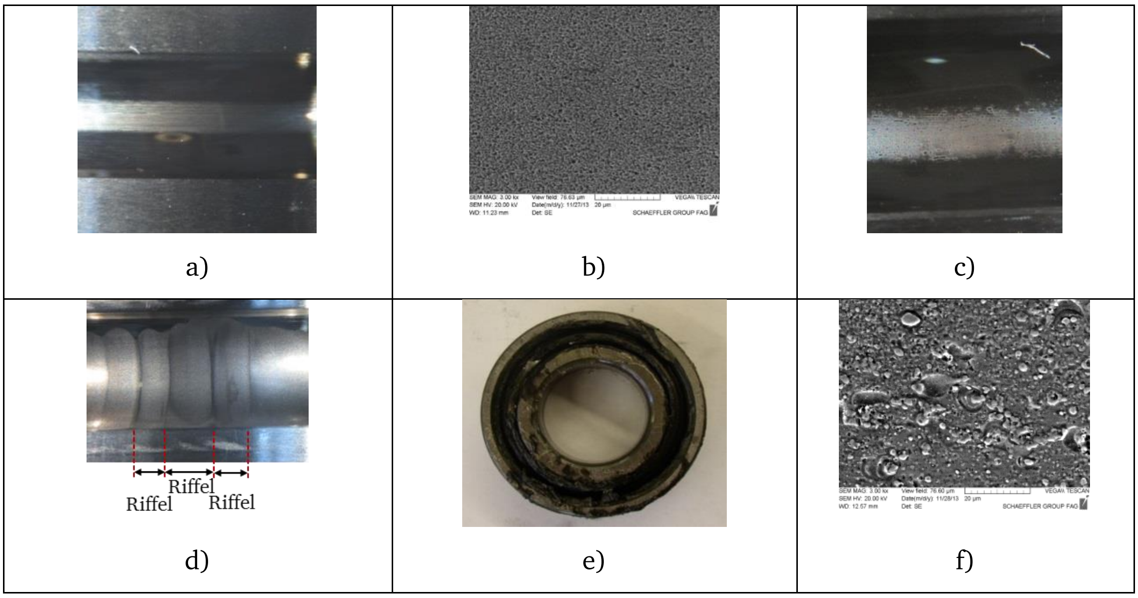


Figure 5: Typical bearing damages caused by bearing currents. Bearing grease consists of mineral oil and thickener.

- **a) Grey race, inner ring of the bearing of the non-drive end after 2000 h operation time under EDM bearing currents (Chapter D.1.2)**
- **b) SEM-picture by *Schaeffler Technologies AG & Co. KG*: 3000-times amplification of the inner ring surface of the bearing of the non-drive end bearing after 2000 h operation time under EDM bearing current (Chapter D.1.2)**
- **c) Crater resp. arc points at the inner bearing ring surface of the drive end bearing after 500 h operation time**
- **d) Fluting (in German "Riffel") at the inner ring surface of the bearing**
- **e) Blackened lubricant grease after 432 h operation time under rotor-to-ground bearing currents (Chapter D.1.3) loading.**
- **f) SEM-picture by *Schaeffler Technologies AG & Co. KG*: 3000-times amplification of the inner ring surface**

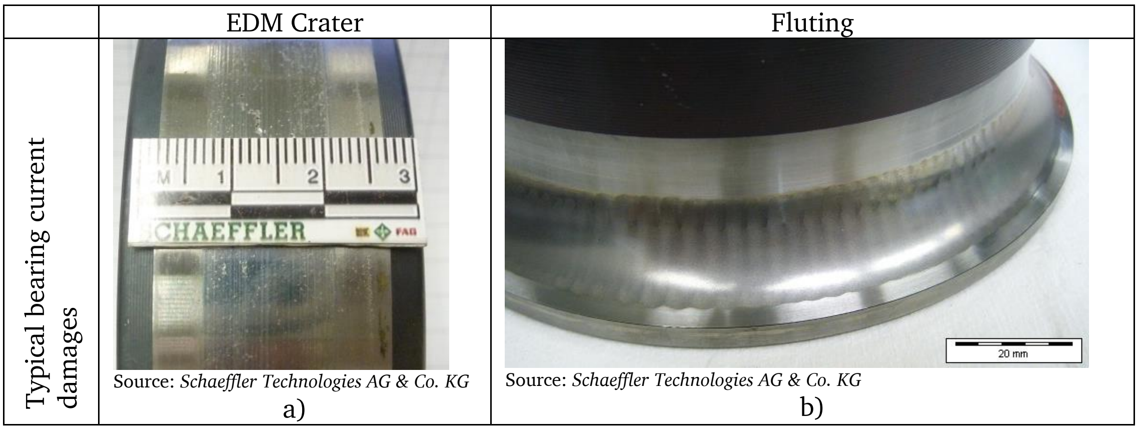


Figure 6: a) Bearing race of a roller bearing with EDM bearing current craters (Chapter D.1.2). Source: *Schaeffler Technologies AG & Co. KG*,
b) Angular contact ball bearing with fluting. Source: *Schaeffler Technologies AG & Co. KG*

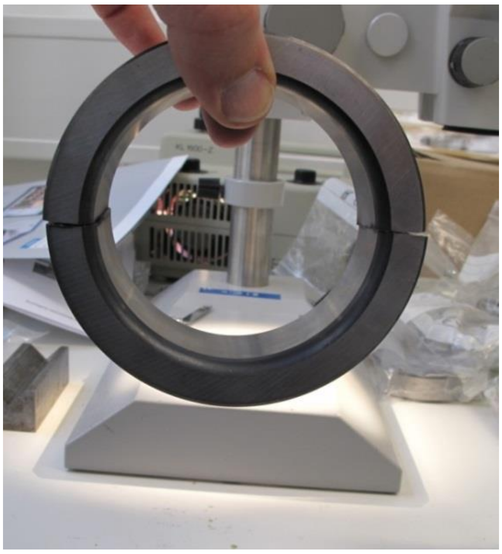


Figure 7: Lifted two halves of a cut bearing (type 6317), holding together by remanence magnet force. The bearing suffered circulating bearing currents for 2000 h [3].

B.1.2 Grades of bearing current surfaces damages

For the comparability the damaged bearing inner and outer ring track surfaces are classified here in six grades (Figure 8) according to [5], where the Grades 1 … 3 are indicators for the typical damage of bearing race surfaces by “Fluting”, due to bearing currents. Grade 0 is a normal bearing race surface, which can occur due to different operation conditions and with this surface a normal bearing operation is possible. Grades 1 … 3 allow typically a normal operation of the bearing, but audible noise due to some minor damage is possible. A vibration measurement with a frequency analysis will show already with Grade 2, but at latest with Grade 3, typically bypass frequencies, which give a hint on the already damaged bearing track surfaces. If such a measurement is done with the described result (e.g. Grade 2), the bearing should be monitored by vibration measurement to see, whether the vibration amplitude at bypass frequency increases with time or keeps stable. Maintenance should be planned if there is an increase detected, either in the audible noise behaviour or in the vibration measurement signal.

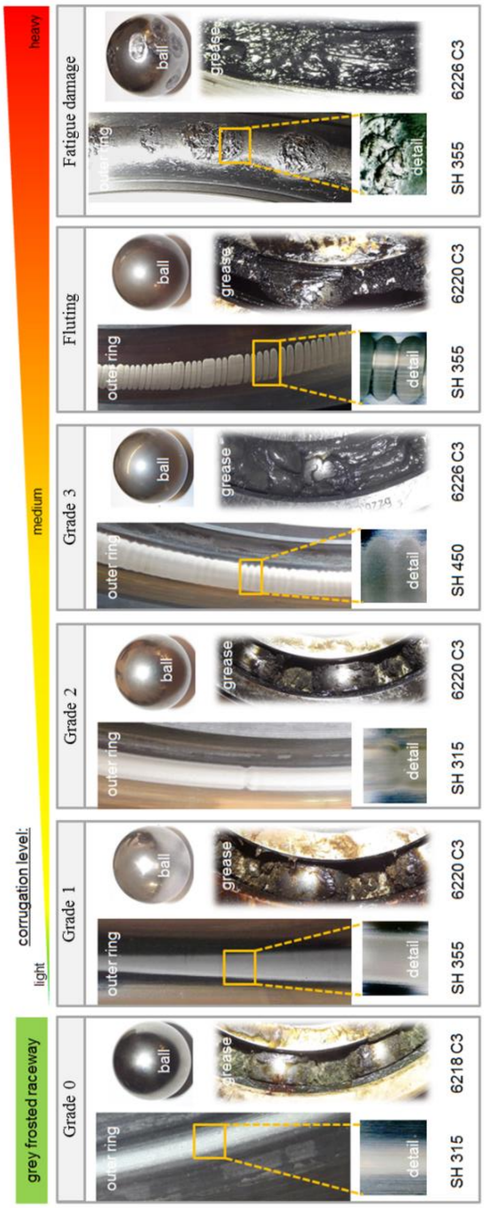


Figure 8: Different grades of bearing damage [5]

If there are then during maintenance found at the dissembled bearing at the ring track surfaces or roller element surfaces some small arcing points (diameter < 1 µm), this would be typical for bearings in inverter-fed machines. In these cases the electrical bearing current is mostly the main cause for the bearing damage. If such a bearing current damage exists, a more detailed bearing surface investigation via SEM pictures could support the assumption of acting bearing currents. Especially when there are two or more effects assumed to be responsible for the bearing damage, a more detailed investigation is necessary. A detailed description of how to proceed for bearing current failure analysis is given, e.g. in “FAG Wälzlagerschäden” pages 9 … 11 [18].

B.1.3 Lubricant diagnostic

The easiest way to do a lubricant diagnostic is done by optical investigation

a) with the eyes and
b) by haptic testing, i.e. by rubbing the lubricant between the fingers to feel the consistency of the lubricant (please consider in that case the safety instructions of the lubricant manufacturer).

<u>**The condition of the lubricant can be determined first via:**</u>

- colour,
- haptic testing of consistency,
- texture (lubricant is "soft", "de-oiled", "thickened")
- odour (usually a damaged lubricant smells bad due to "burned" particles).

<u>**First optical lubricant analysis results for a damaged lubricant in such typical facts as:**</u>

- there is no or less lubricant in the bearing as at the beginning of operation,
- the lubricant is dark coloured,
- the lubricant is thickened, e.g. adhesive or resinous,
- the lubricant has an unobtrusive appearance.

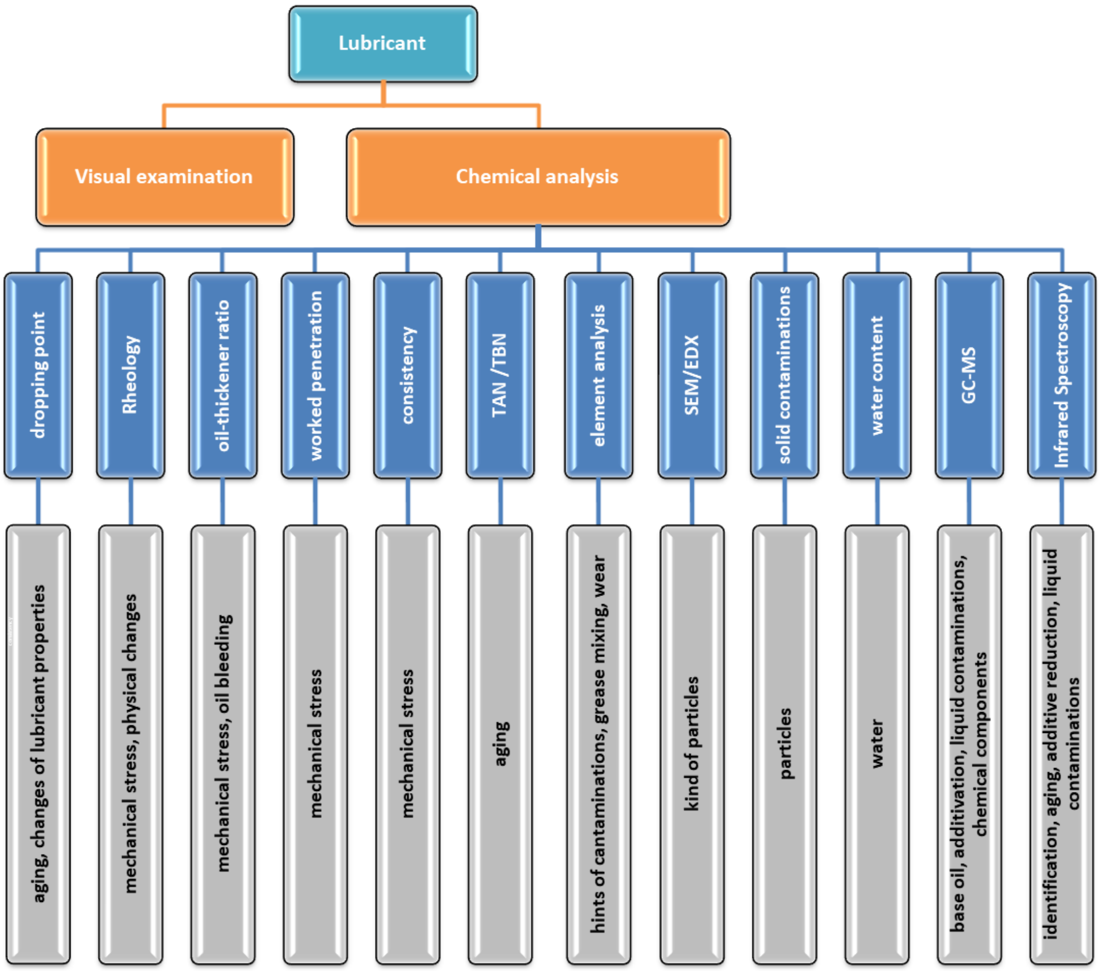


Figure 9: Lubricant diagnostics: Analysis methods

Detailed analysis methods for the determination of the lubricant condition are available at lubricant and bearing manufactures handbooks or by their customer support. Commercially operated research laboratories as given in Figure 9 also offer their services for analysis. For further analysis e.g. at the manufacturer´s lab it is necessary to have a sample of lubricant for further investigation.

Typical analytic methods at the manufacturer´s lab or at a research lab are:

I. Infrared spectroscopy for determination of aging (destruction of carboxylic acid -COOH), identification of lubricant parameters, determination of oxidation processes.
II. Gas chromatography–mass spectrometry GCMS for determination of lubricant composition and further cracking products as well as derived products.
III. Element analysis for determination of additive components, iron particle content, etc.

B.1.4 Issue White Etching Cracks (WEC)

White etching crack damages (WEC) are cracks in the microstructure below the bearing race surface which have a white shape, when they are etched [20], [21]. WEC is not discussed in this application guide. It should be noted that WECs and electrical bearing currents can occur simultaneously, and electrical bearing current flow may accelerate WECs. The resulting damage is a massive damage to the rolling elements and the bearing surfaces of the bearings. This occurs especially when within the usual service life the following fatigue damage pattern occurs: a strong surface ageing is visible, e.g. when big or many surface spalling deeps in the bearing surface exist. With the above discussed surface diagnostic methods the bearing manufacturer can classify the bearing damage, if it is caused by WECs or by other sources of damage.

B.1.5 Comparison of bearing race surface damage due to electrical bearing current currents or due to other failure causes

In some cases it is not easy to determine the failure cause-and-effect chain of bearing damage without doubts. Especially the bearing damage in the beginning or the totally damaged bearing, e.g. broken cage, will not allow a direct hint of the causes for damage. Typically the following damage patterns may be wrong interpreted:

A) Adhesive wear in the bearing due to mixed friction instead of bearing currents
B) Craters due to lubricant pollution e.g. by particles instead by arcing due to EDM bearing currents (Chapter D) or similar damage due to wrong mounting or dissembling the bearing
C) Bearing over-temperature caused e.g. by big rotor-to-ground bearing currents (Chapter D), but also by wrong bearing design

D) Fluting caused by mechanical vibration e.g. at stand still, called vibration damages due to false “brinelling”

E) Bearing surface damage due to corrosion

F) Note: A hybrid bearing (e.g. steel rings with ceramic roller elements) cannot be destroyed by bearing currents, because due to the insulating behaviour of the ceramic rolling elements no bearing current flow is possible. Further usually due to the too large discharge distances between the conductive rings no flash-over occurs.

The mentioned examples are illustrated by the following pictures:

<u>Case A:</u> Mixed friction vs. bearing currents

In this case, the bearing operates due to several issues in the mixed lubrication area. A grey pattern on the bearing surface is developed due to this operation.

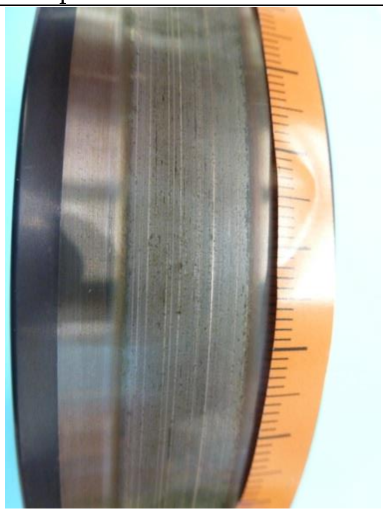
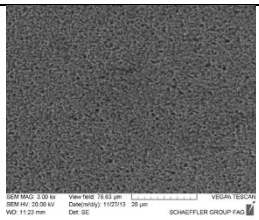
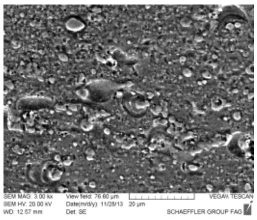
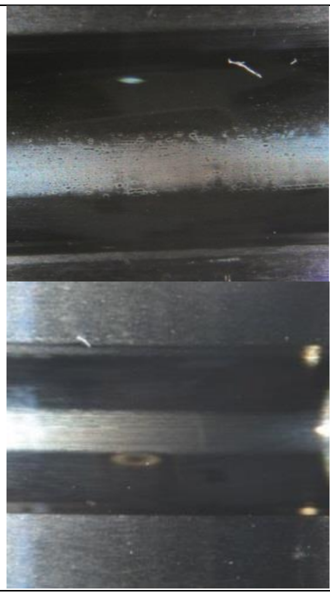
	Comparable surface	Bearing current surface	
Adhesive wear Grade 0	 Source: *Schaeffler Technologies AG & Co. KG*	 IBCE  IBCG,IBCC	

Figure 10: Adhesive wear vs. bearing currents (IBCE: inverter induced EDM bearing currents, IBCG: inverter induced rotor-to-ground bearing currents, IBCC: inverter induced circulating bearing currents)

<u>Case B:</u> Due to a wrong mounting, due to a polluted lubricant or due to some dust a bearing damage may occur. In case of dust these dust particles are overrun by the rolling elements and are pressed into the bearing surface, resulting in visible small craters.

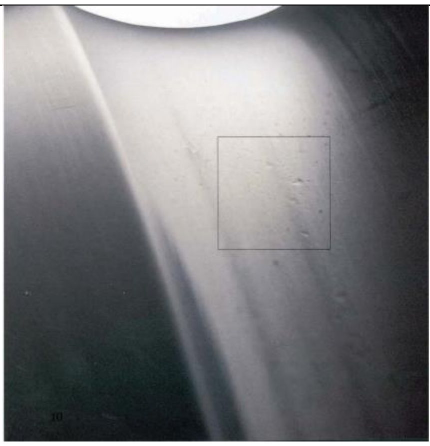
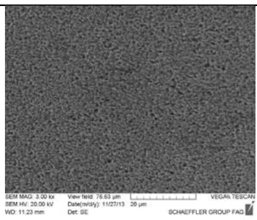
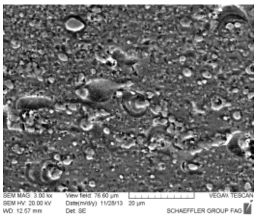
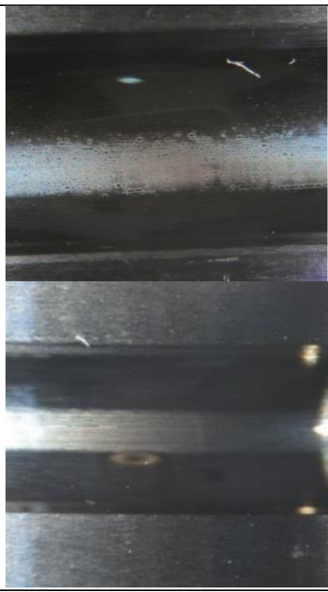
	Comparable surface	Bearing current surface	Exterior view
Contamination Grade 0	 [25]	 IBCE  IBCG,IBCC	

Figure 11: Contamination of lubricant by particles vs. bearing currents (IBCE: inverter induced EDM bearing currents, IBCG: inverter induced rotor-to-ground bearing currents, IBCC: inverter induced circulating bearing currents)

<u>Case C:</u> Bearing operates at too high temperature

For high bearing temperature (> 100 °C) a strong degradation starts for typical lubricants. The chemical structure is destroyed. The lubricant can be coloured black. Similar lubricant modifications can occur, when an electrical current is flowing through the bearing´s lubricant. So in case of over-temperature as well as in case of bigger bearing currents blackened grease can be found. But in case of bearing currents also the raceway of the bearing will show a characteristic damage, e.g. craters or fluting. Therefore the surfaces of the bearing raceways have to be analysed to clarify, if current flow is the reason for the lubricant´s degradation (see Chapter B.1.3).

<u>Case D:</u> Distinguish false brinelling damage from bearing currents damage: False brinelling damage is caused due to micro vibration e.g. mechanical oscillations or vibrations

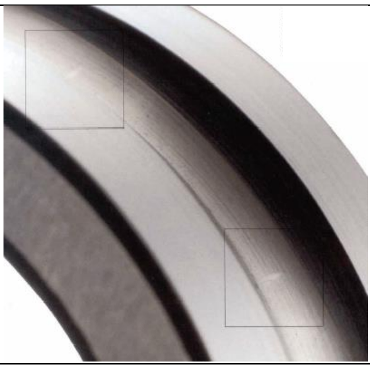
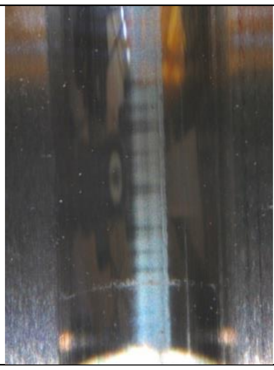
	False brinelling marks	Surface caused by bearing currents
Ripple on the bearing raceway		

Figure 12: False brinelling marks vs. bearing currents. False brinnelling marks are bright, well-defined, and surrounded by debris.

Case E: Corrosion can cause craters on the bearing race surface, which typically differ from the types of craters caused by bearing currents.

	Corrosion surface	Surface caused by bearing currents
	 [25]	

Figure 13: Corrosion vs. rotor-to-ground bearing currents

Case F: Fluting caused not by electrical bearing currents, but by other mechanical influence such as mechanical vibration at stand still. Especially in case of hybrid bearings fluting or craters cannot be caused by an electrical continuous current or by EDM bearing discharge, because the ceramic roller elements are insulating, building up a big flash-over distance.

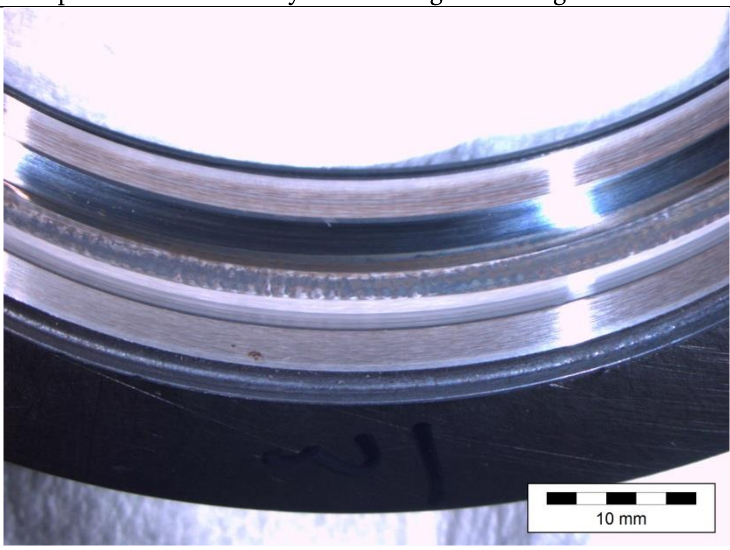
	Comparable surface of hybrid bearing outer ring
Fluting at a hybrid bearing	 Source: *Schaeffler Technologies AG & Co. KG*

Figure 14: Fluting at a hybrid bearing is not caused by bearing currents due to the impossibility of electrical current flow and big flash-over gap between ball and bearing race, which is too big for typical bearing voltages at inverter operation to ignite an arc.

A general overview is given in the damage catalogues of the bearing manufacturers. This literature [18], [19], [20], [21], [22], [23] is only a part of the available literature. More information is available at the homepages of the manufacturers, e.g. Schaeffler, SKF, NSK, NTN, FAG, Koyo, et al.

C. Bearing current measurements

In this Chapter we consider inverter-operated motors, where the inverter will generate at its output a pulsed common-mode voltage u_{CM} with switching frequency, feeding the motor terminals. For further information see also (Chapter D).

Bearing currents (Chapter D) can be measured, when the electric machine and in some cases the whole drive system is modified [1], [3]. For a determination of bearing currents a modification of the bearing seats is required (see Chapter C.1.7.). An overview for measurement methods and necessary modifications is given in [26]. Some measurements at a non-modified drive system are as well possible, but one usually does not get the bearing current itself. Instead typically the bearing and phase voltages and the common-mode currents of the drive system can be measured. What kind of measurement is required in case of a bearing failure depends on the possibilities for measurement at the investigated drive. For example, an industrial drive application in the field does not allow any big drive modification. So typically the bearing voltage (Chapter C.1.6), common-mode voltage (Chapter C.1.2) or the drive-system common-mode current (Chapter C.1.4) can be measured. If necessary, in some cases also measurements of the rotor-to-ground bearing current may be demanded and can be done, according to Chapter C.1.8.

The common-mode voltage can easily be measured with a machine which is connected in star, where there can be applied an electrical connection to the winding star point. In case of machines without access to the star-point or with a delta connection, a star point adapter has to be used. Independent of the motor winding connection it is also possible to measure the three phase-to-ground voltages and calculate the common-mode voltage from the sum of the three phase-to-ground voltages (C.1.2-1).

C.1.1 Minimum requirements for bearing current measurements

Bearing currents occur typically with frequencies in the range of

a) 100 kHz … 1 MHz for rotor-to-ground-bearing currents and for circulating bearing currents, and
b) several MHz for EDM bearing currents.

Hence for getting details of a), the oscilloscope window has to be set in the time scale in 1 μs … 5 μs per division for circulating- and rotor-to-ground bearing currents (Chapter D.1.3). For EDM bearing currents (Chapter D.1.2) the time scale is set to several ns per division. So the necessary resolution of the oscilloscope must be at least 500 Mega-samples per second. For the mentioned measurements typically following equipment is used partially or fully [26], [27]:

a. Oscilloscope with minimum bandwidth of 500 MHz
b. HF-Rogowski coil up to 10 MHz or current probe up to 50 MHz for measuring the bearing and common-mode current (Figure 18), a passive current transformer up to 20 MHz
c. Voltage probe up to 150 MHz for measuring the bearing voltage or phase voltage
d. Differential voltage probes up to 100 MHz for measuring the common-mode voltage up to 2500 V, and the bearing voltage up to 70 V

Additional equipment:

a. Contacts for contacting rotating components
b. Star-point adapter (Figure 15)

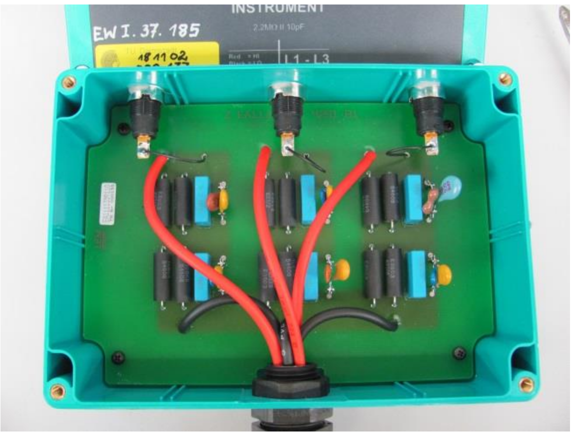


Figure 15: Star point adapter at the motor terminals, with 2.2 MΩ resistance and 10 pF capacitance in parallel per phase and then connected in star to make a measurement of the common-mode voltage possible at non-accessible winding star-point or delta connected stator windings.

C.1.2 Measurement of common-mode voltage u_{CM}

Star connection of the three motor winding phases

If the star-point of the motor windings (which has a star connection of the three phases) is accessible, the common-mode voltage is measurable between this star point and the motor housing, preferably at the motor grounding point. Due to the rather high voltage fed by IGBT-voltage source inverter e.g. at U_{dc} = 580 V DC link voltage (at 400 V grid) and due to the additional voltage overshoots of typically up to 100% rated voltage, caused by reflected traveling voltage waves on the motor supply cable, a differential probe is needed.

Delta connection or non-accessible star point of the three motor winding phases

If the motor phases are delta connected or the star point is not accessible, the star point adapter, which creates a synthetic star point (Figure 15), is to be used to measure the common-mode voltage $u_{CM,syn}$, which is identical with u_{CM}.

Measuring the phase-to-ground voltages and calculating with them the common-mode voltage

Regardless of the type stator winding connection, the common-mode motor voltage can be determined by measuring the three phase-to-ground voltages u_{Ug}, u_{Vg} and u_{Wg} at the same time and by calculating the common-mode voltage with (C.1.2-1).

$$u_{\mathrm{CM}} = \frac{u_{\mathrm{Ug}} + u_{\mathrm{Vg}} + u_{\mathrm{Wg}}}{3} \qquad \text{(C.1.2-1)}$$

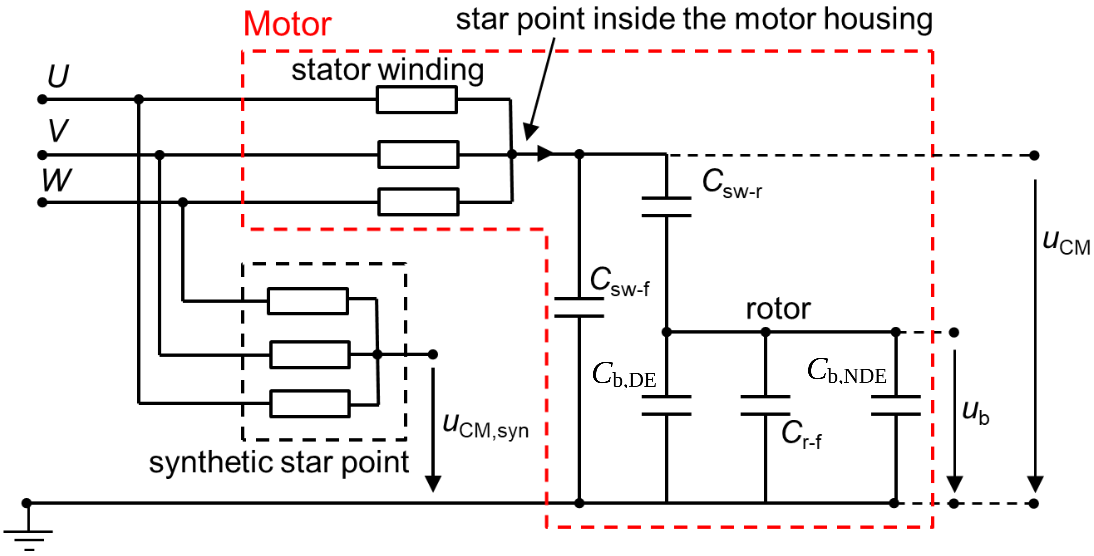


Figure 16: Equivalent circuit for measurement of the common-mode voltage by using a star point adapter ("synthetic star point").

C.1.3 Measurement of the stator-to-ground currents

The stator-to-ground current can be measured:

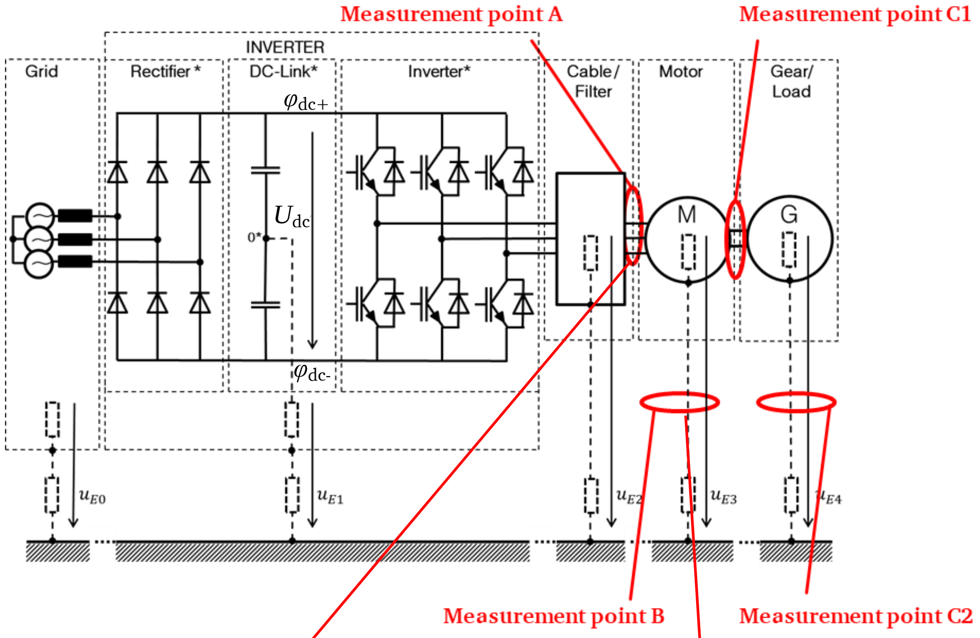
a. Indirectly by total current measurement at the motor feeding cable at the motor terminal without the grounding cable (Figure 17, measurement point A)

b. Directly:

   b1) if the motor shaft not coupled or its coupling to the load is electrically insulated: Figure 17, measurement point B

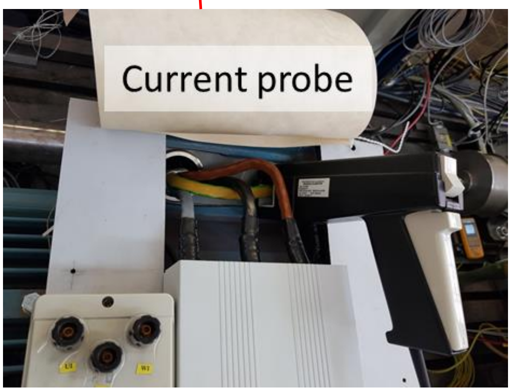
   b2) if the motor shaft is coupled without electrical insulation to the load (e.g. a gear or pump etc.): Measurement of the stator-to-ground current at the electric grounding cable according to Figure 17, measurement point B; and in addition rotor-to-ground currents via measurement point C1 or C2

If a measurement at the motor terminal box is not possible in the drive systems, the alternative measurement position is at the inverter terminal.



a)

b) Measurement point A

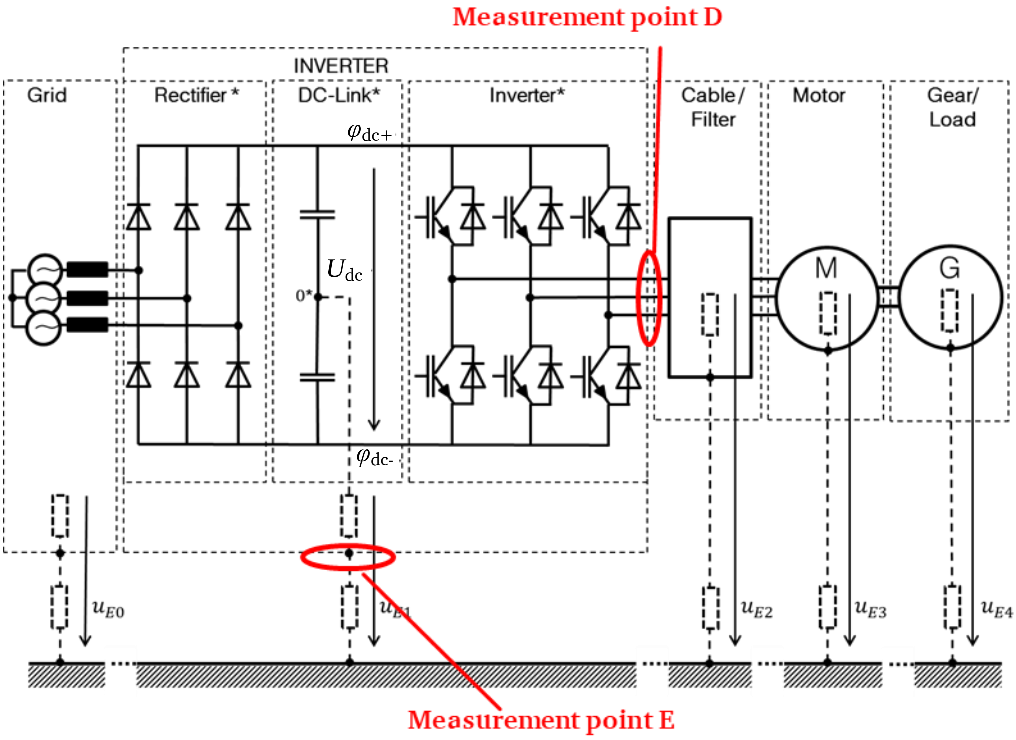


c) Measurement point B

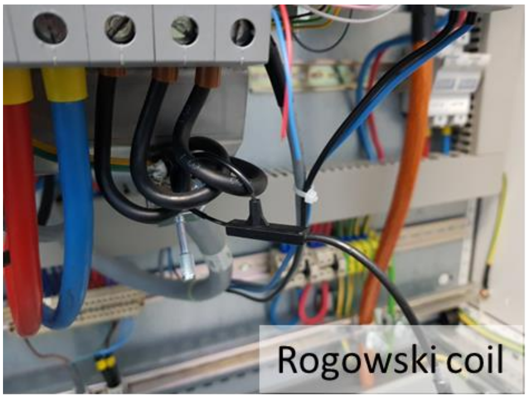
Figure 17: Measurement of the stator-to-ground currents at the motor: a) Overview of the measurement positions, b) Measurement of the stator-to-ground current i_{sg} at a 1.5 kW-induction machine with a Rogowski coil, which measures the sum of the three phase currents, c) Measurement of the stator-to-ground current at a 110 kW-induction machine with a current probe by measuring the current at the stator-to-ground cable.

C.1.4 Measurement of the overall common-mode current

The overall common-mode current can be only measured at the inverter according to Figure 18 at the measurement point D. In the ideal case of identical electrical potential in points D and E, the measurement result at point D should be the same as point E.



a)



b) Measurement point D

c) Measurement point E

Figure 18: Measurement of the stator-to-ground current at the inverter: a) Overview of the measurement positions, b) Measurement of the common-mode current at a 22 kW-induction machine with a Rogowski coil, which measures the sum of the three phase currents, c) Measurement of the common-mode current at a 22 kW-induction machine with a Rogowski coil by measuring the current at the grounding cable, which is connected to the motor.

C.1.5 Determination of a parasitic grounding current

For measuring parasitic grounding currents which do not flow directly by the cable shielding and the motor-to-inverter grounding connection back to the inverter, the measurement depicted in Figure 19 could be done with a Rogowski coil. This parasitic grounding current as the residual common-mode current by further grounding connections is included in the sum of the three phase currents and the current by the grounding cable. Therefore with the Rogowski coil around the total motor cable connections this residual common-mode current will be also measured.

Figure 19: Measurement of the sum of the three phase currents and the current by the grounding cable to determine the local residual common-mode current e.g. by further grounding connections at a 22 kW-induction motor.

C.1.6 Measurement of the bearing voltage

The bearing voltage u_b occurs between inner and outer bearing ring and is measured according to Figure 20. For the connection of the voltage measurement device to the outer and inner bearing ring or the shaft different possibilities exist such as a conducting screw connection at the end shield close to the outer bearing ring and a sliding carbon brush contact at the shaft close to the inner bearing ring. With all these different methods it has to be looked for that there is no interruption of these connection during the measurements, because such an interruption can cause voltage signals which look like a discharge current and will lead to a wrong diagnosis. The two conductors from inner and outer bearing ring to the voltage measurement device must be twisted or be used as coaxial arrangement to avoid EMI with HF EM background noise.

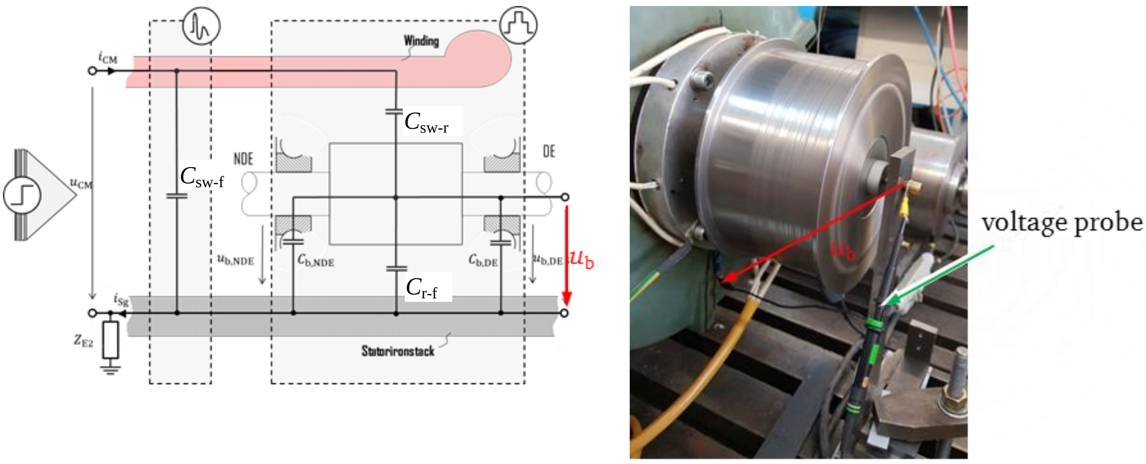
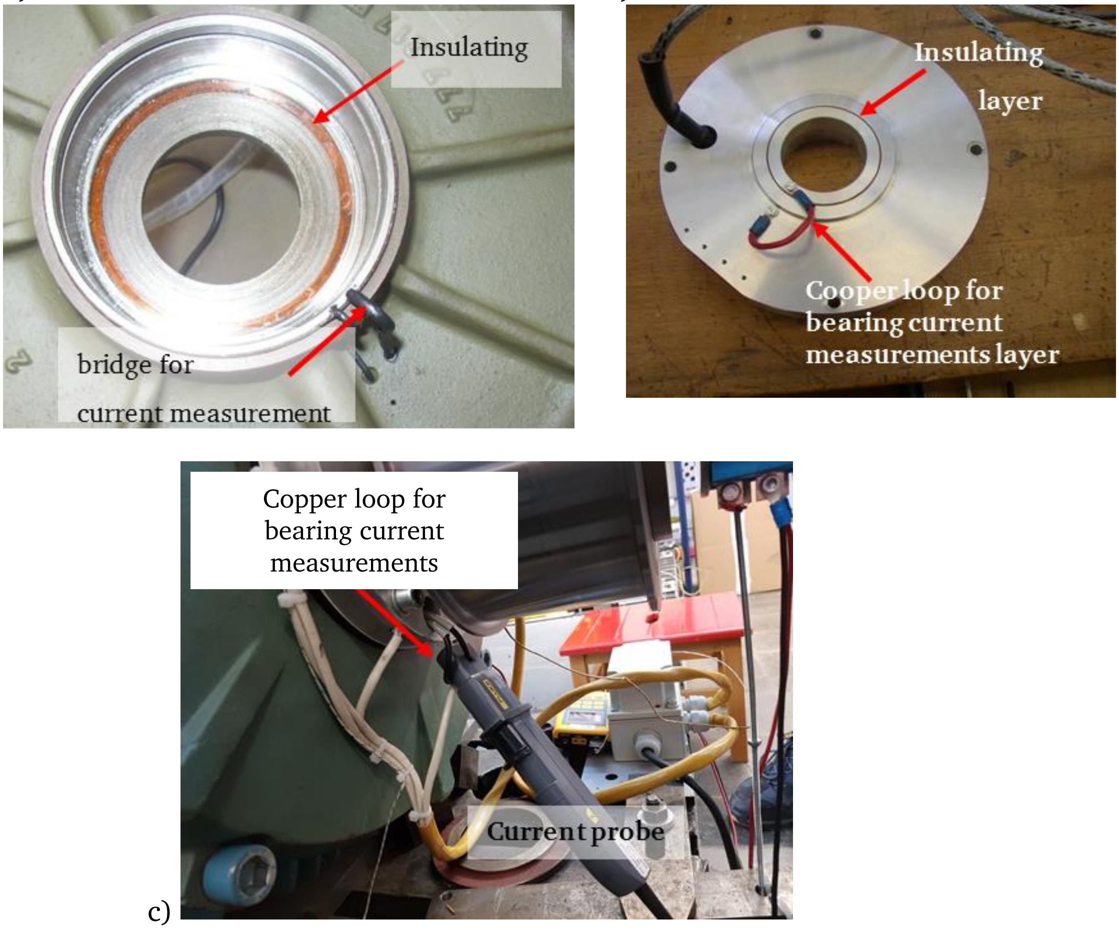


Figure 20: Measurement of the bearing voltage between rotor and end shield at the DE of a 110 kW-induction machine with a voltage probe, in case of rotor-to-ground currents a differential voltage probe is recommended

C.1.7 Necessary modifications of measurement set-up for bearing current measurement

The bearing current may be measured as described in [1], [2], [3], [4], [5], [6]. The bearing current is forced to flow via an insulation layer between outer bearing ring and end shield bearing seat via a conductor, which bridges the insulation layer. This flow via the conductor is not the inner discharge bearing current (EDM), but it is proportional to the real EDM current and in the same order of magnitude. In case of rotor-to-ground bearing currents or circulating bearing currents this current flow is identical with the bearing current. Hence for that measurement, a modification of the bearing seat is necessary (Figure 21). An insulation layer has to be inserted between bearing and bearing seat, bridged by the mentioned conductor, called “cable bypass” which bridges the insulation layer. The current flow in the bypass is measured e.g. by a HF current probe. The insulation layer may be either an insulation foil (e.g. *Kapton* of 0.5 mm thickness) as depicted in Figure 21, or in case of an electrically insulated bearing that Al-oxide-insulation layer at the outer bearing ring. Note that the measurement circuit changes the resulting HF impedance of the current path for the bearing current slightly, because due to the insertion of that insulation a small additional capacitance C exists at this position and the bypass cable adds a small resistance R and inductance L. This R-C-L damped series resonance circuit has a high resonance frequency, which influences the bearing current only in a minor way. Anyway the measured bearing current shape form differs slightly from the real bearing current wave form without that additional bypass, as described in [1], [2], [3], [4], [5], [6].

a) b)

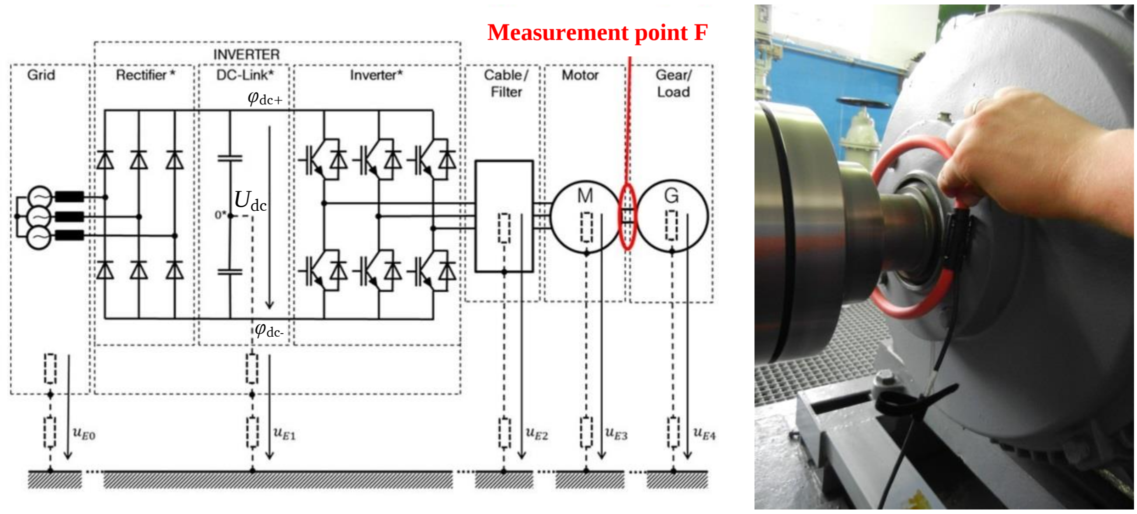


c)

Figure 21: Modified motor shield with insulation layer for bearing current measurements with cable bypass (“bridge” or “copper loop”) at a) 11 kW-induction machine and at b) 1.5 kW-induction machine. c) Measurement at a modified motor shield of an 110 kW-induction machine with a HF current probe.

C.1.8 Current passing at attached components

In order to measure parasitic common-mode currents through attached grounded components, a Rogowski coil can be placed around the motor shaft as shown in Figure 22. As other electromagnetic fields (EM) may also induce the coil as "background EM noise", this noise may be measured separately by the Rogowski coil, if that coil is positioned outside, but close to the shaft with the same enclosed area.



a) b)

Figure 22: Measurement of the parasitic rotor-to-ground currents at the coupling between machine and load/gear: a) Overview of the measurement position, b) measurement of the rotor-to-ground currents at a 22 kW-induction machine with a Rogowski coil.

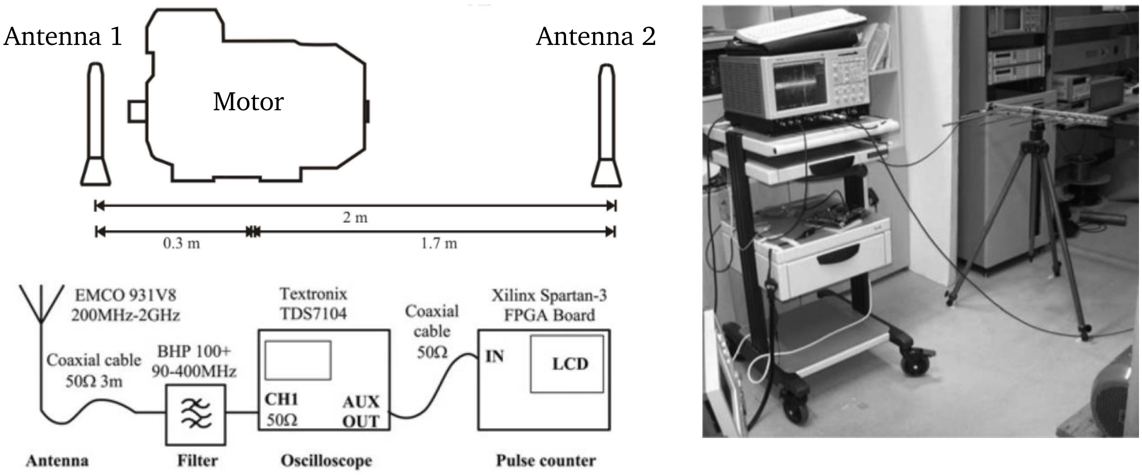
C.1.9 Alternative EDM measurement techniques by radio frequency (RF) voltage measurements

EDM currents are discharge currents at the intact bearing lubricant film. These small electrical arcs generate RF EM waves like an antenna and radiate these waves to the environment. Therefore measuring these radiated EM waves by a receiving antenna will give a hint that EDM bearing currents occur within the bearing. Hence by radio frequency voltage measurements the sparking in the bearings may be detected [11], Figure 23. Using this radio frequency measurement device (receiving antenna), with increasing distance of the measurement device from the bearing the measured signal will decay. Further the EM noise generated by other electronic nearby sources will influence the measured signal. Basically a single-receiving-antenna measurement is subject to this external radio frequency noise, whereas with two receiving-antennas by differential signal analysis this external noise can be canceled. Note that the RF voltage signal is influenced due to induced HF shielding eddy currents of the radiated EM waves

- by type of motor housing (e.g. cast iron or aluminum housing),
- by open or closed motor terminal box
- and by other metallic conductive drive parts, e.g. a metallic coupling protection.

This kind of RF measurement does not detect directly the EDM bearing current, but the magnitude of voltage signal, measured over a longer time period, can give a long-term trend. Note that circulating and rotor-to-ground bearing currents, which are not discharge currents, will not be detected properly by the RF measurement method!

Some measurement devices do not give the radio frequency voltage level itself (e.g. as RMS value), but they count events, when this RF voltage surpasses a predefined a voltage threshold. The rate of events is taken as a measure for EDM bearing current occurrence, but gives no information on the magnitude of signal amplitude. As it is a single source measurement, any other EMI may contribute to the counting rate of events and will lead to misinterpretation. Anyway, all these radio frequency methods do not allow any statement on the absolute value of bearing current and on the degree of bearing damage.



a) b)

Figure 23: a) Example of a test setup for detecting EDM bearing currents with two receiving antennas 1 and 2, using the time-difference-of-arrival method, *e. g.* with a time difference of 6 ns [11], and necessary measurement equipment for one receiving-antenna [29]. b) The photograph is illustrating the structure of the setup to monitor the electric discharge bearing currents via radio frequency voltage antenna signals [29].

D. Bearing currents

The occurring type of bearing current should be known for selecting the correct countermeasure. Bearing currents may occur in line-operated motors as “classical” bearing currents as well as with inverter-fed drive systems. In both cases the bearing currents may damage the bearings of the considered machine [1]. The classical bearing currents (Table 2 a)) are caused at a symmetric feeding grid, where the common-mode voltage is zero, mainly by a magnetic asymmetry within the electrical machine. They occur therefore especially in bigger machines, where the asymmetry has bigger impact. This asymmetry results mainly in circulating bearing currents at rather low frequencies in the low kHz range and below, such as a slot frequency.
At a three-phase asymmetric grid a grid-frequent common-mode voltage u_{CM} exists. Due to the low frequency of $f = 50\ \mathrm{Hz} \ldots 60\ \mathrm{Hz}$ the stator winding main insulation capacitance $C_{\mathrm{sw\text{-}f}}$ leads to a big common-mode impedance $\sim 1/(f \cdot C_{\mathrm{sw\text{-}f}})$, hence the stator common-mode current $i_{\mathrm{CM}} \sim u_{\mathrm{CM}} \cdot f \cdot C_{\mathrm{sw\text{-}f}}$ is (intentionally) very small, when the winding insulation is intact. In case of a grounded rotor a part of this very small current may flow as rotor-to-ground current via the bearings, but again with negligible influence.
In case of inverter-operated motors even at the symmetric grid the inverter will generate at its output a pulsed common-mode voltage u_{CM} with switching frequency, feeding the motor terminals. Due to the steep voltage impulses with big $\mathrm{d}u_{\mathrm{CM}}/\mathrm{d}t$ the stator winding-to-ground common-mode current $i_{\mathrm{CM}} = (\mathrm{d}u_{\mathrm{CM}}/\mathrm{d}t) \cdot C_{\mathrm{sw\text{-}f}}$ is much bigger than in the above noted grid-operated case and occurs with the repetition rate of the switching frequency as a series of current impulses. Also the inverter causes bearing current, which are originating by the same inverter-output common-mode voltage u_{CM} and are grouped into four types, where only ii), iii), iv) usually may be harmful to the bearings (Table 2 b)):
i) “Capacitive” bearing currents,
ii) “Electric-Discharge-Machining (EDM)” bearing currents,
iii) “HF-Circulating” bearing currents,
iv) “HF rotor-to-ground” bearing currents.
The common-mode bearing voltage u_{b} is a part of the terminal common-mode voltage u_{CM} according to $u_{\mathrm{b}} = BVR \cdot u_{\mathrm{CM}}$. Stator-fed AC machines have a small “bearing voltage ratio” BVR = ca. 0.05 … 0.1.

ad i) Together with the small bearing capacitance C_{b} = ca. $C_{\mathrm{sw\text{-}f}}/100$ at fully active lubrication film thickness the capacitive bearing current $i_{\mathrm{b}} = (\mathrm{d}u_{\mathrm{b}}/\mathrm{d}t) \cdot C_{\mathrm{b}}$ is negligibly small, leading to small HF dielectric losses in the lubricant. In via the inverter rotor-fed slip-ring induction machines (mainly as doubly-fed generators) BVR = ca. 0.8 … 0.9. Still the small capacitance C_{b} yields usually harmless capacitive currents.

ad ii) But if the small bearing voltage yields at a given lubrication film thickness a sufficiently high electric field within the film, surpassing the discharge threshold, a short arc occurs, discharging the loaded film immediately with a current spike, called EDM bearing current, which may be harmful, especially in rotor-fed AC machines. Typically EDM bearing currents (IBCE) are critical especially for small machines, as the operation voltage (*e.g.* 560 V DC link) and hence the bearing voltage and discharge energy are the same for big and small machines, but smaller bearings suffer more than bigger bearings.

ad iii) The HF magnetic field of the stator winding-to-ground common-mode current $i_{CM} = (du_{CM} / dt) \cdot C_{sw\text{-}f}$ induces in the "loop" of stator iron, end shields and rotor shaft and iron a HF shaft voltage, which drives a circulating current in this "loop" via the two (non-insulated) bearings. This "circulating" bearing current is directly proportional to i_{CM} via the factor $0 < BCR < 1$. This bearing current ratio BCR depends on the motor geometry. In both bearings this circulating bearing current appears with opposite sign. It is not a discharge current, but a pulsed current with switching frequency, which is especially big at low motor speed due to the metallic contact in the bearings. In small electrical machines the "loop area" and hence the linked HF flux are too small for inducing a sufficiently big HF shaft voltage to punch through the bearing lubrication film. So in smaller machines no circulating bearing currents occur (Table 2).

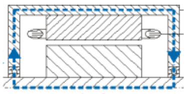
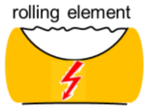
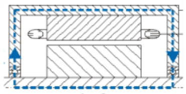
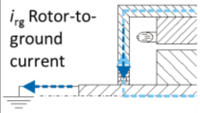
ad iv) In case of a grounded rotor a part of the common-mode currant will flow as "rotor-to-ground" bearing current from the stator via the bearings to the rotor and from there to the ground. It is like the circulating bearing current directly proportional to i_{CM} via a factor < 1, which depends on the common-mode impedances of the whole drive system.

Hence, harmful are only EDM-, HF-circulating- and rotor-to-ground bearing currents. All four inverter-caused bearing currents i), ii), iii), iv) occur

a) due to the high common-mode du/dt of the inverter output voltage pulse pattern and
b) due to the capacitive behaviour of the motor and the drive system.

Such capacitances occur at all insulating parts such as air, oil, paper, resin, plastics, …, which exist between two metallic electrodes, charged at different electrical potential. Such capacitances exist in each component of an inverter-fed drive drain (inverter, cable, electric machine).

Table 2: Classification of bearing currents: **a) Classical bearing currents, mainly as CBC: Circulating bearing current for sinusoidal-fed machine, b) inverter caused bearing currents as IBCE: Electric Discharge Machining bearing currents (EDM bearing currents), IBCC: Circulating bearing currents, IBCG: Rotor-to-ground bearing currents**

Classical bearing currents	Inverter-caused bearing currents due to the common-mode voltage		
CBC	IBCE	IBCC	IBCG
Circulating bearing currents	Electric-Discharge-Machining (EDM)-bearing currents	High frequency (HF) circulating bearing currents	Rotor-to-ground currents
→ Magnetic ring flux due to magnetic assymetries → induced shaft voltage frame  shaft	Flash-over the insulating lubricant. EDM = „Electric Discharge Machining“ rolling element  raceway	HF ground current → HF magnetic ring flux → induced shaft voltage frame  shaft	If shaft is grounded i_{rg} Rotor-to-ground current 
at bigger machine size at low speed	at medium/high rotor speed	at bigger machine size at low speed	independent of machine size

a) b)

Table 3: Significance of HF bearing currents depend on machine size.

Frame size x (mm)	EDM bearing currents	Circulating bearing currents	Rotor-to-ground bearing currents*
Small $x < 180$	++	--	-
Medium $18 > x > 315$	+/++	+/++	+
Large $x > 315$	+	++	++

*in case of direct rotor grounding

Each bearing current type ii), iii), iv) has a typical wave form and can thus be classified together with the background information on the drive system configuration. Hence the typical wave forms and properties for the inverter-fed bearing currents are given in the next chapters.

The HF electrical potential difference across the bearings, called bearing voltage u_b, depends on the grounding system HF capacitive and inductive parameters. A typical inverter-fed drive system and its grounding conditions, according to Figure 24, have all or a part of the shown components: DC-link-Inverter, with a B6 rectifier or active front end, grid and motor cable connections, grid and motor side filters, electrical machine (called “motor”), gears (cog-wheel type, or belt type, or …) and load machine (not shown).

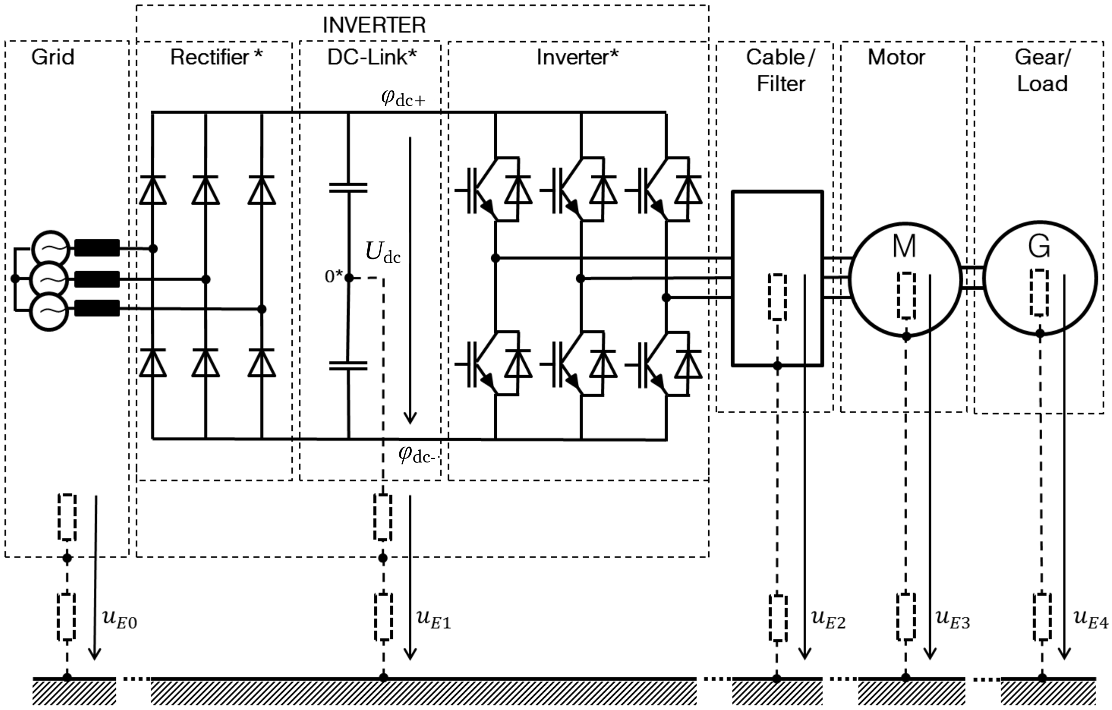


Figure 24: Typical inverter-fed drive system with its characterization according to IEC 61800-8 of the properties of the earthing (grounding) system.

The grounding properties and their possible influence on bearing currents depend on the installed grid type (TN- or IT-grid, see DIN VDE 0100-310). Thus a correct electric installation of the drive system with all components is absolutely necessary to reduce the probability of occurrence of bearing currents. The total HF common-mode system behaviour is mainly described by its capacitive components (e.g. the capacitive coupling of the cable conductors and ground), as inductive components have a high HF impedance, whereas capacitive impedance decrease with frequency. Note that the high-frequency model e.g. of the motor cable consists of inductances and capacitances in a kind of daisy chain, resulting in travelling voltage waves between inverter output and motor terminal with voltage overshoot due to wave reflections at the high impedance of inductive winding motor input terminal. This voltage overshoot due to the reflection depends on motor size, cable length, du/dt of voltage impulses and of the cable type. This overshoot decays, as the electric energy per voltage impulse enters the motor winding, hence minimum and maximum steady state values of the common-mode voltage u_{CM} at the motor terminals are not influenced by the cable type, see Figure 46.

D.1.1 Bearing current evaluation methods

In order to determine, whether a bearing current amplitude is critical or not to the bearing life time, different research experiments have been carried out at modified electrical AC test machines, mainly cage induction motors. In real drive systems there is often the problem, that no bearing current can be measured directly. But if there is a bearing current measurement possible, one can derive the electric current and energy per bearing size, namely per *Hertz´*ian area between roller elements and bearing race way due to elastic deformation mainly of the roller elements under the mechanical baring forces, in order to get limits, which are independent of the different bearing sizes. As the bearing current flows punctually at a much smaller area than the *Hertz´*ian area, the corresponding current density is much smaller than the real one. It is therefore called “apparent” bearing current density. The electrical power per discharge or bearing current “event” has also to be evaluated per bearing size, as bigger bearings allow more current flow resp. more electrical power, before being severely damaged. Therefore the energy per discharge as an absolute value [3], [9] is useful as a limit value only in combination with a given bearing size. So also e.g. the electrical discharge energy must be taken as a “per area” value, where again the *Hertz´*ian area is a useful parameter. Electric energy or power as values in J or W allow only <u>in combination with a given bearing size</u> a limiting value.

- Apparent bearing current density J_b [1], [3]
- Energy [3], [9]
- Apparent bearing power $\hat{S}_b$ [5]

Apparent bearing current density J_b*:*

The appararent current density is defined as the measured amplitude of the bearing current, divided by the total *Hertz*’ian contact area A_{Hertz} of the loaded bearing.

Following values have been checked as useful limits for the apparent bearing current density:

Bearing will be destroyed soon	$\hat{J}_b > 1\,A/mm^2$
Bearing may be destroyed	$0.1 < \hat{J}_b < 1\,A/mm^2$
Bearing will be probably not destroyed	$\hat{J}_b < 0.1\,A/mm^2$

Energy methods (Only published for EDM bearing currents [3]):

The discharge energy during an EDM event is the time integral over the instantaneous electrical power in the bearing (which is the product of time signals of bearing voltage and bearing current). For the investigated bearing sizes it was found, that a bearing may be destroyed, if the discharge energy is > 4 nJ, which occurs repetitively at switching frequency of e.g. 8 kHz. For bigger bearing sizes bigger energy value limits will exist. For higher switching frequencies smaller energy values will already lead to damage. As mentioned, electric energy or power as values in J or W allow only <u>in combination with a given bearing size</u> a limiting value.

Apparent bearing power (Only published for EDM bearing currents [5]):

Apparent power $\hat{S}_\mathrm{b}$ for EDM bearing currents is obtained by multiplying the voltage amplitude before arcing and the first EDM bearing current peak amplitude after arcing. For example for a bearing type 6210 C3 in [5], it is measured that above 20 VA the bearing will be destroyed. In more detail:

Bearing will be destroy soon	$\hat{S}_\mathrm{b} > 60\,\mathrm{VA}$
Bearing can be destroyed	$20 < \hat{S}_\mathrm{b} < 60\,\mathrm{VA}$
Bearing will not be destroyed	$\hat{S}_\mathrm{b} < 20\,\mathrm{VA}$

In order to compare different bearing sizes, the apparent bearing power is related to the total *Hertz*'ian contact area of the bearing:

$$\hat{S}_\mathrm{b} = \hat{U}_\mathrm{b} \cdot \hat{I}_\mathrm{b} \ , \ \frac{\hat{S}_\mathrm{b}}{A_\mathrm{Hertz}} = \hat{U}_\mathrm{b} \cdot \hat{J}_\mathrm{b} = \hat{\sigma}_\mathrm{b} \quad .$$

As mentioned, it is important how often the bearing currents penetrate the bearing [3], [5]. All investigations have been done for typical IGBT inverter switching frequencies of several kHz. For these values the above noted limits are valid. A reduction of switching frequency leads to a reduction of bearing current events and thus to a longer bearing life time.

I. The inverter voltage pulse pattern as voltage source of the bearing currents at inverter-operation

The bearing currents at inverter-operation are caused by the common-mode voltage u_CM, which can be measured at the star point of the motor terminal (Figure 25). Figure 25 shows the voltage measurements at the motor terminals with the phase-to-ground voltages u_Ug, u_Vg and u_Wg, as well the three line-to-line voltages u_VW, u_WU, u_UV and the corresponding common-mode voltage u_CM. The common-mode voltage can be as well calculated by the arithmetic average of the three phase voltages ([13], see Chapter 8). The common-mode current occurs at each switching event and pass the capacitances which are located towards the ground (Figure 25). Hence the ground current and the bearing current occurrence probability are proportional to the switching frequency.

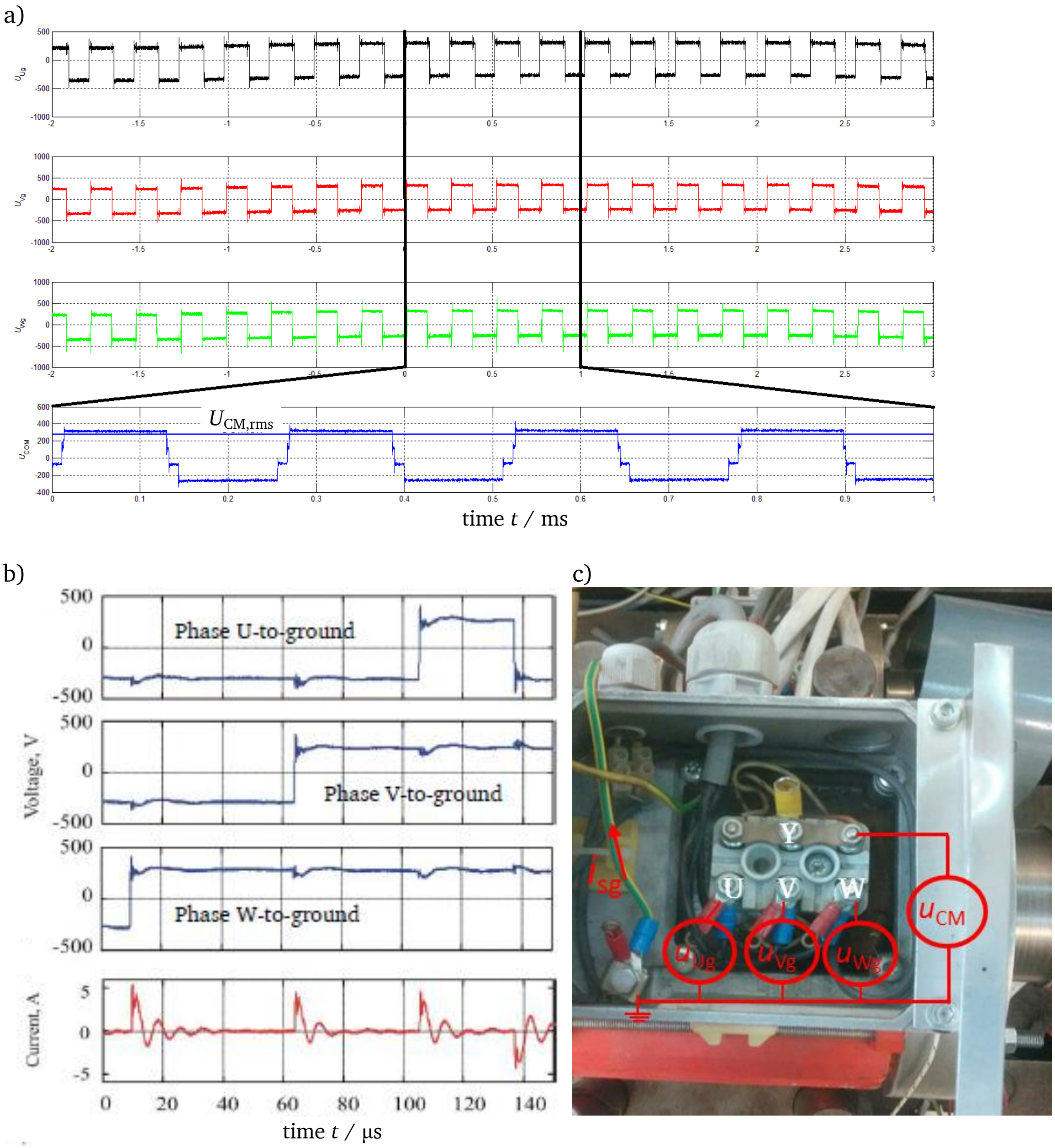


Figure 25: a) Measured line-to-ground voltages at operation with 2 m unshielded motor cable, DC link voltage 560 V, 4 kHz switching frequency, b) measured common-mode stator-to-ground current on a 240 kW-induction motor, c) measurement points at a star connected 1.5 kW-induction machine for the common-mode voltage u_{CM} at the star point at the motor terminals.

II. The influence of the motor supply cable on bearing currents [15]

For a review of a bearing damage or for the minimization of bearing current failures during system design, the cable issue has to be taken into account. The capacitances and inductances per unit length of the motor cable and the cable length, connected between inverter and motor, must be charged or discharged at each voltage step of the inverter. Thus the cable has an influence on the waveform of the voltage and acts similar to a low-pass filter. But depending on the length of the cable and on the du/dt of the voltage pulses, the corresponding travelling voltage waves may cause due to voltage wave reflections at the motor terminals an overvoltage there. For electric drive drains the terminating impedance of the cable is defined by the machine input impedance, which due to the winding inductance is big for high frequencies. Hence it is usually much higher than the wave impedance of the motor cable. Therefore especially with smaller motors (lower kW-range) with their higher number of turns per phase and thus higher winding impedance the common-mode voltage is nearly doubled by wave reflections. Thus twice the nominal voltage of the machine according to IEC 60034 [14] may occur. The second case why the cable topic is important is the EMC case, where the increase of ground currents has to be discussed. According to Figure 26 a capacitance to ground exists also for cables. Due to the voltage steps a common-mode current flow across this capacitance exists as a part of the total common-mode current. So the cable has an influence on the ground currents, hence also on the rotor-to-ground bearing currents. The lower the common-mode impedance of the cable to the ground, the less rotor-to-ground current will flow via the motor bearings in case of grounded rotor (Figure 27).

Cable type influence on:

- Common-mode current
- Common-mode voltage overshoot at motor terminals
- EMC (shielded vs. unshielded cable)

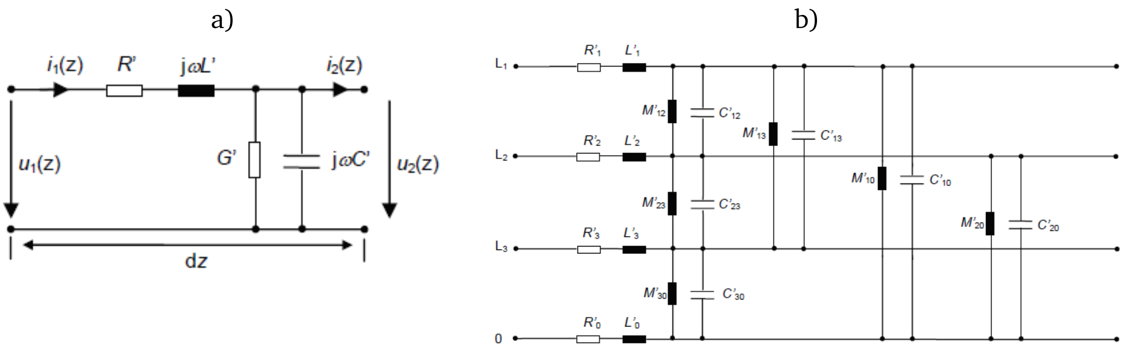


Figure 26: Equivalent circuit of a cable for a) one phase, b) for a three phase cable with consideration of the line and coupling elements, neglecting the low-valued conductances *G* [15]

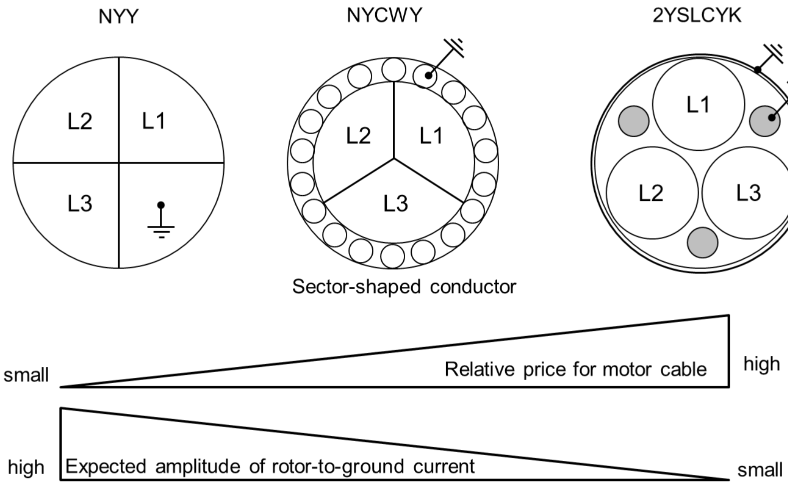


Figure 27: Influence of the cable type on rotor-to-ground bearing currents

III. The electric machine as capacitive network

The most common used AC electrical machines are induction machines (IM, mostly with cage rotor) and (permanent magnet) synchronous machines (SM resp. PMSM). Here cage induction machine and PM synchronous machine are considered. Both machine types have basically the same type of equivalent capacitive network, which is of interest at higher frequencies, hence especially at inverter operation (Figure 28). Three typical cases for the electric potential of the rotor of the electric machine are common:

- The rotor (and a coupled load) are electrically contacted via the bearings (either resistive at metallic bearing contact or capacitive at fully intact lubrication film) to the grounded frame (Figure 28)
- The rotor is directly grounded (e.g. by load like in a rolling mill by the steel rolls, or by a coupled planetary gear via the cog-wheels, or by grounding brushes to avoid electrostatic charging of the rotor etc.). A rotor is grounded in defined way, when a constant low impedance (also at HF) electric connection to ground is given (Figure 29).
- The rotor is intentionally electrically insulated (e.g. by an electrically insulated coupling to the load an encoder and by hybrid or ceramic bearings). Hence its potential is floating and is defined by capacitive coupling only.

Depending on the coupled drive components to the rotor (e.g. encoder (Chapter B-IV) or gears (Chapter B-V) and belt drive systems etc.), the capacitive equivalent network has to be modified (Figure 30, Figure 31). Thus the rotor may have an electric ground connection not always, but only at certain time intervals, or always, e.g. depending on the lubrication state of the metallic lubricated roller bearings with either partial metallic contact (“mixed” lubrication) or full lubrication with completely intact lubrication film thickness. For belt drive systems also electrostatic charging of the rotor is possible, which can cause discharges at the bearings as EDM bearing currents.

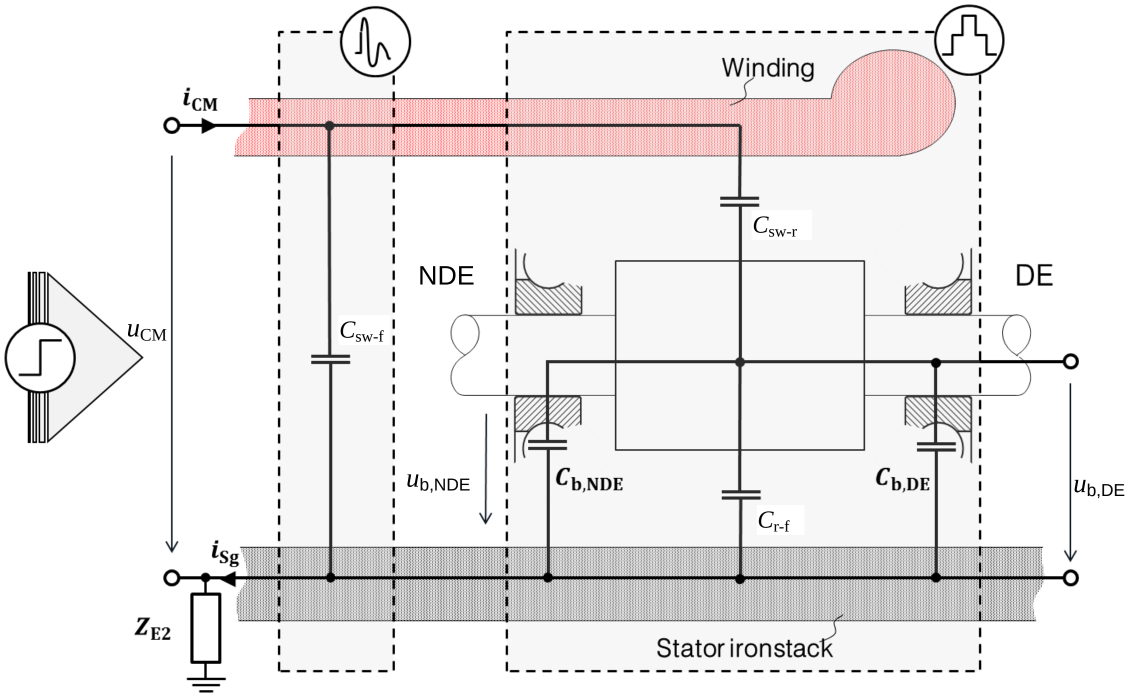


Figure 28: Equivalent capacitive circuit of an inner rotor cage induction or permanent magnet synchronous machine with insulated rotor, u_{CM}: common-mode voltage, u_b: bearing voltage; i_{CM}: common-mode current, i_{Sg}: stator-to-ground current, C_{sw-f}: stator winding-to-frame capacitance, C_{sw-r}: stator winding-to-rotor capacitance, C_{r-f}: rotor-to-frame capacitance, C_b: bearing capacitance, DE: drive end, NDE: non-drive end, Z_{E2}: grounding impedance of the machine housing.

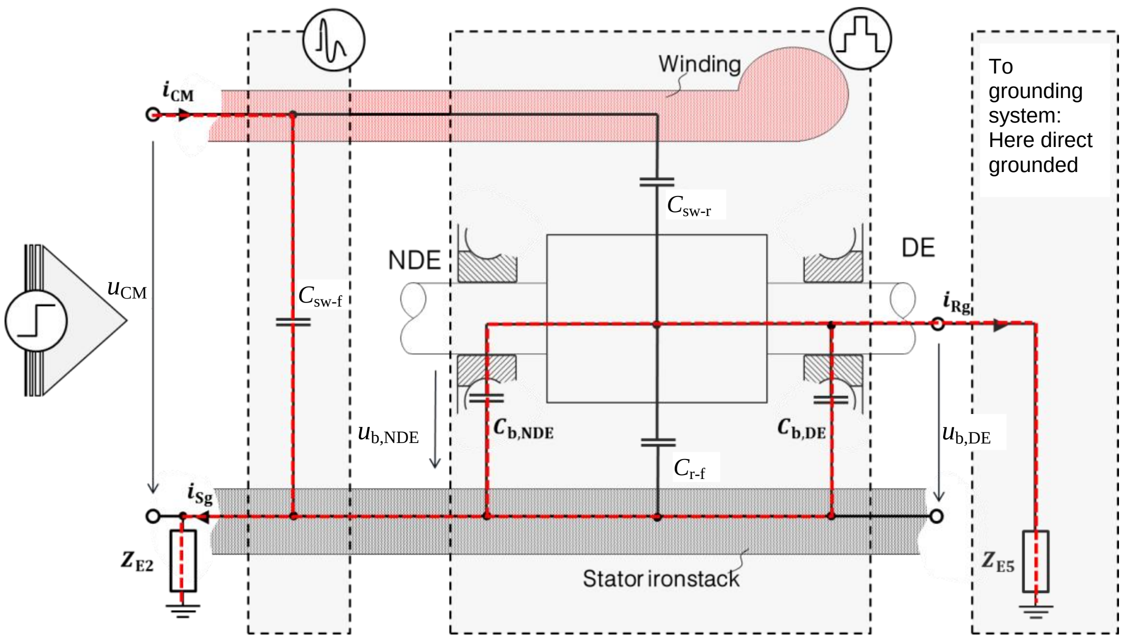


Figure 29: Equivalent capacitive circuit of an inner rotor cage induction or permanent magnet synchronous machine with a grounded rotor, u_{CM}: common-mode voltage, u_b: bearing voltage; i_{CM}: common-mode current, i_{Sg}: stator-to-ground current, i_{Rg}: rotor-to-ground current, C_{sw-f}: stator winding-to-frame capacitance, C_{sw-r}: stator winding-to-rotor capacitance, C_{r-f}: rotor-to-stator capacitance, C_b: bearing capacitance, DE: drive end, NDE: non drive end, Z_{E2}:grounding impedance of the machine housing; Z_{E5}:grounding impedance of the rotor of the electrical machine.

IV. Subsystem encoder: HF-equivalent circuit of an E-Machine with an encoder

For position or speed control in many applications an encoder is used, often directly coupled to the rotor of the E-machine. The encoder can therefore be also affected by the three bearing current types ii), iii), iv), as the encoder bearings (Figure 30) are in parallel to the machine rotor bearings. For EDM bearing currents the bearing voltage acts in the same way at the encoder bearings as at the parallel motor bearing. In case of circulating bearing currents with insulated rotor bearing e.g. at the non-drive end (NDE), and the encoder mounted on that NDE, the circulating bearing current loop will be closed via the encoder bearings. Hence the encoder bearings may be damaged.

A rotor-to-ground current can flow via the encoder bearings, when e.g. the metallic shielding of the encoder cable is connected at both ends (at the machine side and at the inverter side, as it should be done for full EMI protection), because then an electrical grounding path from the rotor to ground exists via the encoder.

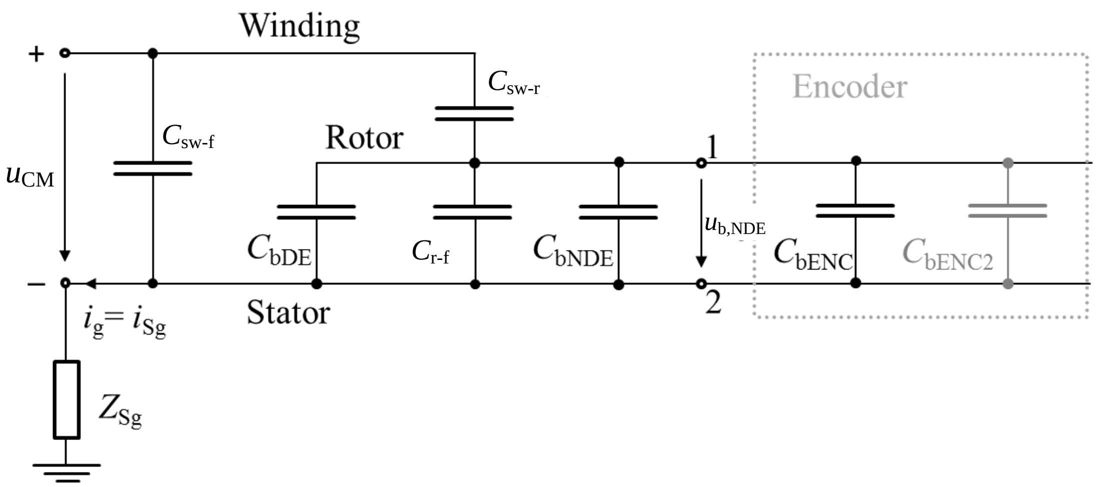


Figure 30: HF-capacitive network for induction machines (IM) and permanent magnet synchronous machines (PMSM) with an idealized encoder and with idealized motor bearings; Machine Capacitances: sw-f: stator winding-to-frame, sw-r: stator winding-to-rotor, r-f: rotor-to-frame, $C_{b,DE}$: bearing capacitance drive end, $C_{b,NDE}$: bearing capacitance non-drive-end, $C_{b,ENC}$ bearing capacitance encoder u_b: bearing voltage, u_{CM}: common-mode voltage, stator-to-ground impedance Z_{Sg}

V. Subsystem Gear: HF-equivalent circuit of an E-Machine with a gear [6]

If a gearbox is coupled to rotor of the machine, the capacitive HF voltage is acting via a voltage divider also on that component. Depending on the type of gear the type of equivalent capacitive models varies strongly (e.g. single stage gear box Figure 31). It is therefore recommended to contact a gear expert in case of damage to the bearing gears. A general description to the flow of HF bearing currents in gears is given in [6].

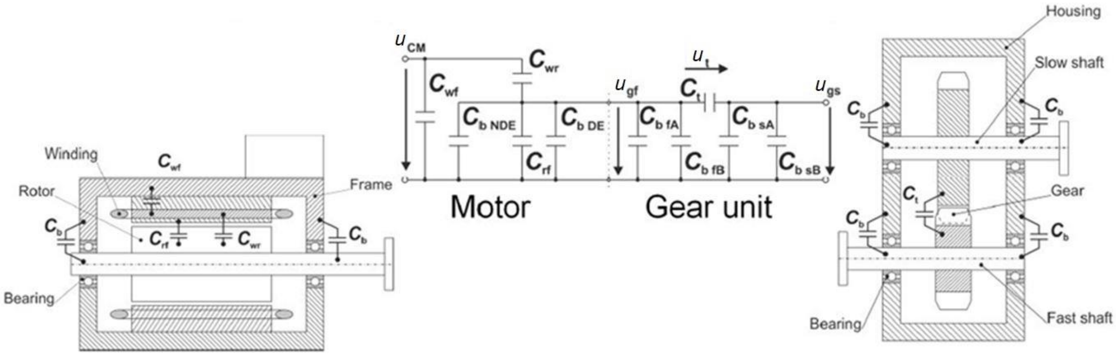


Figure 31: Combined equivalent circuit for a drivetrain consisting of an electrical motor and a single stage gearbox

VI. Influence of grounding conditions

The grounding conditions influence strongly the magnitude and the paths of HF grounding currents. With low HF impedance this will lead to higher grounding currents, which may lead to higher bearing currents, if the rotor is grounded. Three issues strongly depend on the grounding conditions of an electrical inverter-fed drive system:

A) Avoiding a parasitic ground current flow
B) Floating rotor electrical potential
C) Measures to ensure electromagnetic compatibility (EMC)

A) Avoiding a parasitic ground current flow

A ground current flow is called “parasitic”, when it flows in an unforeseen way e.g.

I) At multiple grounding,
II) At ring grounding,
III) If the main grounding impedance is in reality much higher as expected,
IV) If grounding paths exist, which were not intended

Hence the grounding system shall always be planned thoroughly with an electric circuit plan. Be careful in adding additional grounding cables at the existing drive without following the original grounding concept.

B) Floating rotor electrical potential

A floating rotor electrical potential is especially found, where:

I) no defined rotor grounding,
II) a bad rotor grounding (with an unstable rotor-to-ground connection),
III) a too high rotor grounding HF impedance,
IV) an additional voltage source, which is electrically coupled to the rotor (such as a electrostatic charging by belt friction or steam turbine friction in generator sets)

exists. Such a floating potential can put the rotor to unwanted high electrical potentials with high discharge currents in the rotor bearings and should be avoided.

C) Measures to ensure electromagnetic compatibility (EMC):

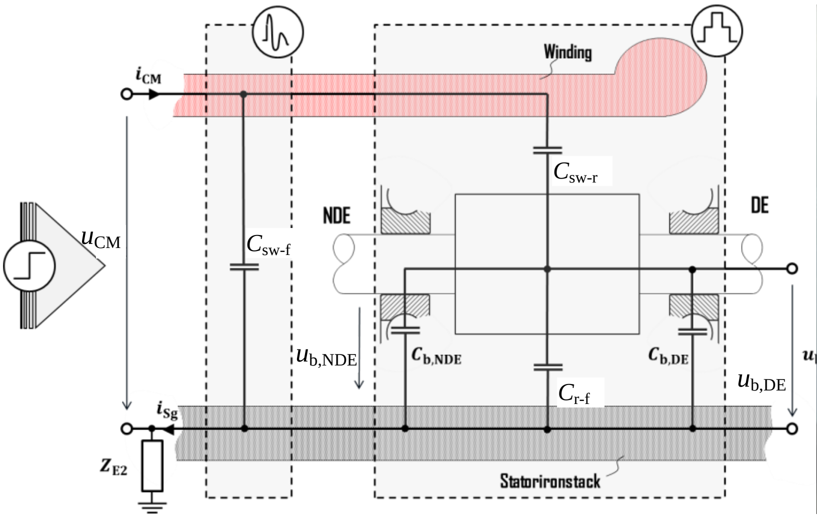
- I) Proper grounding is a demand for good EMC, hence obey A) and B),
- II) Suitable selection of drive system components with proper EMC design,
- III) Use fully shielded motor cables with the cable shield connected by special connectors fully to the metallic surface of motor and inverter housing.

In order to comply with demands C I), II), III) follow the EMC and grounding guidelines in the technical handbooks of the manufacturers for the used drive components, when installing the inverter-fed drive.

D.1.2 EDM bearing currents

„Electric-Discharge-Machining“ (EDM) bearing currents are discharge currents via short electrical arcs, which occur when the charged lubrication film is electrically punched through. Such EDM bearing currents are generated in bearings of inverter-fed machines, because a part *BVR* of the stator winding common-mode voltage u_{CM} is charging as bearing voltage u_b at each inverter switching the bearing across the intact electrically insulating (“high-impedance”) lubricant film thickness h_{grease} (see: the capacitive network of the electrical machine (Figure 32) and coupled drive components (Figure 24)). The ratio of the bearing voltage to the common-mode voltage is called bearing voltage ratio (BVR, equation (D1.2-1) and is typically in the range of 0 … 10% for stator-fed electrical machines and up to 90% for rotor-fed electrical machines.

If the corresponding electric field strength in the bearing´s lubrication film $E_b = u_b/h_{grease}$ is lower than the electric breakdown field strength E_{th} of the lubricant, then the bearing voltage u_b is the part *BVR* of stator winding the common-mode voltage, which is fed by the inverter. If E_b surpasses E_{th}, the oppositely charged inner and outer bearing ring and roller elements are discharged with a short arc (“sparking”). For typical high-impedance lubricant and typical film thickness already a small bearing voltage of e.g. 0.5 V may cause such an arc across the lubricant film with its discharge current called EDM bearing current. This may happen as well in the bearings of a coupled encoder or in the gear bearing, which are in the electrical network in parallel to the motor bearings, depending on the local flash-over conditions.



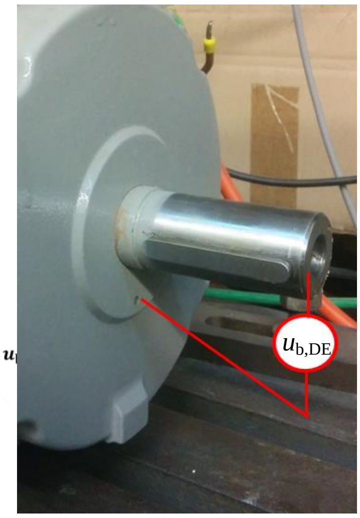


Figure 32: a) HF-Capacitive network for inner rotor cage induction machine (IM) and permanent magnet synchronous machine (PMSM) with idealized bearings; Machine capacitances: sw-f: stator winding-to-frame, sw-r: stator winding-to-rotor, r-f: rotor-to-frame, $C_{\mathrm{b,DE}}$: bearing capacitance drive end, $C_{\mathrm{b,NDE}}$: bearing capacitance non-drive-end, u_{b}: bearing voltage, u_{CM}: common-mode-voltage, stator-ground-impedance Z_2, b) Measurement position of bearing voltage at the drive end of an induction machine with inner rotor.

$$BVR = \frac{u_{\mathrm{b}}}{u_{\mathrm{CM}}} = \frac{C_{\mathrm{sw-r}}}{C_{\mathrm{sw-r}} + C_{\mathrm{r-f}} + 2 \cdot C_{\mathrm{b}}} \qquad \text{(D1.2-1)}$$

<u>**For EDM bearing currents the following is typical:**</u> (see Figure 34)

- A sudden breakdown of the bearing voltage u_{b} at the time t_{arc}, when the discharge occurs
- This EDM-breakdown time t_{arc} is usually different from the time t_{CM}, when the common mode voltage u_{CM} and hence the stator-to-ground current change due to inverter switching
- It may occur that no EDM bearing currents occur although the inverter is switching
- With increased inverter switching frequency the common-mode voltage and the bearing voltage change more often, so more often an EDM bearing current event may occur.
- EDM bearing currents may only occur, if the lubricating film thickness is insulating sufficiently to allow a voltage build-up, so when the bearing operates in mixed and full lubrication state, mainly at high-impedance lubricants.
- As with increasing bearing temperature the viscosity of lubricant decreases and thus the film thickness, the same thickness like in a cold bearing will occur at higher speed due to the hydrodynamic build-up effect. Hence in a hot machine the EDM occurs at higher speed than in a cold machine.
- Typical bearing damage due to EDM are arc craters at the bearing raceway and roller element surfaces, which may lead due to the over-rolling effect of the crater rims to a greyish surface. The discharge energy is usually too small to “burn” or blacken the lubricant significantly (see Chapter B).

Influence of the bearing operation state:

Bearing temperature:

- Consider a bearing at given speed and load force. The higher the bearing temperature, the smaller the lubrication film thickness, and the bigger the electric field strength at a given bearing voltage. So the film will break down already at a small bearing voltage. So for each discharge event, the discharge energy is lower and the bearing current amplitude is smaller than at bigger lubrication film thickness, as shown in Figure 43.

Bearing load:

- Consider a bearing at given speed and temperature. A higher bearing load force leads to a bigger *Hertz´*ian and a smaller apparent EDM bearing current density, especially at higher axial bearing load.

Bearing type:

- Radial and axial roller bearings typically have no metallic contact in the nominal operation range at “full lubrication” i.e. at intact lubricating fil thickness. But in axial bearings all e.g. roller ball elements have the same load force, so the discharge may happen at all elements with the same probability. In radial bearings the roller elements in the load zone suffer from the discharges due to the narrow film thickness there. So fluting will occur at the roller elements and the inner ring raceway surface uniformly distributed, but at the outer ring raceway surface only in the load zone.
- For bearings with possible rim contact such as cylindrical roller bearings, the arc may occur due to a short distance to the rim.

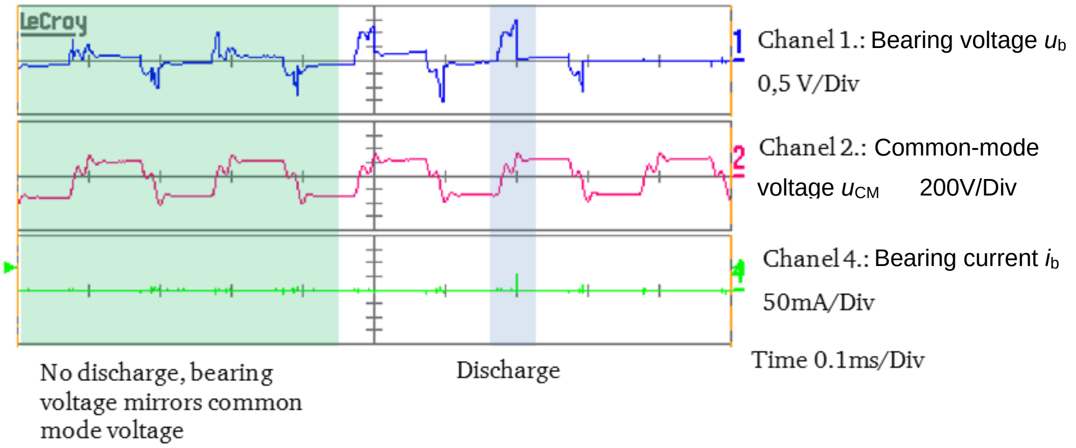


Figure 33: Measurement for 1 ms of EDM bearing current for a especially prepared inverter-fed 1.5 kW-induction machine (insulating layer at the bearing seat), speed of n = 300 min^{-1}, average inner/outer ring bearing temperature ϑ_{mb} = 24 °C, radial bearing load F_r = 63 N, axial bearing load F_a = 50 N: Channel 1 – bearing voltage u_b, channel 2 – common-mode voltage u_{CM}, channel 4 – EDM bearing current i_b .

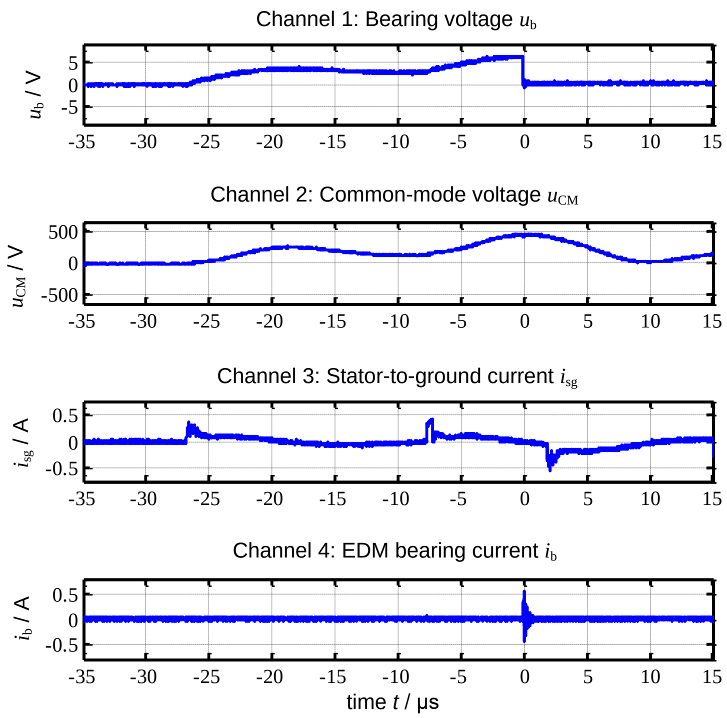


Figure 34: Example for an EDM bearing current event for an especially prepared inverter-fed 1.5 kW-induction machine (insulating layer at the bearing seat), speed of n = 1500 min^{-1}, average inner/outer ring bearing temperature ϑ_{mb} = 58 °C, radial bearing load F_r = 63 N, axial bearing load F_a = 50 N: Channel 1 – bearing voltage u_b, channel 2 –common-mode voltage u_{CM}, channel 3 – stator-to-ground current $i_g = i_{Sg}$, channel 4 – EDM bearing current i_b.

D.1.3 Rotor-to-ground bearing currents

Rotor-to-ground bearing currents may occur, when the rotor is grounded intentionally or inherently via the drive system via a grounding connection. The rotor grounding condition is therefore intentionally by brush sliding contacts and grounding cable, but often it is an inherent "parasitic" grounding connection, e.g. via the shielding of the encoder cable or via the coupled shaft and cog-wheel of a coupled gear. As both bearings are electrically in parallel, the share of current per bearing depends on the actual bearing impedance and may fluctuate between 0% and 100% current share. Once one bearing has taken over the ground current, it very often stays conductive and bears the full 100% rotor-to-ground current load. The ratio of stator-to-ground impedance to rotor-to-ground impedance (Z_{Sg} / Z_{Rg}; in Fig. 35: Z_{E2} / Z_{E5}) defines via a "current divider" the amount of ground current flowing by the rotor-to-ground path via the bearings. Hence the rotor-to-ground current wave shape is similar to the stator-to-ground current wave shape. Both are summing up to be the total common-mode HF current flowing across the stator winding insulation due to the capacitive coupling, caused by the common-mode voltage.

Hence an increase of the amplitude of the total winding-to-ground directly increases the amplitude of the rotor-to-ground current. The total winding-to-ground current is depending via the common-mode voltage on the used inverter output-voltage pulse pattern, on the type and length of the motor cable, on the inverter output filters (if there are any) and as well the motor geometry (stator slot count, slot insulation thickness, winding overhang geometry, geometrical dimensions, etc.) have a big influence. In case of rotor-fed electrical machines the rotor slot count and geometry are of decisive influence.

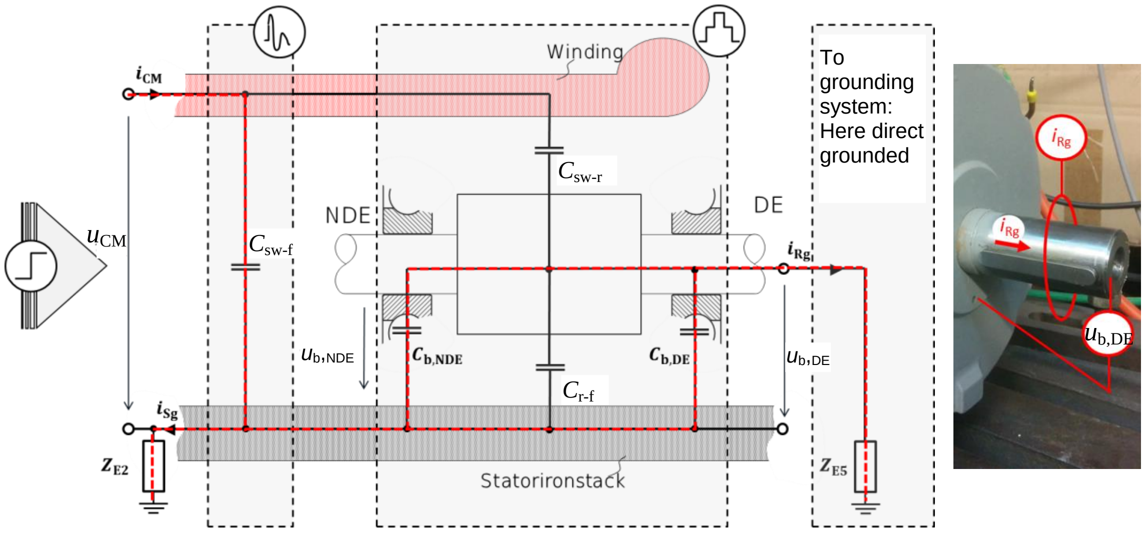


Figure 35: a) HF-Capacitive network for stator-fed, inner rotor induction machines (IM) and permanent-magnet synchronous machines (PMSM) with (idealized) capacitive bearings. Motor capacitances: sw-f: stator winding-to-frame, sw-r: stator winding-to-rotor, r-f: rotor-to-frame, $C_{b,DE}$: bearing capacitance drive end, $C_{b,NDE}$: bearing capacitance non-drive end, u_b: bearing voltage, u_{CM}: common-mode voltage, stator-to-ground impedance Z_{E2} (red dashed line: possible rotor-to-ground current path, rotor-to-ground impedance Z_{E5}), b) Measurement point (e.g. *Rogowski* coil) for rotor-to-ground current i_{Rg}.

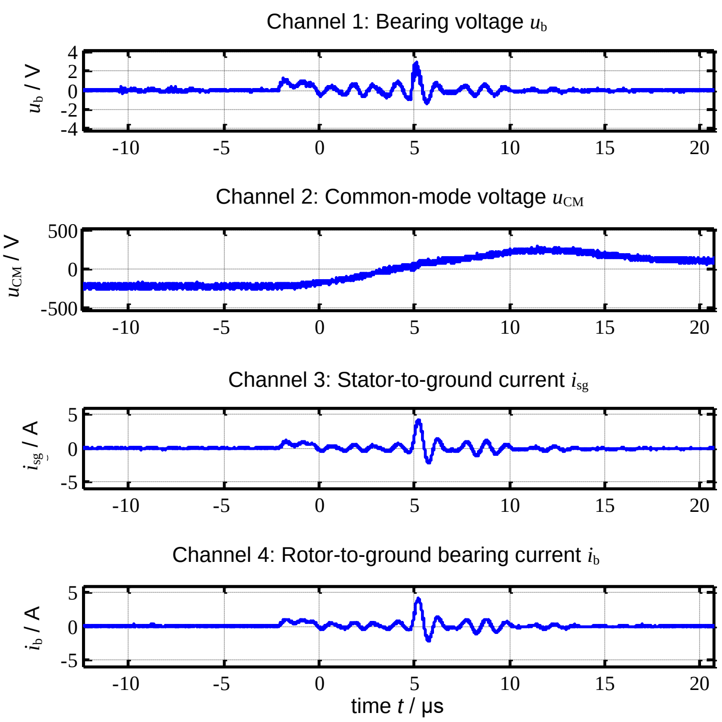


Figure 36: Example for a measured rotor-to-ground current at an especially prepared inverter-fed 1.5 kW-induction machine, speed of n = 1500 min^{-1}, bearing type 6205 C3, average outer/inner ring bearing temperature ϑ_{mb} = 100 °C, radial bearing load F_r = 240 N, axial bearing load F_a = 350 N: Channel 1 – bearing voltage u_b, channel 2 –common-mode voltage u_{CM}, channel 3 – stator-to-ground current $i_g = i_{sg}$, channel 4 – rotor-to-ground bearing current i_b

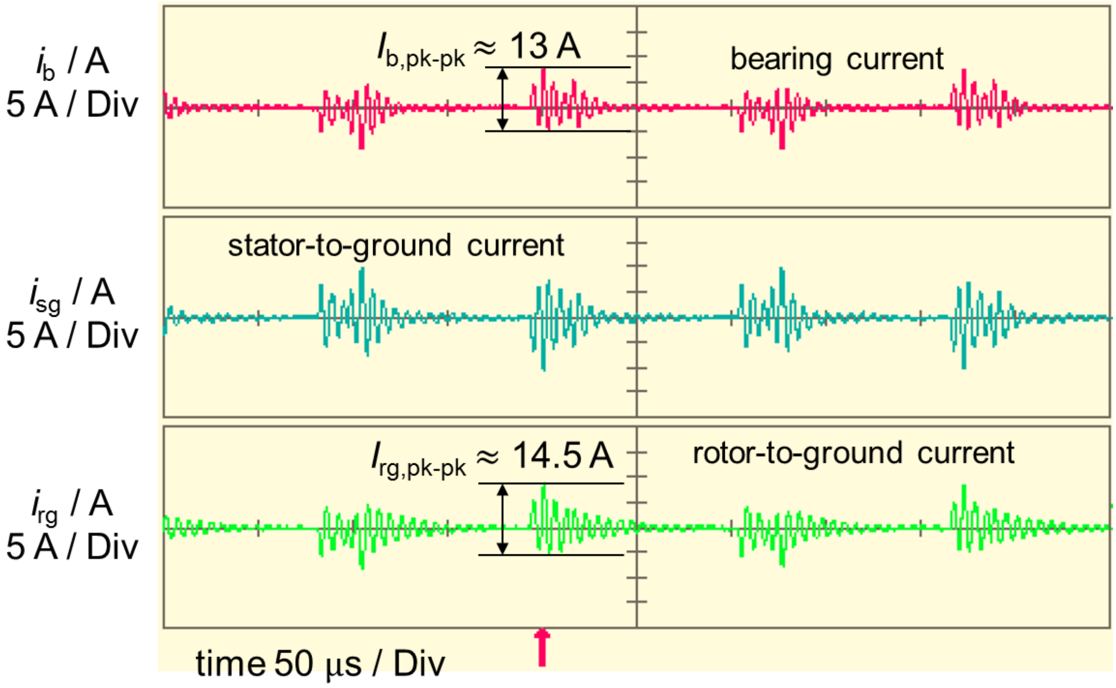


Figure 37: Example for a measured rotor-to-ground bearing current at an especially prepared inverter-fed 110 kW-induction machine with grounded rotor. Grease type: Arcanol MULTI3, bearing type 6317 C3, rotor speed n = 300 min^{-1}, average bearing temperature ϑ_{mb} = 70 °C, radial bearing load F_r = 2500 N and axial bearing load F_a = 1300 N: Channel 1 – bearing current i_b at drive end, channel 2 – stator-to-ground current $i_g = i_{Sg}$, channel 3 – rotor-to-ground current i_{rg}

For rotor-to-ground bearing currents it is typical, that they:

- have the same wave shape as the stator-to-ground current,
- occur with their peak amplitudes at the same time t_{CM} as the stator-to-ground current peaks,
- occurs at the same time t_{CM}, when the common-mode voltage is changed due to switching,
- occur with a rate, which is proportional to inverter switching frequency,
- very often do not occur directly after starting the drive, but with a certain time delay (to get the bearing into a conductive state).
- cause due to their considerable magnitude a greyish raceway, but very often in the long run fluting of the bearing raceway and a strongly aged lubricant, which is black coloured (see Chapter B)

Influence of the bearing operation state on the rotor-to-ground bearing currents:

Bearing temperature:

- No influence

Bearing load:

- Higher bearing loads, especially higher axial bearing loads, leads via the increased *Hertz´*ian area to lower apparent bearing current density and allow longer operation time until final bearing failure

Bearing type:

- Independ of bearing type

Lubrication type:

- Grease lubricated systems are destroyed faster than oil lubricated systems
- Low-impedance lubricants are not suitable to reduce the rotor-to-ground bearing currents

D.1.4 Circulating bearing currents

Circulating bearing currents occur only in bigger inverter-fed AC machines with typical machine frame sizes bigger than 225 mm, corresponding to a typical rated power above 50 kW at 1500/min. The circulating bearing current is driven by a parasitic HF shaft voltage, which is induced by a parasitic HF circulating magnetic flux, which is excited by the total winding-to-ground current, which at insulated rotors is identical with the stator-to-ground current i_{sg}. The stator-to-ground current is caused in inverter-fed AC machines due to the common-mode winding voltage, fed by the inverter. At the stator winding-to-stator capacity $C_{sw\text{-}f}$ (Figure 35) this capacitive current occurs and rises with increased du/dt-voltage rise of the inverter pulse-width modulated output voltage. The parasitic HF circular magnetic flux is linked to the “loop”, constituted by the stator iron stack, the end shields with the bearings, and the rotor shaft. This flux magnitude rises with the machine size. Above a frame size 250 mm its induced HF loop voltage (with a frequency in the range of some hundreds of kHz) is big enough to drive the circulating bearing current in that loop, if the roller bearings are not insulated. If the bearings are insulating via the lubrication film or via the intended bearing insulation, no circulating current will flow. Then this induced HF voltage can be measured e.g. as HF shaft voltage between the two outer bearing rings at NDE and DE. If a circular bearing current is flowing, the corresponding voltage drop due to that current occurs as “shaft voltage”. Especially at low speed (e.g. 150/min, Fig. 38), when the bearings have a partially metallic contact between inner and outer bearing ring via the roller elements, they are conductive. Hence non-insulated bearings show especially at low speed considerably high circulating bearing current. Again, with a coupled gear, this circulating bearing current may also flow via the gear bearing, if the DE bearing of the motor is insulated.

Hence an insulated coupling to the gear or an insulated DE gear bearing can interrupt the circulating current flow. Note that the bearing current signal at DE and NDE has the same wave shape, but with the same current direction from outer to inner bearing ring with opposite polarity (Fig. 40). As the "loop" acts as a secondary winding of a current transformer with the stator-to-ground current as the primary current and the circulating bearing current as the secondary current, both stator-to-ground current and circulating bearing current have the same wave shape (Fig. 38). The ratio of amplitudes of circulating bearing current and stator-to-ground current is called "bearing current ratio" BCR with $0 < BCR < 1$, which depends on frequency and usually decreases strongly with rising speed, as the bearings impedance rises (Fig. 38: n = 150/min, BCR = ca. 0.2). Other parameters, that influence the bearing impedance and thus the BCR, are bearing temperature and bearing load.

Note that due to magnetic asymmetries especially in 2-pole cage induction machines of bigger frame size, but also due to rotor eccentricities, a parasitic circular magnetic flux may occur e.g. at stator slot frequency. This low-frequent flux is excited by the fundamental stator current and induces a low-frequent shaft voltage, which causes additional low-frequent circular bearing currents. These additional "classical" circular bearing currents also endanger the bearings. Countermeasures are identical with those for HF circular bearing currents.

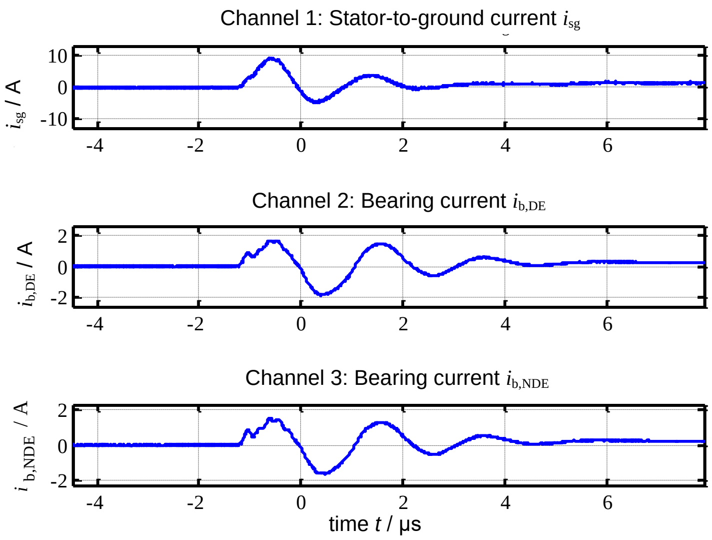


Figure 38: Example for a measured circulating bearing current for an especially prepared inverter-fed 110 kW-cage induction machine, speed of n = 150 min^{-1}, average outer/inner ring bearing temperature ϑ_{mb} = 40 °C, radial bearing load F_r = 2500 N, axial bearing load F_a = 1300 N: Channel 1 – stator-to-ground current i_{sg}, channel 2 – circulating bearing current at drive end side $i_{b,DE}$ (from <u>inner to outer</u> bearing ring) , channel 3 – circulating bearing current at non-drive end side $i_{b,NDE}$ (from <u>outer to inner</u> bearing ring)

Hence the circulating bearing current can only flow with considerable amplitude, if the "loop" is conductive, hence when the impedance of the bearings is small. This is the case as long as the bearings operate in a conductive case, hence at low speed with metallic contact in the bearings. At elevated speed bearings with synthetic and mineral high-impedance oil lubrication operate in full lubrication and will reduce the circulating bearing current to a harmless value. But then discharge currents (EDM) may occur, which will for short time lead the bearing into conductive state, causing again an intermittent circulating bearing current. Low-impedance lubricants are therefore not suitable for the reduction of bearing currents. A typical method to prevent circulating currents in electric machines is the use of insulated bearings, at least at on side e.g. DE.

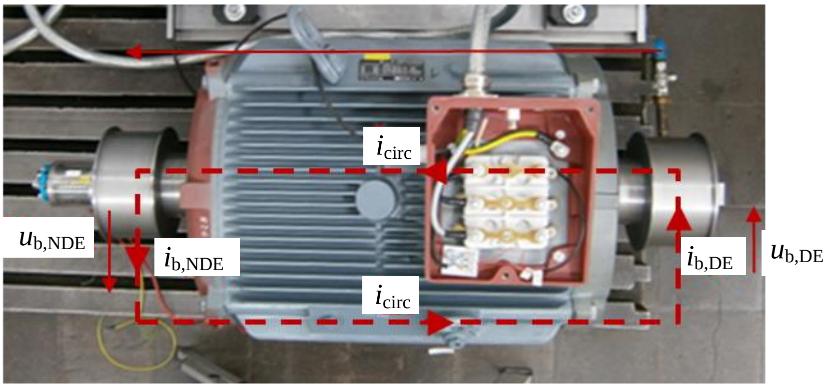


Figure 39: Current flow in case of circulating bearing currents, presented at 110 kW-cage induction machine (here with belt drives at both sides).

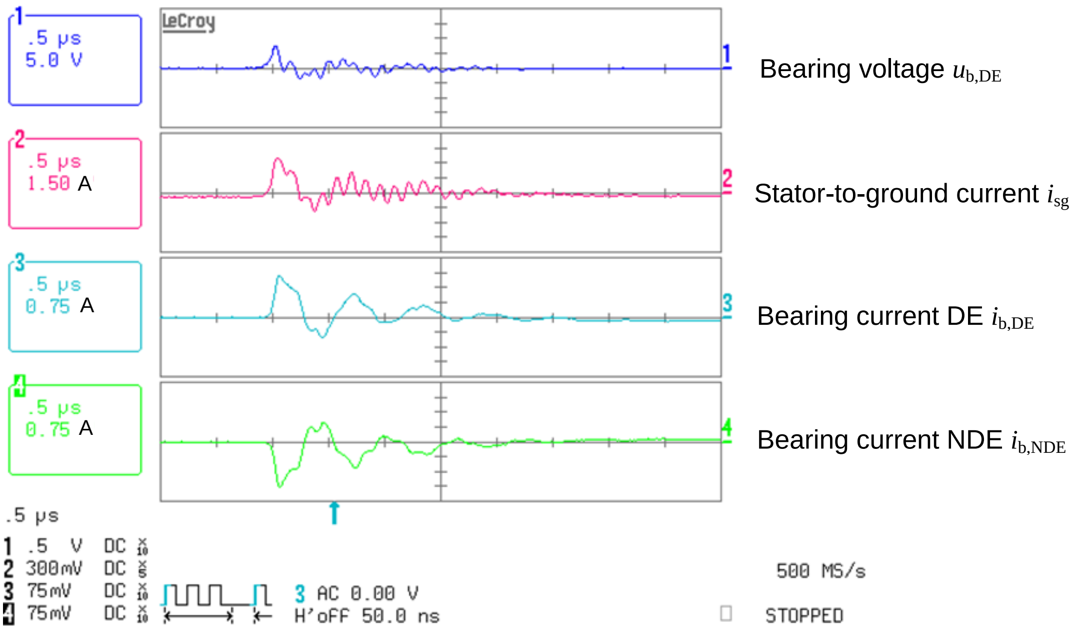


Figure 40: Example for a measured circulating bearing current for an especially prepared inverter-fed 110 kW-cage induction machine, speed of n = 300 min^{-1}, average inner/outer ring bearing temperature ϑ_{mb} = 40 °C, radial bearing load F_r = 2500 N, axial bearing load F_a = 1300 N: Channel 1 – bearing voltage u_b, channel 2 – stator-to-ground current i_{Sg}, channel 3 – circulating bearing current at drive end side $i_{b,DE}$ (current direction from inner to outer ring), channel 4 – circulating bearing current non-drive end side $i_{b,NDE}$ (current direction from inner to outer ring).

A typical AC machine in the field application, which therefore has no special insulated bearing seats, does not allow the circulating bearing current measurement. Therefore only the bearing voltage and the stator ground current could be measured. Due to the ohmic behaviour of the conductive bearing the measured signal wave forms of the bearing voltage (being proportional to the bearing current) and stator-to-ground current should be similar (Fig. 40). This is a strong hint that a circulating bearing current is flowing. In special cases of big machines, a placing of the *Rogowski* coil around the shaft within the machine might be possible to measure the circulating bearing current directly.

For circulating bearing currents it is typical, that they:

- have the wave form shapes as the stator-to-ground-current,
- occur at the same time t_{CM} as the stator-to-ground current,
- occur at the same time t_{CM}, when the common-mode voltage changes,
- have an occurrence rate proportional with the switching frequency,
- occur mainly in the low speed range, if high impedance lubricants are used in the bearings (which is mostly the case),
- occur only in bigger AC machines, typically > 50 kW or frame sizes > 250 mm
- cause due to their considerable magnitude a greyish raceway, but very often in the long run fluting of the bearing raceway and a strongly aged lubricant, which is black coloured (see Chapter B)

Influence of the bearing operations state:

Bearing temperature:

- Strong influence of bearing temperature, because hot bearings with then low lubricant viscosity have smaller lubricant thickness and are easier penetrated by circulating bearing currents

Bearing load:

- Higher bearing loads, especially higher axial bearing loads, leads via the increased *Hertz*´ian area to lower apparent bearing current density and allow longer operation time until final bearing failure

Bearing type:

- Independ of bearing type

Lubrication type:

- Grease lubricated systems are destroyed faster than oil lubricated systems
- Low-impedance lubricants are not suitable to reduce the circulating bearing currents

D.1.5 Bearing currents at other machine types

So far, mainly cage induction machines have been discussed due to their wide use in industrial applications. PM synchronous machines with inner rotor are usually less sensitive to bearing currents, especially with surface mounted magnets due to the bigger equivalent magnetic air gap. Other types of AC machines have different equivalent capacitive circuits, which define the occurring HF bearing currents. Two often discussed machine topologies are the doubly-fed induction machine (DFIM), used as wind generator, and the permanent synchronous machines with outer rotor, used in small power application for variable-speed fan drives.

a) Doubly-fed induction machine (DFIM) [16]

For the rotor-fed DFIM the BVR is very big, typically in the range of 60% … 80%. Thus the bearing voltage exceeds the threshold voltage nearly always, so an electric breakdown occurs anyway, and an EDM bearing current flows. Hence, in DFIMs the bearings remain nearly always electrically conductive after such an initial electric discharge (EDM bearing current event), and the lubricant loses its isolating properties. Therefore at each change of the rotor-side common-mode voltage a high rotor-to-ground current flows via the big rotor winding-to-rotor capacitance C_{rw-r} directly to the ground, if the rotor is grounded, and will not pass by the bearings. This can be seen in the simplified equivalent circuit in Figure 41. Therefore the bearings have to be insulated in any case, and the rotor has to be grounded to avoid a bearing current flow.

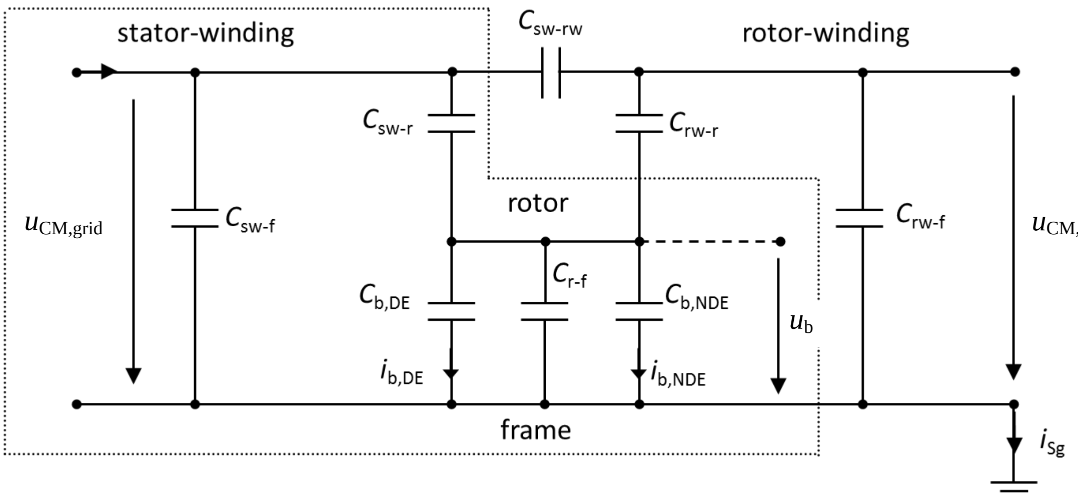


Figure 41: Equivalent circuit for doubly-fed induction machines (DFIM), bearing voltage u_b from the rotor-side common-mode voltage $u_{CM,inv}$. The stator-side common-mode voltage u_{CM} has grid-frequency e.g. 50 Hz and therefore does not generate any considerable common-mode current. HF machine capacitances of a DFIM, sw: stator winding, rw: rotor winding, f: frame, r: rotor, b: bearing, DE: drive end, NDE: non-drive end (The dashed line encircles the stator-fed cage induction machine, where the non-insulated rotor cage has the same electrical potential as the rotor iron r) (Figure 28).

b) Permanent-magnet synchronous machine with outer rotor

The equivalent circuit with HF parasitic capacitances for PMSM with outer rotor design is similar to induction machines, shown for a small fan drive in Figure 42 b). Due to the small size of this motor no circulating bearing currents can occur, but only discharge bearing currents. The apparent bearing current density is high for such small machines, if the same rated voltage is used as for bigger machines, because of the smaller *Hertz*'ian area of the small bearings.

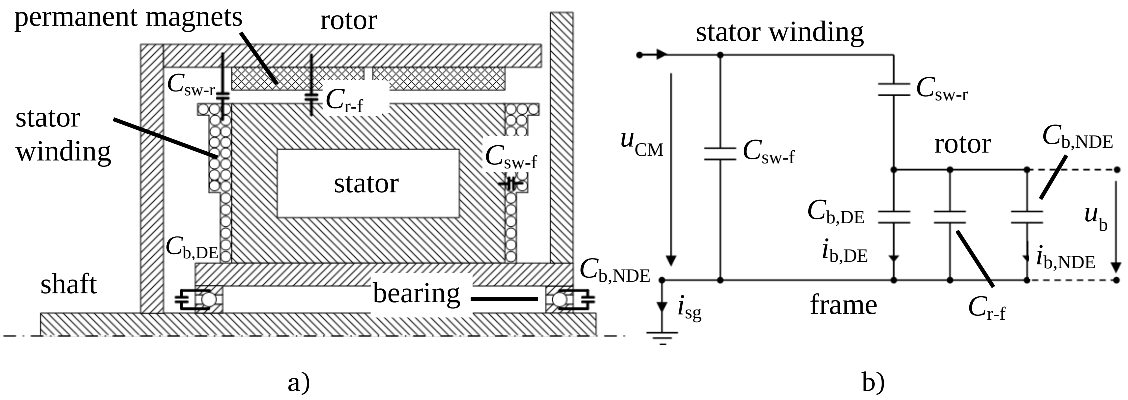
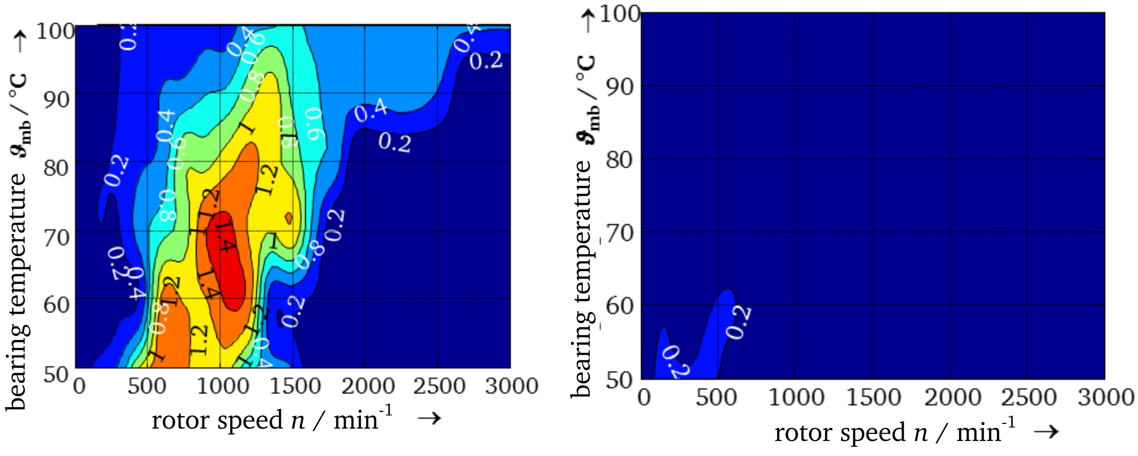


Figure 42: a) Schematic cross section of the upper half of a fan drive with parasitic machine capacitances, b) Equivalent capacitive circuit for calculating the bearing voltage u_b from the common-mode voltage u_{CM} via the HF machine capacitances. u_{CM}: common-mode voltage, u_b: bearing voltage, sw: stator winding, r: rotor, f: frame, isg: stator-to-ground current, DE: drive end, NDE: non-drive end).

D.1.6 Influence of lubricant condition on bearing currents

The condition of the lubrication film influences the bearing current type, amplitude and probability of occurrence. Depending on the operation parameters (speed, bearing load, bearing temperature) the lubricated bearing state could be conductive, mixed friction or fully lubricated. For conductive state (metallic contact between inner and outer bearing ring) the bearing behaves electrically resistive, in the mixed friction state the bearing changes between resistive and capacitive behaviour and in the fully lubricated state the bearing behaves electrically as a capacitance. Further the electric properties of the lubricant have an influence on the electric behaviour of the lubricated bearing. So we distinguish between low impedance and high impedance lubricant as Low-Impedance Grease (LIG) and High-Impedance-Grease (HIG) with a difference in conductivity by typically 6 orders of magnitude [6].



a) b)

Figure 43: Measured EDM bearing current occurrence at a 1.5 kW-induction motor, bearing type 6205 C3, drive end. Measured pk-to-pk EDM bearing currents a) for a High-Impedance-Grease (HIG) and b) for a Low-Impedance-Grease (LIG) for different bearing temperatures and speeds [3]

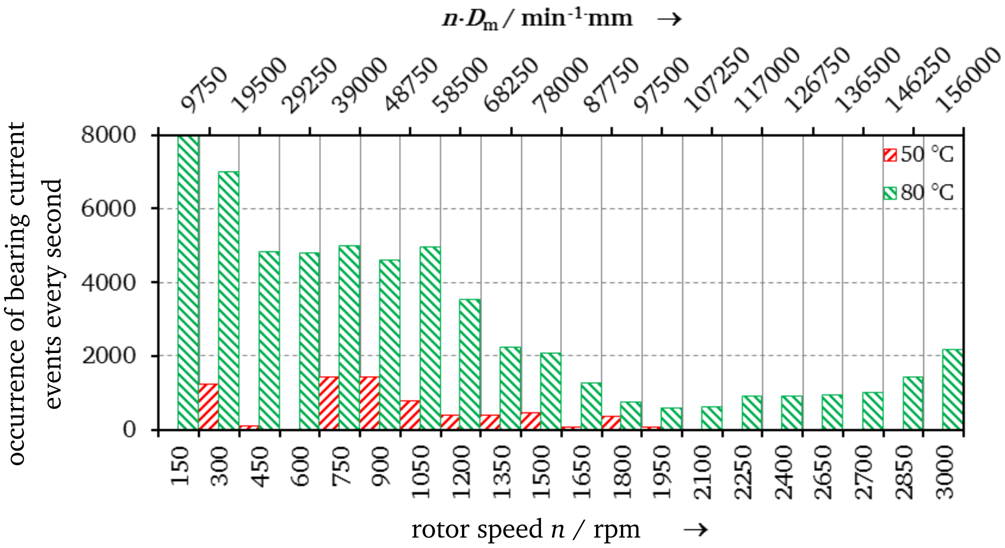


Figure 44: Measured occurrence of EDM bearing current events at a 1.5 kW-induction motor, bearing type 6205 C3, non-drive end. High-Impedance-Grease (HIG), outer/inner ring average bearing temperature 50 °C and 80 °C. [3]

Influence of lubricant properties on the bearing currents:

a) EDM bearing currents:

High-impedance lubricant:

As explained above, the EDM bearing current amplitude rises with increased film thickness, hence at a given temperature with rising speed, as film thickness increases with rising speed. Above a certain speed (and thickness) the bearing voltage is not any longer able to cause a film discharge, so the EDM bearing currents vanish or get seldom events. With higher temperature and thus lower lubricant viscosity the same film thickness occurs at higher speed, so the maximum of EDM bearing current occurrence shifts with rising bearing temperature to higher speed values. So EDM peak currents typically occur with the highest amplitudes in a certain band of bearing temperature and rotor speed. The biggest amplitudes were measured at a specific normalized lubricant film thickness (film thickness divided by surface roughness) $\lambda = 3 \dots 5$. With too high bearing temperature the low viscosity and corresponding lower lubricant film thickness leads only to small bearing current amplitudes (Fig. 43a).

Low-impedance lubricant:
The conductive behaviour of the lubricant does not allow a voltage build-up across the film, so no discharge currents can occur (Fig. 43b). Hence a LIG is a good counter-measure to reduce EDM bearing currents (Fig. 44).

b) Rotor-to-ground bearing currents:

As the total grounding circuit impedance determines the rotor-to-ground current flow, the type of HIG or LIG influences the rotor-to-ground current flow only in a minor way. Hence for rotor-to-ground bearing currents with apparent current densities above $0.3\,A/mm^2$ a damage of the bearing can occur independent of the lubricant type. At higher radial and axial load e.g. for radial bearings, the lower current density allow the bearing to withstand longer these currents without damage.

c) Circulating bearing currents:

High-impedance lubricant:
The amplitude and the speed range, where circulating bearing currents occur, depend on the bearing and as well on the lubricant type and its electric properties. For HIG circulating bearing currents mainly occur in the non- or mixed lubricated state, hence at low speed. At rated speed with its full lubrication there will not be a circulating bearing current. But this could change due to longer operation time, if conductive particles due to abrasion in the bearing contaminate the lubricant and allows it to become more conductive. The also at higher speed such circulating bearing current flow is possible. So according to ICE60034 it is recommended that one bearing is insulated for machines above a frame size of 315 mm.

Low-impedance lubricant:
Especially for LIG the bearing will be conductive also at elevated speed and there will be circulating currents over the full speed range. So a good combination might be a motor with one insulated bearing to interrupt circulating bearing currents and a LIG to avoid EDM bearing currents.

E. Grounding aspects which cause or increase bearing currents effect

According to Chapter D, the possibilities to reduce HF common-mode bearing current effects are mainly based on the reduction of the spectral amplitudes of the common-mode sources, hence:

a) inverter output common-mode voltage,

b) inverter output and electric machines common-mode currents,

c) parasitic HF electrical voltages which act directly at the bearing.

But also the grounding system may cause additional parasitic HF currents, which may influence the HF bearing currents. The drive component- or drive system suppliers have therefore design handbooks with technical guidelines, where they describe the system installation for minimizing bearing currents (Chapter D) and EMC effects. Typically those applied methods, which reduce HF bearing current effects, may reduce as well EMC effects. Only in the optimum case these guidelines are already considered in the design phase, when the power train is set up. In other cases they might be disregarded, e.g. due to too high installation costs, either in the case when a drive system is newly installed or if an existing drive system is retrofit or added with new components. Hence an inappropriate installation might be done, which may lead to the generating of HF bearing currents. Then the discussion starts on the reasons for the parasitic currents and on responsibility. Often different companies are contributing to the installed drive system, so the decision on who is responsible is often difficult.

Therefore, to avoid such a situation, e.g. in case of adding additional components to an existing drive system, the original actual drive system set-up must be analysed thoroughly, checking the wiring plan with the existing installation, before adding new components. Concerning common-mode currents like the grounding and HF bearing currents, the actual electric grounding impedance has to be measured and the grounding wiring has to be analysed, also if only a part of the drive system is changed. The grounding issues such as defined sufficiently low HF grounding impedances to avoid "floating" electrical potentials have to be discussed. A floating potential may increase the electrical common-mode potential at the bearings and at the motor terminals, which may influence bearing EDM currents and rotor-to-ground bearing currents. Further a check of the grounding wiring should allow a minimization of an unwanted "parasitic" HF current flow to an acceptable level acc. to VDE0100.

Basically "Single point grounding" or "Meshed electrical grounding" is possible:

- Single point electrical grounding: All drive components must be ground-connected directly to a single "neutral" point to avoid circulating parasitic currents in the electrical grounding system! Conductive cable shielding should only be connected to the ground only on one cable terminal side!
- Meshed electrical grounding: If the grounding is done at several different points to avoid long grounding connections, we get a "meshed" grounding situation. Then unwanted circulating currents between parallel grounding paths are possible. These circulating cur-

rents may be minimized by using only a small size of the total grounding mesh, if possible! Conductive cable shielding should then be connected to the ground on both cable terminal sides!

Some typical electrical installation errors concerning a proper HF grounding are listed below.

a. An electrical grounding system is missing!
b. Electrical grounding connection is done directly on the painted housing e.g. of an electrical machine, without before scratching away the paint. The electrically insulating paint layer will lead to a non-grounded situation.
c. High HF impedance electrical grounding, which may lead to floating potentials. Too high grounding impedance may be caused by too small grounding cable cross section!
d. Grounding cable especially for HF ground currents are composed with stranded conductors instead of a massive solid conductor:
    - Too high HF-impedance, if no stranded conductor arrangement is used.
    - Motor cable shielding is connected to low-frequency terminal block, without a direct connection to the inverter-drive-system
e. A too high grounding impedance may also occur, if the electrical stator grounding is done via the long feeding motor cable neutral conductor instead of using a local short electrical grounding conductor to a nearby grounding point.
f. Electrical grounding system errors of the building, where the drive is installed:
    - Electrical grounding system in the building is not meshed, thus high compensation currents can occur.
    - If electrically connected drive systems are in different buildings (e.g. inverters at Building I and motors at Building II), and no electrical grounding connection between the two buildings exist
    - Improper grounding by using existing building system components, e.g. a steel cable of an elevator, instead of using a proper grounding cable
g. Electrical grounding connection is interrupted due to high-impedance metal corrosion
h. Ignored parallel grounding paths, e.g. an unintentionally electrically bridged bearing insulation or an accidental rotor grounding via a gear or rolling mill. Additional (often ignored) grounding paths are:
    - Encoder and encoder cable shields, general connected only on one side
    - Conductive hydraulic tubes
    - Conductive tubes of the re-lubrication system
    - Conductive connections of sensor systems, for e.g. vibration or temperature measurement
    - Conductive attachments to the motor such as e.g. brakes
i. A “pigtail” connection of the motor cable shield to the conductive motor housing allows HF noise to be radiated to other components and should be avoided by fully connected shields on the whole shield circumference e.g. with special cable glands.
j. Shield connection by wrong cable gland:
    - Plastic cable grand
    - Wrong size of cable gland
    - Not fully connected shield connected to the cable gland

k. Mounting errors of the motor cable shield may occur, even if the correct components are used, but:
    - The cable shielding wires are sheared off by too strong screwing of the gland
    - Not enough shielding wires connected to the cable gland
l. Motor cable shielding is not connected to motor and inverter conductive housing parts, which are connected e.g. on the inverter side to the grounding system
m. In some cases as an extraordinary effect a capacitive coupling between motor cable and sensor cable may occur, especially if they are lying close side by side and are not properly shielded (e.g. no shields or shields not properly connected, see i) … l)).

F. Remedial actions

A remedial action can already be chosen at the design state of the drive system, but as well later on, to reduce the effects due bearing currents or EMC problems. The Standard IEC 60034 [14] offers several possibilities to reduce bearing current effects. Different remedial actions are discussed in the following for the different bearing current types, because not all possible remedial actions help for each bearing current problem. Generally a filtering of the common-mode inverter output voltage as a general HF common-mode source will reduce HF bearing currents, but such filters are available only at smaller inverter ratings due to their size and cost. Further a general possibility is to reduce the slew rate du/dt and the inverter switching frequency of the inverter output voltage pattern to reduce the capacitive reasons for current flow. This was the case with older thyristor-switched inverters, but then on the expense of higher additional losses in the electrical machines due to the non-sinusoidal motor currents, which of course is unwanted. Hence following remedial actions may be grouped as follows:

A) Remedial actions at the drive system:

- Reduction of **common-mode voltage** and transient motor terminal overvoltage via common-mode voltage filter and – to a smaller extent - via the HF motor cable impedance
- Reduction of **common-mode current** via common-mode voltage filter and (cheaper) via common-mode current filter, and by the backflow of CM current via the Cable shielding

B) Remedial actions at the bearing:

I) du/dt- and EDM bearing currents:
    - Reduction or avoiding of **potential difference** across the bearing

II) Rotor-to-ground- and circulating bearing currents
    - Having a **bypass** of the current across the bearing to avoid current flow by the bearing.
    - **Increase** of the HF **impedance** for the bearing current path e.g. via common mode rings.

Table 4: Available remedial actions

Countermeasure	Bearing current type: EDM bearing currents	Circulating bearing currents	Rotor-to-ground bearing currents
Inverter side			
Shielded motor cable	Not effective [1)]	Poor, small increase due to smaller ground impedance [1)]	Effective [1)]
Common-mode choke,	Not effective	Effective	Effective
d*u*/d*t*-filter	Not effective	Effective	Effective
Machine side			
Hybrid bearings	Effective	Effective	Effective
Ceramic bearings	Effective	Effective	Effective
Ground brush contact	Effective: Short-out the bearing voltage	Not effective: Protects only one bearing	Effective: Carry the bearing current, does not protect bearings in driven load
Conductive sealing disk	Very Effective	Effective	Effective, but does not protect bearings in driven load
Conductive greases	Effective: Depends on condition of materials. [1)]	Poor	Poor
Microfiber Ring [2)]	Effective	Effective	Effective, but does not protect bearings in driven load

[1)] A. Muetze, "Bearing Currents in inverter-fed AC-Motors," Ph.D. TU Darmstadt, 2004.

[2)] A. Muetze and H. W. Oh, "Design aspects of conductive microfiber rings for shaft grounding purposes," Proc. of IEEE Industry Applications Annual Meeting, New Orleans, Louisiana, USA, 23. - 27. September 2007, S. 229 – 236.

Motor cable

The motor cable should not only provide reliably the inverter current flow to the motor, but its HF differential and common-mode components have some additional influence on the inverter-fed drive system. One big issue for cable is the HF cross-talk between parallel cables, lying in the neighbourhood, causing e.g. to disturbance in signal lines or EMI effects, such as an induced HF voltage in the controller cable, leading to disturbances of the signal transmission and controller action. Due to the high slew rate d*u*/d*t* of modern fast switching IGBT- or SiC-based MOSFET-inverters with their nearly ideal voltage steps (in the range of rise time of ns), the cable capacitances to ground are charged or discharged at each voltage step, causing a HF grounding current. The travelling voltage waves at each switching event cause voltage reflections at the motor terminals with an unwanted voltage overshoot, which depends on the parameters of cable (such as cable length) and of the connected components (such as the motor winding input impedance). The influence of motor cable type and length on the bearing currents was investigated at TU Darmstadt for two power levels and different cable length [1], where unshielded and shielded cables were researched up to 50 m length (Table 5).

Table 5: Cable length up to 50 m: Influence of cable type on bearing currents [1]

Motor power level	cable type	Length /m	Effect and Evaluation
11 kW	Y-JZ (unshielded)	2/10/50	Same EDM bearing currents for all cable lengths and for unshielded as well as shielded cable. Lower rotor-to-ground bearing currents for shielded cables.
	NY-CY (shielded)	50	
110 kW	NYY-J (unshielded)	10/50	Circulating bearing currents remain almost unaffected
	2YSLCY-J (shielded)	10/50/80	Circulating bearing currents remain almost unaffected. Lower rotor-to-ground bearing currents.
500 kW	NYY-J (unshielded)	10 (parallel)	Circulating bearing currents remain almost unaffected
	2YSLCY-J (shielded)	10 (parallel)	Circulating bearing currents remain almost unaffected. Lower rotor-to-ground bearing currents.

The effect of use of “Shielded” instead of “Unshielded” motor cables may be summarized as [1]

- Use of a shielded instead of unshielded motor cable increases the HF stator ground currents by up to 40% due to the lower HF grounding impedance.
- Shielded or unshielded cable type does not influence the amplitude and occurrence of EDM bearing currents of small motors, but leads to increase of the circulating bearing current amplitudes at high motor speed of larger electrical motors.
- The influence of shielded or unshielded cable type on bearing current occurrence is much smaller than the influence of motor size (e.g. small motors have no circulating bearing currents).

Influence of motor cable length [1]

- A reduction of the cable length does not influence the EDM bearing currents, and it leaves almost unaffected the circulating bearing currents that occur at low motor speed at larger motors. Hence the influence of motor cable length on bearing current amplitude is negligible, as it is much smaller than the influence of shielded or unshielded motor cable type, and much smaller than the impact of motor size.
- HF stator-to-ground current is in most cases reduced with reduced motor cable length due to the smaller cable-to-ground capacitance.

Influence of stator grounding configuration (without rotor grounding) [1]

- If unshielded motor cable is used and the $\mathrm{d}u/\mathrm{d}t$ at the motor terminals is not limited by a filter, large rotor-to-ground currents pass the bearings. The magnitude of the currents increases with increasing length of the motor cable. Use of shielded motor cables reduces the rotor-to-ground bearing currents. Maximum length of the motor cable in the investigations was $l_c = 50\,\mathrm{m}$.

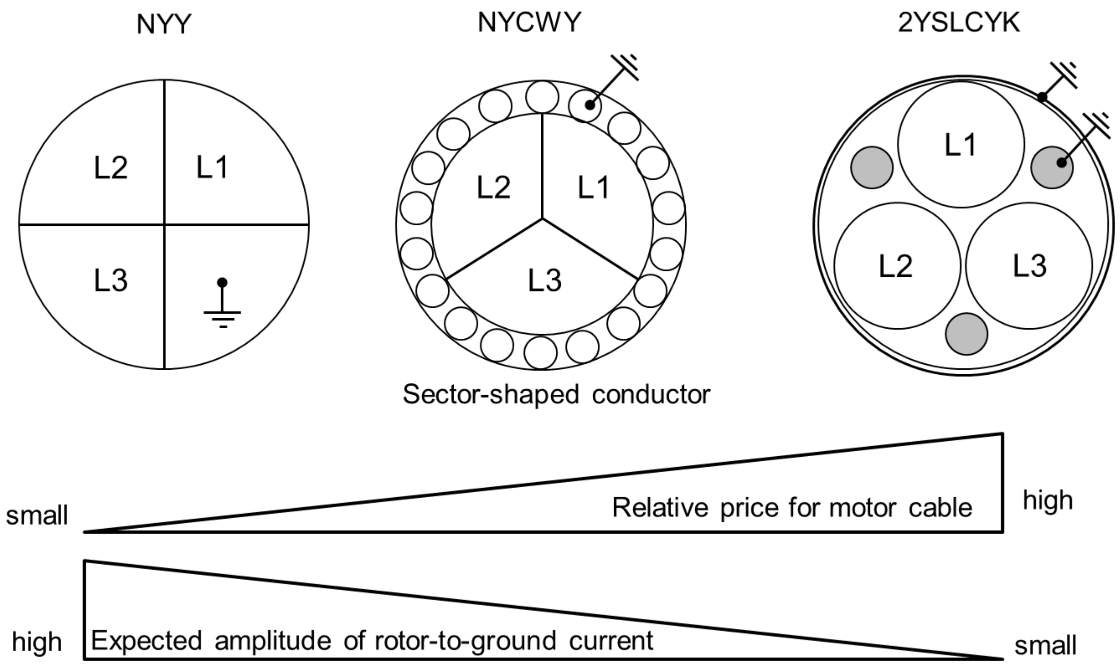


Figure 45: Cross-section of the three different investigated unshielded (NYY, NYCWY) and shielded (2YSLCYK) three-phase low-voltage motor cable types.

Table 6: Motor cable length 50 … 300 m: Influence on bearing currents [TU Darmstadt]

Motor power level	Motor cable type	Cable length /m	Effect and Evaluation
11 kW, 15 kW	NYY-J (unshielded)	50/150/300	Same EDM bearing currents for - all cable lengths, - for unshielded/shielded cables. Lower rotor-to-ground bearing currents for shielded cable type.
	2YSLCYK-J (shielded)	50/150/300	
110 kW	NYY-J (unshielded)	50/150/300	Nearly no influence on bearing currents for these two different unshielded cable types.
	NYCWY (unshielded)	50/150/300	
	2YSLCYK-J (shielded)	50/150/300	Slight reduction of circulating bearing currents in comparison with unshielded cable types.

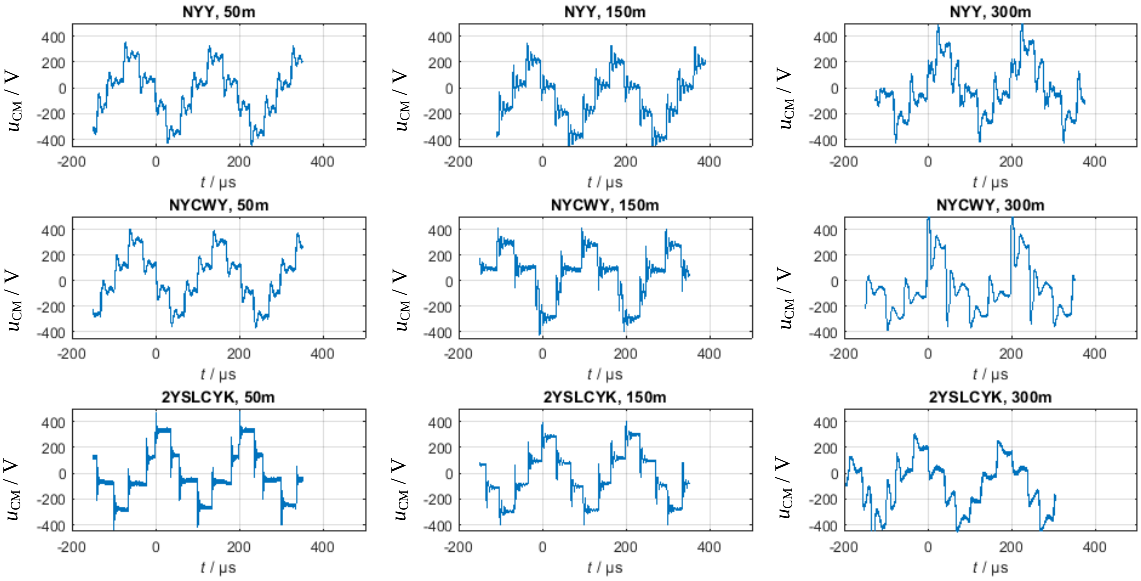


Figure 46: Measured common-mode voltages u_{CM} at the motor terminal of a 4-pole 110 kW-cage induction machine in dependence of cable length (50 m, 150 m, 300 m) and cable types (unshielded NYY, unshielded NYCWY, shielded 2YSLCYK), see Figure 45. Two-level IGBT-voltage source inverter with 560 V DC link voltage and switching frequency of 5 kHz.

Electrical bearing bypass

In order to protect the bearings from all different kinds of bearing currents, an electric parallel bypass as bridge over the bearing from inner to outer ring is added as remedial action. Thus the bearing voltage over the bearing is shorted or strongly reduced, thus avoiding EDM bearing currents. In case of circulating bearing currents and rotor-to-ground bearing currents this highly conductive bridge takes over the current. This added parallel electric path as a remedial action works only properly, if the HF impedance of this bridge is smaller than the bearing impedance. The bearing *impedance* is low for low speed operation due to partially metallic contact. Here circulating bearing currents may flow. It increases with increasing speed due to the bigger lubrication fil thickness. In this speed range EDM bearing currents may occur ([3], [5]). Examples for such low impedance bypasses as remedial actions are discussed in the next sub-chapters:

- Graphite brushes as a classical remedial action,
- Conductive sealings as a newer remedial action,
- Carbon micro fibres at a metallic ring (microfiber ring), touching the conductive rotor shaft.

Of course, all these bridges need to contact the rotating shaft, so friction will lead to wear, needing a maintenance inspection at certain intervals, and in case of need an exchange of the worn bridge. Sliding contacts require maintenance. In order to ensure a safe, long-lasting contact with low brush contact impedance, the operating and environmental conditions must be taken into account. In addition to the perhaps too high circumferential speed at the sliding contact, the influence of contamination of the sliding electrical contact by oil, dust and other contamination must be considered.

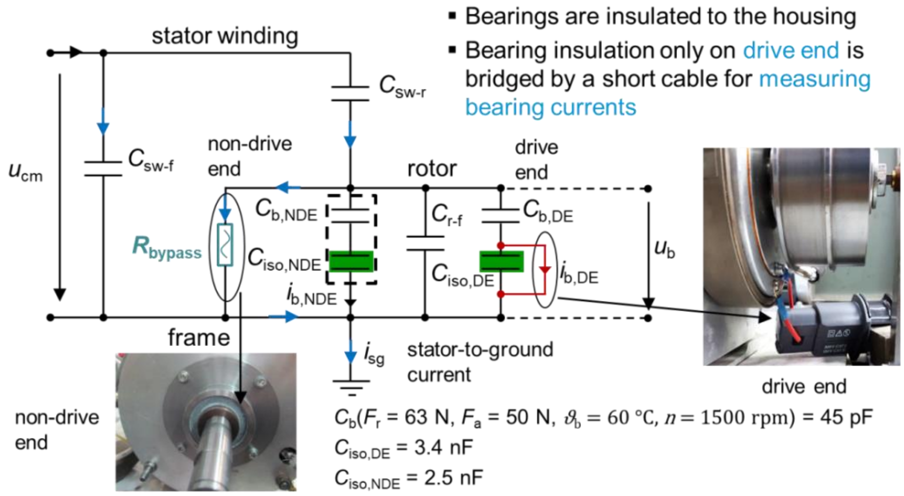


Figure 47: Electric circuit for the EDM bearing current measurement with a conductive bypass at the non-drive end side R_{bypass}. The specified values refer to a 4-pole 1.5 kW-cage induction machine.

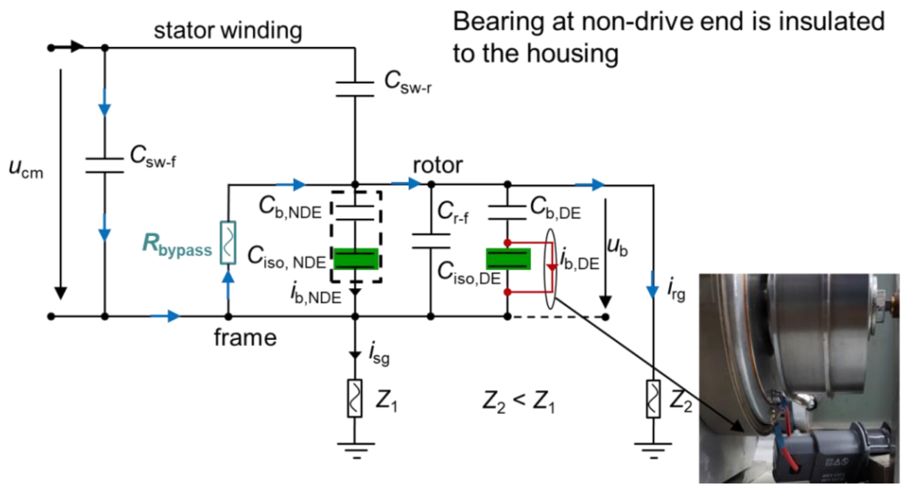


Figure 48: Electric circuit for the rotor-to-ground bearing current measurement with a conductive bypass at the non-drive end side R_{bypass} and a grounded rotor.

Graphite brushes

Graphite brushes are sliding contacts which require maintenance. As described in Section F, remedial actions for the reduction of bearing currents are grouped into two main areas with the purpose of:

(**B.I**) Avoiding of potential difference (bearing voltage u_b) across the bearings to reduce EDM bearing currents. The effectiveness of this measure depends strongly on the operating conditions and maintenance status.

(**B.II**) Bypass of rotor-to-ground and circulating bearing currents across the motor bearing: When the grounding brush is mounted on DE, the driven load is not protected by this measure (see Figure 49 a-c). When the grounding brushes are mounted on NDE, the use of an insulated coupling to the load machine is required to prevent circulating bearing currents in the loop of motor and load.

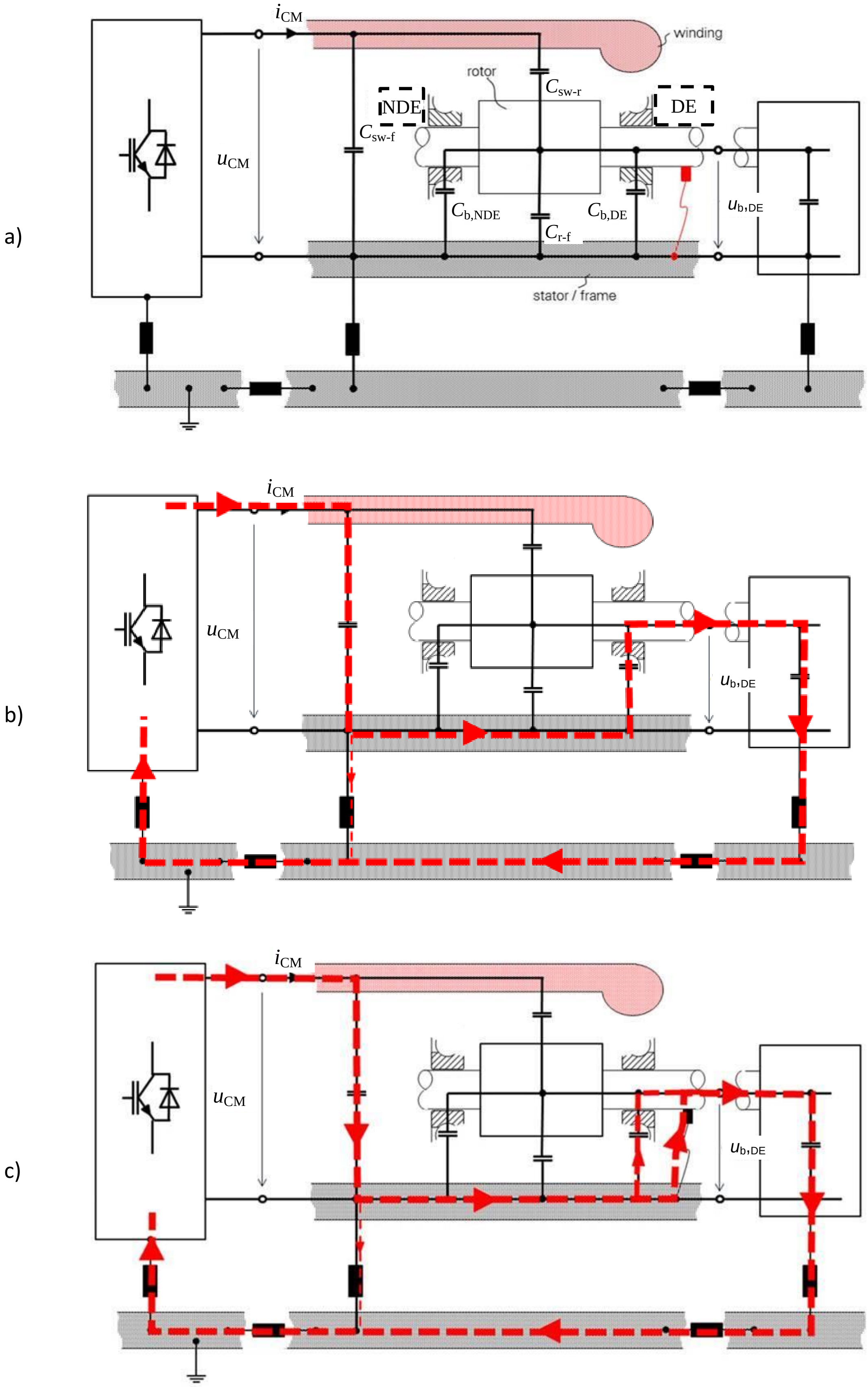


Figure 49: HF-capacitive network for cage induction machines with a) grounding brush (red) at drive end side (DE), b) Rotor-to-ground current flow without grounding brush, c) Rotor-to-ground current flow with DE-side grounding brush.

The conductive sealing *Simmerring*® bridges the bearing electrically across the bearing by a conductive non-woven sliding material. It is designed for the use in electrical motors and gears (Figure 50) especially for automotive applications. The main advantage is the wide applicable temperature range (-40 °C to +250 °C) and the high electrical conductivity (bridge resistance < 10 Ω). This value is independent of direction of rotation.

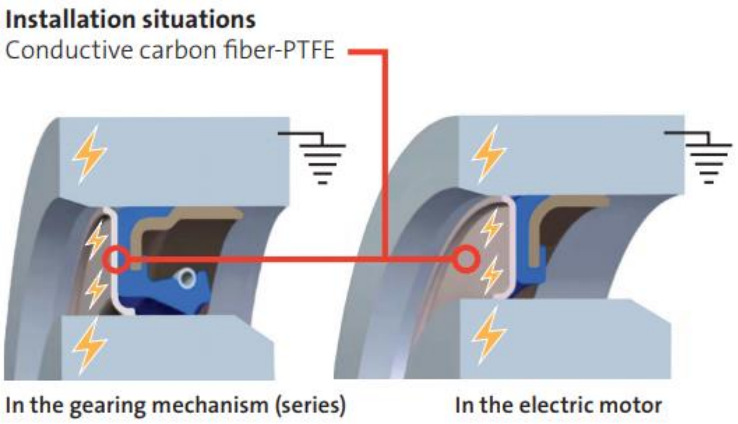


Figure 50: Cross-section of the conductive sealing *Simmerring*® , made of electrically conductive non-woven sealing material [31].

The conductive sealing *Simmerring*® was tested for EDM- and rotor-to-ground bearing currents at an especially prepared 4-pole 1.5 kW-cage induction machine, where bearing currents could be measured [30]. The installation of the conductive sealing *Simmerring*® was done according to Figure 47 at the NDE of the electric machine.

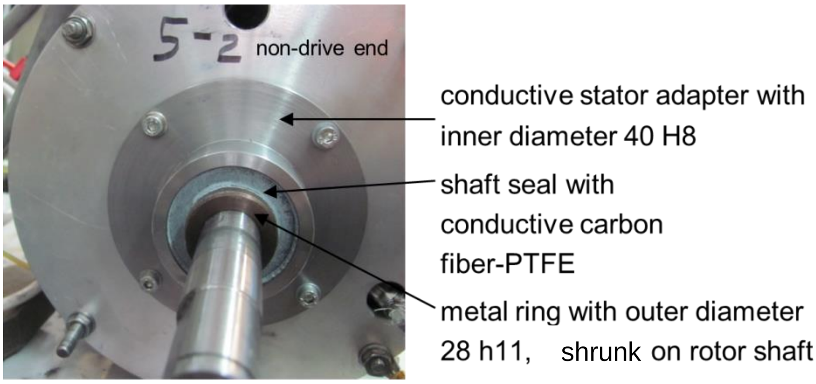


Figure 51: Installation of one conductive sealing *Simmerring*® at the NDE of an especially prepared 4-pole 1.5 kW-cage induction machine for bearing current measurement at TU Darmstadt.

The capacitive electrical equivalent circuit for the 1.5 kW-induction machine with the installed conductive sealing *Simmerring*® for the EDM bearing current measurement is shown in Figure 47. The conductive sealing *Simmerring*® reduces the electrical potential across the bearing to such low voltage levels that discharges and arcing at the lubricant film in the neighbouring bearings is avoided. Hence no EDM bearing currents may flow.

Figure 48 shows the equivalent capacitive electric network of the 1.5 kW-induction machine for grounded rotor with installed conductive sealing *Simmerring®* in parallel to the bearings. In this case rotor-to-ground bearing currents will flow, which should use the conductive sealing *Simmerring* as bypass to the bearings. Hence the conductive sealing *Simmerring®* should have a smaller resistance than the bearing impedance, so that the current flows across the conductive sealing *Simmerring®* and not via the parallel bearings. It was proven by experiment that above a speed of approx. 600/min the lubricant film increases the bearing impedance sufficiently, so that the rotor-to-ground current flows mainly across the conductive sealing *Simmerring®*. This leads to a reduction of bearing current flow of approx. 94.5%. Below 600 rpm the bearing is in mixed friction and metallic contact, so that the bearing current reduction is not so big, being dependent on the impedance ratio of conductive sealing *Simmerring®* and the bearing impedance.

Microfiber ring

The conductive microfiber ring is an electrical bypass of the bearing. Many hundreds of carbon microfibers ensure, that there are always a lot of them with their tips in close contact with the conductive shaft surface. The increase of electric field strength at the sharp ends of the micro fibres cause local small discharges when being separated from the shaft surface, which immediately re-establishes the electrical contact between ring and shaft. Even if a lot of fibres are worn, there are many others still active, so that the microfiber ring may be used for long term without much maintenance. A further advantage is the low mechanical friction, if any. It must be secured that the microfibers are not sticking together due to environmental influences like grease contamination. Two examples of microfiber rings are shown in Figure 52.

Figure 52: Two examples of microfiber rings with multitudes of conductive microfibers electrically in parallel [32].

Conductive Grease

Bearings are generally lubricated by grease, apart from special applications such as e.g. high-speed movement, where a steady direct inflow of small amounts of oil drops is applied as “minimum oil lubrication”. Grease is used, as most of the bearings can be lubricated only infrequently, so that the lubricating oil would not stay in position. Grease is a solid or semisolid lubricant formed as a dispersion of thickening agents in a liquid lubricant. Hence it generally consists of a soap emulsified with oil (e.g. mineral or synthetic oil), keeping the oil by the soap in right position. Having a high initial viscosity, the grease drops under shear forces to give the effect of an oil-lubricated bearing of approximately the same viscosity as the base oil used in the grease. This change in viscosity (“shear thinning”) still keeps up a high viscosity with corresponding much greater frictional characteristics than direct “minimum oil lubrication” (hence it is not useful for very high-speed application).

For lubricating bearings of electrical motors, the typical bearing consists of the lubricating oil (such as mineral oil, synthetic hydro carbon oil, ester oil, etc.), of the above noted thickener and in many cases of an additive package e.g. for bearing surface protection. The specific electrical resistivity is generally rather high with $10^9 \ldots 10^{14}$ Ω·cm (High-Impedance-Grease HIG). By using conductive grease the bearing voltage build-up may be reduced considerably, thus avoiding a sudden electrical discharge when surpassing the breakdown field strength in the lubricating film. EDM bearing currents are by this method strongly reduced. Such conductive grease has a specific electrical resistivity of typically $10^5 \ldots 10^8$ Ω·cm (Low-Impedance Grease LIG). This decrease of resistivity by a factor of typically 10 000 … 100 000 is achieved by additional components in the additive package, e.g.

a) electrically conductive solid particles (e.g. graphite particles to avoid too high friction)

or

b) a conductive fluid such as ionic fluids.

The bearing voltage is strongly reduced due to the strongly decreased resistance between the contact areas of ball and raceway. The conductive lubricant is a good remedial action on **EDM bearing currents, but not on rotor-to-ground currents or circulating currents** [3].

In Table 7 Low-Impedance Grease (LIG) G2 and G4 and High-Impedance-Grease (HIG) G1, G3, G5 are compared in their effect on EDM bearing currents, and in Table 8 with regard to rotor-to-ground bearing currents [3] , [5]. G1 is a standard HIG with mineral oil as a low price commercially available product. The HIG G3 is based on ester oil and G5 on synthetic oil. The LIG G2 is based on ester oil and has an ionic liquid, whereas G4 is based on synthetic oil and contains small dispersed graphite solid particles. G2 ... G5 are tailor-made test samples, manufactured by company *Klüber Lubrication München SE & Co. KG*, and were designed especially for these tests.

The conductive lubricant G4 with solid graphite particles according to a) usually does not keep up its lowered resistivity in the long run (above 1000 hours at rated conditions), as the conductive solid particles are pressed aside by the huge local contact pressure in the mechanical bearing contact. The LIG G2 led during a 1000 hour test to a stable operation with reduced EDM bearing currents. The bearing races after the test showed also a very good surface condition (Table 7).

Table 7: Comparison of five different lubricants G1 … G5 at an inverter-operated four-pole 1.5 kW–cage induction motor under EDM-bearing current conditions: Motor bearing type 6205 C3, inverter switching frequency f_c = 10 kHz, radial bearing load F_r = 63 N, axial bearing load F_a = 50 N, speed n = 1500 rpm, outer/inner ring average bearing temperature ϑ_{mb} ca. 60 °C

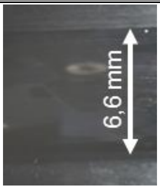
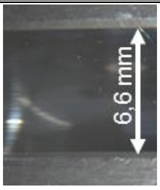
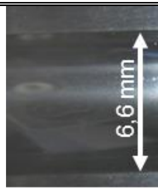
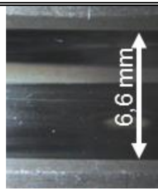
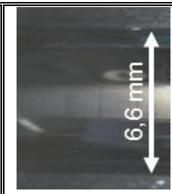
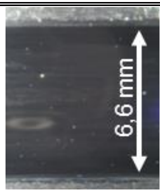
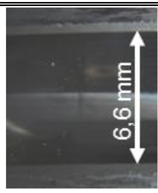
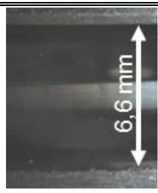
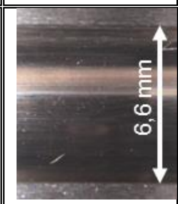
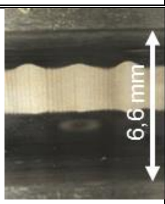
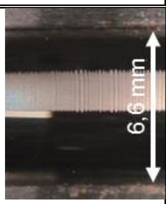
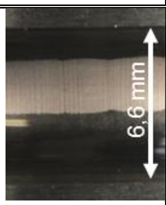
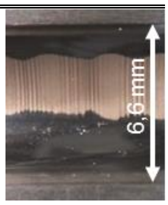
Lubricant	G1	G2	G3	G4	G5
Raceway of inner bearing ring DE					
Raceway of inner bearing ring NDE					

Table 8: Comparison of five different lubricants G1 … G5 at an inverter-operated four-pole 1.5 kW–cage induction motor under rotor-to-ground-bearing current conditions with grounded rotor: Motor bearing type 6205 C3, inverter switching frequency f_c = 10 kHz, radial bearing load F_r = 63 N, axial bearing load F_a = 50 N, speed n = 1500 rpm, outer/inner ring average bearing temperature ϑ_{mb} ca. 60 °C

Lubricant	G1	G2*	G3	G4	G5
Raceway of inner bearing ring DE					
Bearing condition after test					

For the 1000 h test with a rotor-to-ground current (Table 8) via the DE bearing and an electrically insulated NDE bearing, an apparent bearing current density of 1.5 A/mm² was adjusted via additional parallel terminal-to-housing capacities to increase the rotor-to-ground bearing current artificially. Hence with that critical value, all lubricants showed a strong ageing with darkened grease. Only the bearing with mineral oil based lubricant G1 did not show any fluting, whereas the raceways of the other bearings were deteriorated by fluting. We conclude that in general there is at the moment no lubricant available which withstands an apparent bearing current density above 0.7 A/mm² for long run use without considerable aging, which especially affects the –

COOH parts of the oil molecules [3], [5]. As the loading of the lubricant by electrical effects is only one part of the story, where first all the mechanical issues must be considered (and other environmental impacts), you have to ask for suitable grease for your application your lubricant sales engineer. Only by considering all relevant drive parameters, the best grease option for your application may be chosen.

Filter

Filtering of the common-mode inverter output voltage or of the motor currents may help to reduce HF bearing currents considerably. There are also patents on electrostatic shielding of the stator winding e.g. with conductive slot wedges especially for open slots or conductive shielding of the winding overhangs especially for 2-pole motors, where the winding overhang is big. These electrostatic shields are connected to the stator potential and reduce the capacitive coupling of the rotor considerably. The *BVR* gets very small, reducing the bearing voltage u_b to small values. Hence usually EDM bearing currents will vanish. Such shielding measures will not affect circulating bearing currents or rotor-to-ground bearing currents considerably. Such shielding measures are very special alterations of the electrical motor and are not state of the art. Therefore they are not considered here in detail.

Opposite to that, filters (Table 9) may very often be used even in existing drive set-ups as an additional measure to reduce unwanted parasitic electrical HF currents. All content of this following "Filter section" is based on [28].

Table 9: Overview of the influence of different filter topologies on effects such as EMI, motor issues such as bearing currents and inverter issues
(Technical impact: X: beneficial, XX: highly beneficial, XXX: very high beneficial;
Cost: +: cheap, 0: neutral, −: expensive, − −: very expensive)

	EMI		motor						inverter		Cost
						Bearing currents					
	conducted/radiated EMI	leakage currents	motor isolation	motor audible noise	motor losses	Circulating currents	Rotor-ground currents	EDM currents	inverter losses	output charging currents	
Common mode ring cores	XX	X				XXX	XXX				+
Differential Mode d*u*/d*t*-filter			X			X	X		X	X	0
Dual mode d*u*/d*t*-filter	XX	X	X			XXX	XXX		X	X	–
Differential mode sine filter			XX	XXX	XX	X	X		XX	XX	–
Dual mode sine filter	XXX	XXX	XXX	XXX	XXX	XXX	XXX	XXX	XXX	XXX	– –

A) Common-mode ring cores

Nanocrystalline or ferrite ring cores have a high magnetic permeability. An AC magnetic field will induce an electrical voltage in the core, but due to their high ohmic resistance the corresponding current will be very small, so additional losses will be also small. If e.g. the three phase conductors carry in total a common-mode AC current due to a feeding CM voltage e.g. from the inverter, a resulting AC common-mode field will be excited around these conductors. If a CM ring is placed around these conductors (Figure 52), this CM magnetic field is increased inside the ring core, resulting in a high AC CM flux. This AC flux induces an additional CM voltage in these conductors, opposite to the original CM voltage. Thus the total CM voltage and hence the resulting CM current is reduced strongly, improving the EMI immunity of the drive system. In addition, the reduction of stator CM current in the electrical machine reduces in the same way via the *BCR* the circulating bearing currents (if there are any, e.g. in bigger electrical machines) and directly the rotor-to-ground bearing currents (if the rotor has a conductive ground connection).

The choice of ring size (diameter and cross-section area) depends geometrically on the motor cable diameter and electrically on the magnitude of CM cable current, which should be reduced. Ring core material saturation due to a high CM cable current must be avoided by choosing a sufficiently big ring cross section area to keep the resulting CM magnetic ring induction below the saturation limit, which is given by the manufacturer. If this limit is surpassed, an additional ring increases the resulting cross section area and the CM cable inductance, so the CM cable current is reduced and thus the ring flux density. By guiding the motor cable more than one time through the ring increases the exciting CM Ampere-turns linear by the number of turns, this increasing linear the flux density in the ring core. Hence the CM induction and its ring flux increase, and the CM cable current is reduced to a bigger extent. Again ring core saturation must be avoided.

Due to the CM cable-to-ground capacities a CM resonance circuit is established by the CM ring core inductance. The resonance frequency, typically 80 kHz … 300 kHz, decreases with

- increased ring permeability,
- increased ring core cross section,
- increased number of turns of the motor cable via the ring and with
- increased parasitic cable-to-ground and motor-to-ground capacitances, i.e. with longer motor cable. At this frequency the resulting CM motor cable impedance is at minimum and will lead to a big CM current component at this frequency (“resonance”). An excitation of this resonance frequency by a CM harmonic inverter output voltage component of this frequency must be avoided by changing the resonance frequency, e.g. by changing the motor cable type or length. Otherwise the CM cable and motor current is bigger than without CM rings. The resonance effect is also influenced by the damping due to ring and cable losses by reducing the resonance peak of CM current and by reducing the resonance frequency slightly. Hence the common-mode motor

voltage u_{CM} resonance overshoot depends on ohmic damping, provided mainly by the eddy current losses and the hysteresis losses in the ring core.

Note that the ring cores have only a negligible effect on the phase or line-to-line voltage waveforms (which are not Common Mode CM, but Differential Mode DM). Hence the du/dt of the phase and line-to-line voltage is unaffected, causing still by wave reflection at the motor terminals a voltage overshoot. So CM rings are not reducing the probability of insulation faults in the motor. As the rings mainly reduce CM currents and not CM voltage (Figure 55), also the occurrence of EDM bearing currents is not affected. As the CM cable current is usually much smaller than the motor phase currents (DM current!), the influence of CM rings on losses in the inverter, motor cable or electric motor is very low. An advantage of the ring cores is that they do not reduce the phase or line-to-line voltages at the motor terminal (Figure 54), so no additional motor voltage drop is generated. They can be used in drives with high dynamic control, because nearly no differential mode inductance is provided.

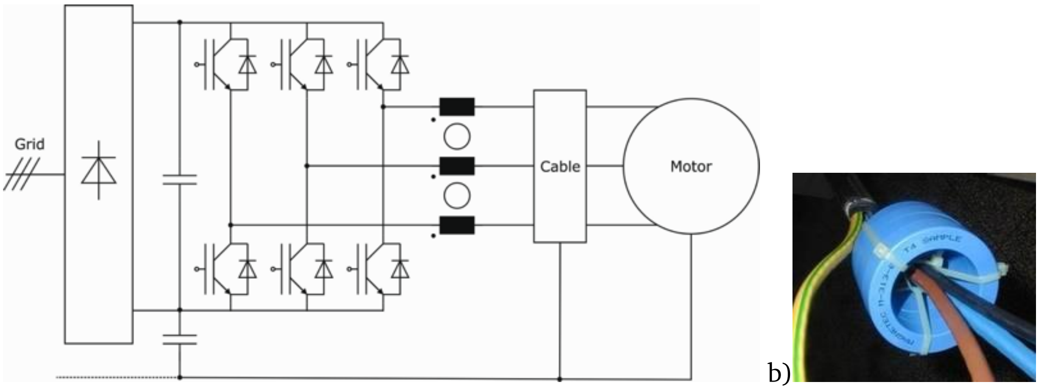
a) 

Figure 53: a) Inverter-cable-motor drive setup with common-mode ring cores, b) The PE conductor for grounding of e.g. the motor housing, passes by outside the ring cores

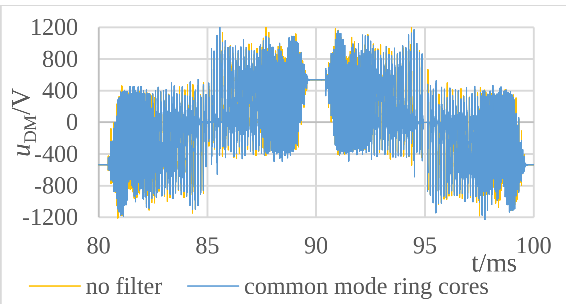


Figure 54: Measured differential mode motor voltage u_{DM}:
Nearly no voltage shaping effect by ring cores.

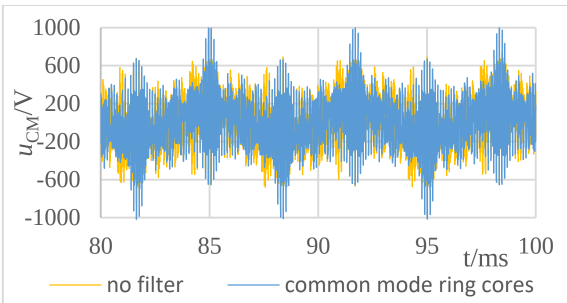


Figure 55: Measured common-mode motor voltage u_{CM}:
Very small voltage shaping effect by ring cores.

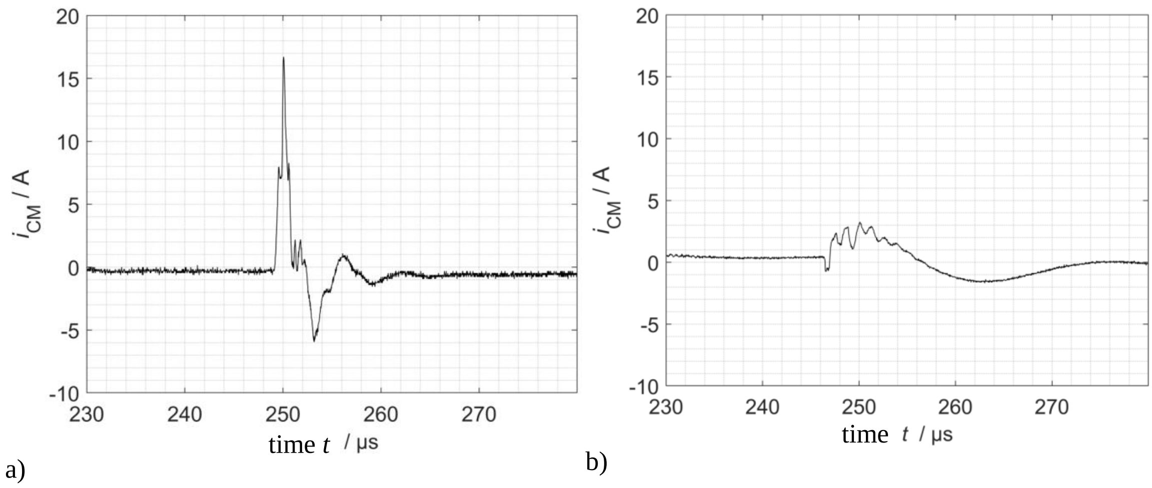


Figure 56: Measured common-mode current i_{CM} in a 4-pole 110 kW-cage induction machine with shielded motor cable type 2YSLCYK with length 50 m: a) Without any inverter output filter, b) with eight common-mode ring cores, type M-302, Magnetec: Reduction from 17 A to 3 A.

B) Differential mode d*u*/d*t*-filter

The reduction of the du/dt of the inverter output voltage reduces the capacitive charging current of the motor cable, which is proportional to the cable-to-ground capacitance and the du/dt. Also the motor terminal voltage overshoot due to voltage wave reflections at the terminals is reduced, depending on cable length and motor input impedance. This can be achieved by a per phase inverter output inductance ("motor choke"). The application of a Differential Mode du/dt-filter at the inverter output terminal (Figure 57), has the advantage, that below its resonance frequency it does not affect the inverter voltage. For example, the control dynamics of the drive are not influenced. It consists per phase of a differential mode inductance with parallel ohmic damping resistor and a capacitance, usually star connected. Hence it builds up per phase a series resonance circuit. Due to its arrangement at the inverter output the filter effect is independent from cable length and its ground capacitance. The resonance frequency of this filter is designed by the rather small capacities much higher than the switching frequency of the inverter, typically 80 kHz … 500 kHz. Hence only the high frequency components of the inverter output voltage above this resonance frequency are reduced strongly, thus reducing the du/dt. The pulse-width modulated inverter output voltage pattern remains more or less unaffected. The damping resistors set the voltage overshoot at the motor terminals. Being DM components, CM effects are not influenced (Figure 58). So, like the motor choke, differential mode du/dt-filters only offer insulation protection between the phases and not against ground. The benefit of a du/dt-filter in comparison to a motor choke is that the filter effect is decoupled from the cable parameters. Further the du/dt and the corresponding motor terminal voltage overshoot can be defined in advance via the filter parameters, independent of the motor cable length and type, to meet different standard limits (Figure 59). The rather big damping resistors shall avoid a big resonance voltage overshoot. But then the filter generates quite high ohmic losses. As mentioned, it has a beneficial effect on inverter and cable losses by damping the parasitic cable capacitance charging currents. EMI improvement or bearing current reduction is offered by this filter solution only partly by the stray inductance of the filter inductance.

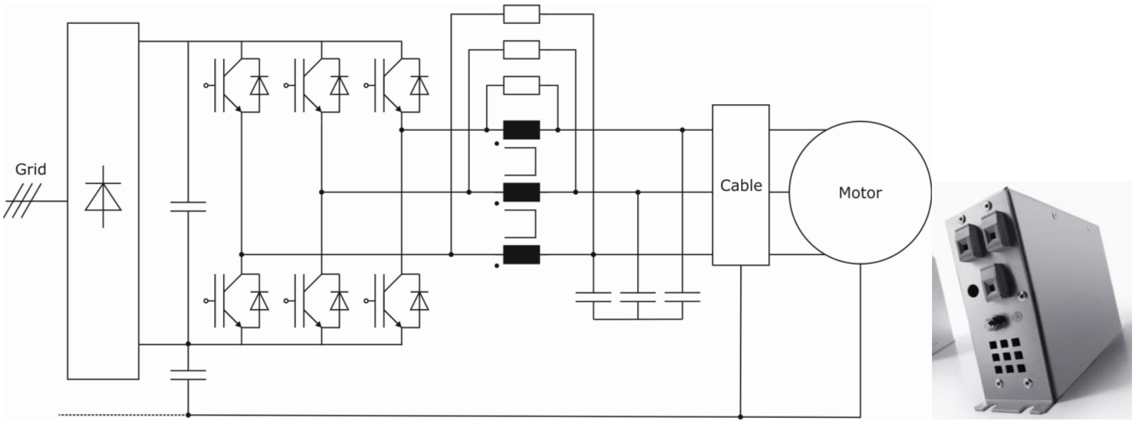


Figure 57: Inverter-motor cable-motor drive setup with differential mode d*u*/d*t*-filter at the inverter output terminal

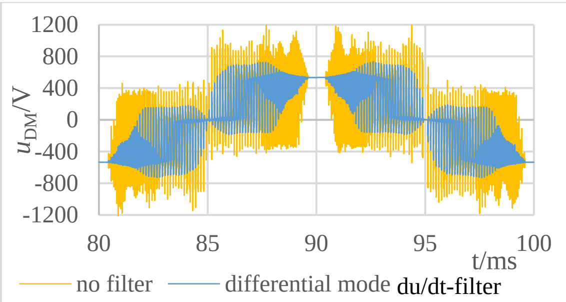


Figure 58: Measured differential mode motor voltage u_{DM}: Strong voltage shaping effect (*du/dt* and peak voltage) with filter.

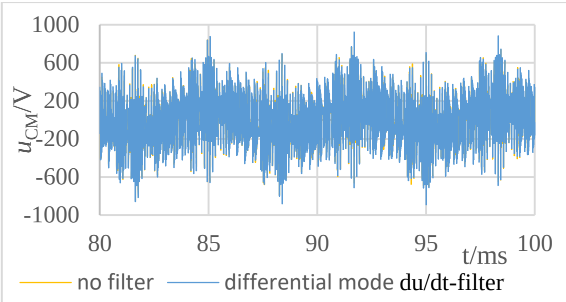


Figure 59: Measured common mode motor voltage u_{CM}: Nearly no effect by filter. "No filter"-signal and *du/dt*-filter signal coincide!

C) Dual mode (Differential and Common-mode) d*u*/d*t*-filter

The Dual Mode filter type offers a common mode low pass circuit in addition to the differential mode d*u*/d*t*-filter (Figure 52). The Dual Mode or "all-pole" d*u*/d*t*-filters feature a common mode inductance and might also have a neutral point clamping (star point-connection) to ground or to DC link, so that also a common mode low pass filter is provided. By that, the shape of the common mode voltage at the motor terminal is influenced in a defined way, reducing especially the harmful HF component. Excellent EMI reduction and reduction of rotor-to-ground and circulating bearing currents like using a couple of nanocrystalline ring cores is provided in addition to the characteristics of a differential mode d*u*/d*t*-filter. By reduction of the CM voltage the EDM bearing currents also strongly reduced. The filter itself is rather big, especially with increased inverter size, and expensive, bit covers all DM and CM parasitic effects, hence also all bearing current effects.

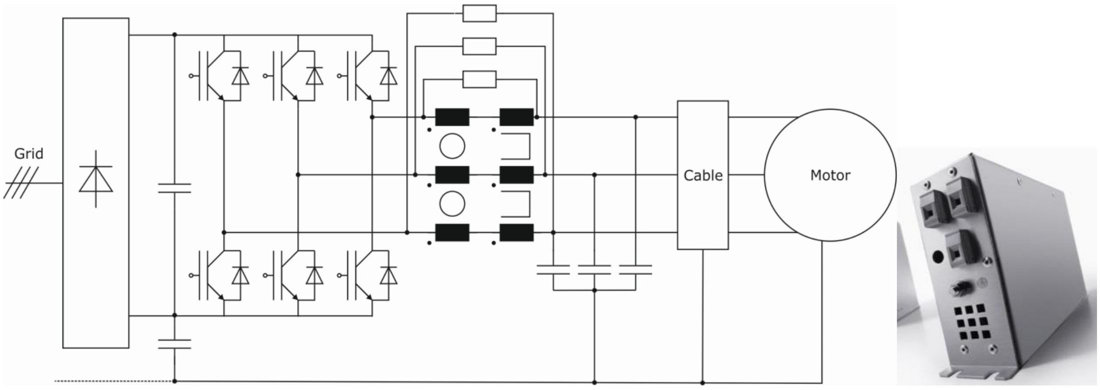


Figure 60: Inverter-motor cable-motor drive setup with dual mode d*u*/d*t*-filter

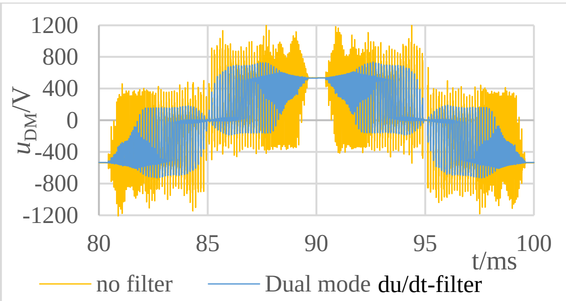


Figure 61: Measured differential mode motor voltage u_{DM}: Strong voltage shaping effect (d*u*/d*t* and peak voltage) with filter.

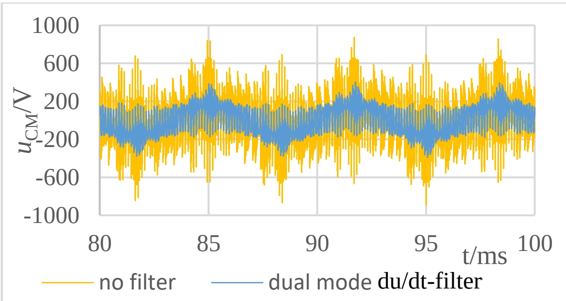


Figure 62: Measured common-mode motor voltage u_{CM}: Strong voltage shaping effect (d*u*/d*t* and peak voltage) with filter.

D) Differential mode sine filters

A series resonance circuit per phase at the inverter output with a rather low resonance frequency between the inverter fundamental frequency and the inverter switching frequency reduces all voltage harmonics due to inverter switching strongly (Figure 64). The filter resonance frequency is set typically between 500 Hz and 5 kHz for IGBT inverters, which have nowadays switching frequencies above 4 … 8 kHz in the medium power range. Hence the line-to-line and the phase voltage tend to be nearly sinusoidal, like in a grid feeding situation (Figure 64). So the filter eliminates PWM and high frequency losses in the motor cable and in the motor. Also, inverter losses are reduced. The low resonance frequency is achieved by rather big inductances and capacitances, so the sine filter is rather big and expensive. Because of the high inductance value, a voltage drop of up to 8% nominal voltage at nominal current will occur. This increase in inductance is bad for dynamic change of current. So this filter might be used preferably in uncontrolled or low dynamic controlled drives. Differential mode sine filters have been used as a high-end filter solution for motor protection in the past to avoid any voltage overshoots at the motor terminals, independent of cable length. So differential mode sine filters only offer insulation protection between the phases. Being a DM filter, the CM current to ground and the voltage to ground are not affected (Figure 65). So an additional insulation protection to ground is not possible. The inductance is built as a differential mode three phase choke. The capacitances are star-connected with no connection to ground or DC-link. In comparison to du/dt-filters, the inductance and capacitance values are higher, and no additional ohmic damping is required. EMI improvement or bearing current reduction is offered by this solution only partly by the stray inductance of the choke, as no CM voltage reduction is achieved.

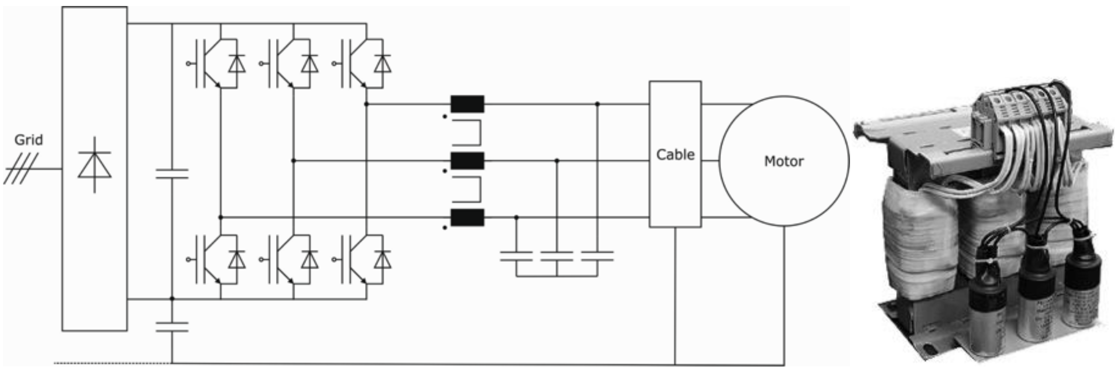


Figure 63: Inverter-motor cable-motor setup with a sine filter

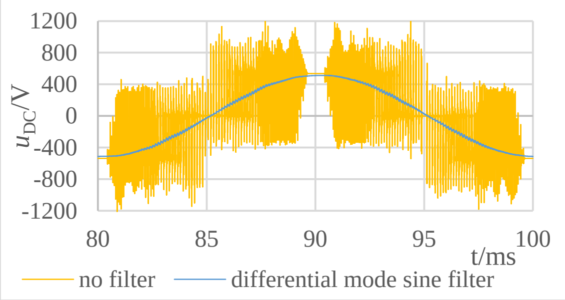


Figure 64: Measured differential mode motor voltage u_{DM}:
Pure sine wave voltage.

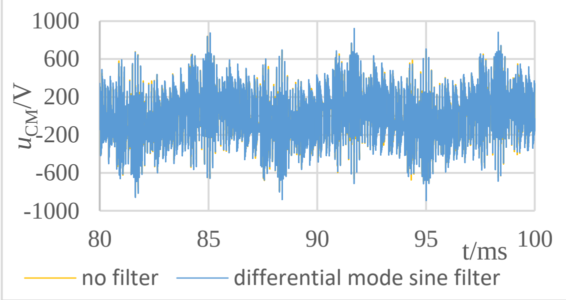


Figure 65: Measured common mode motor voltage u_{CM}: Nearly no effect by filter. "No filter"-signal and *du/dt*-filter signal coincide!

E) Dual mode (Differential and Common-mode) sine filters

Dual Mode or All-pole sine filters are sine filters with a CM current feed back to the DC link or to the ground (Figure 66). They have occurred on the market since some years and offer a real high-end motor protection for differential and common mode parasitic effects. Common mode currents are led back to the DC-link directly by the neutral-point clamping of the star-connected capacitors, which would be the optimal situation. They may also be guided back to ground, if no DC link connection is available. These Dual Mode sine filters reduce the CM voltage, so inverter-caused bearing currents are avoided. The sine wave line-to-line voltage (Figure 67) avoids the voltage reflection phenomenon with its motor terminal voltage overshoot. But also the terminal-to-ground CM voltage is reduced to its fundamental frequency sine wave component (Figure 68), so motor insulation faults due to inverter supply are avoided. A high EMI reduction is offered by this solution. The low harmonic current components lead to a reduction of total drive system losses. EMI effects and parasitic HF current flow are excellently reduced. So, even unshielded and very long motor cables might be used. In addition, the grid side EMI filter of the inverter can be designed with smaller size of components.

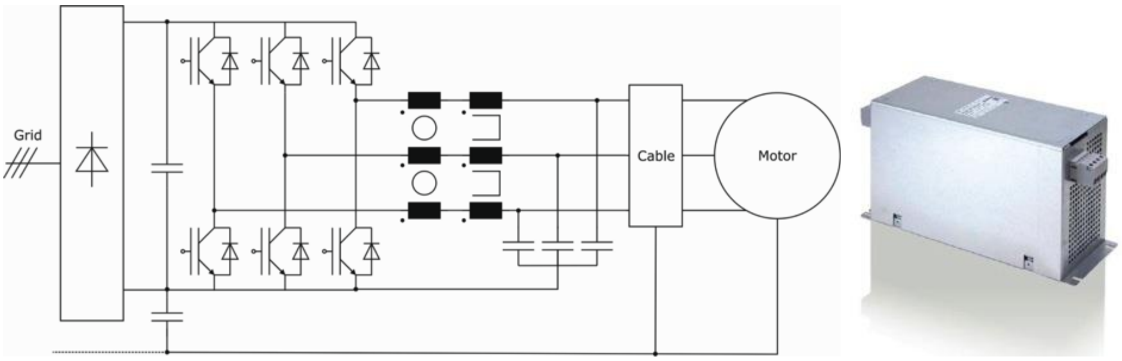
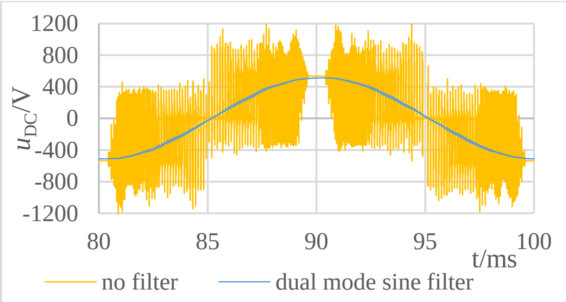


Figure 66: Inverter-motor cable- motor drive setup with dual mode sine filter. The designed resonance frequency for differential and common mode is typically 500 Hz … 5 kHz for IGBT inverters.



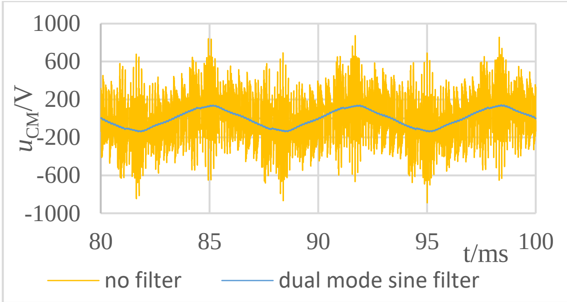


Figure 67: Measured differential mode motor voltage u_{DM}: Pure sine wave voltage.

Figure 68: Measured common-mode motor voltage u_{CM}: No switching frequency voltage components occur any more due to filtering.

G. Literature

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H. Subject index