Calculation of Parasitic High Frequency Currents in Inverter-Fed AC Machines

TECHNISCHE UNIVERSITÄT DARMSTADT

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Contents

- Introduction
- Common-Mode Stator Ground Currents
- Circulating Bearing Currents
- EDM Bearing Currents
- Conclusion

Overview

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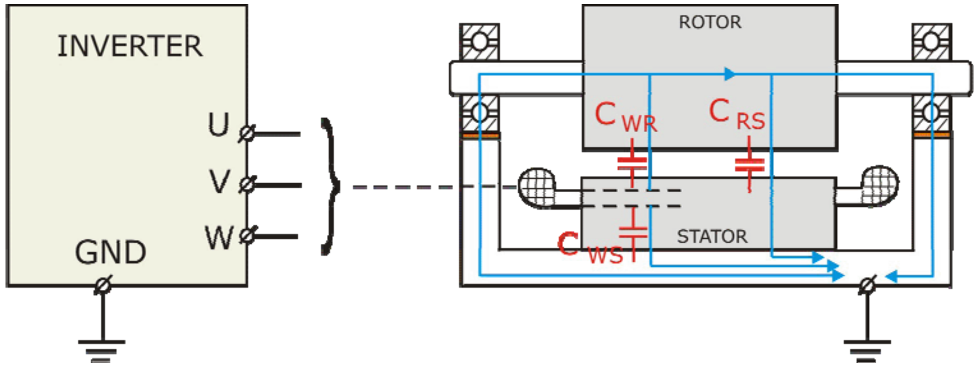
- Introduction
  - Parasitic HF Currents
  - Influence of Machine Capacitances on HF Parasitic Currents
- Common-Mode Stator Ground Currents
- Circulating Bearing Currents
- EDM Bearing Currents
- Conclusion

Introduction - Parasitic High Frequency Currents

Fast switching inverter causes common-mode voltages at electrical machine terminal and different types of HF parasitic currents occur.



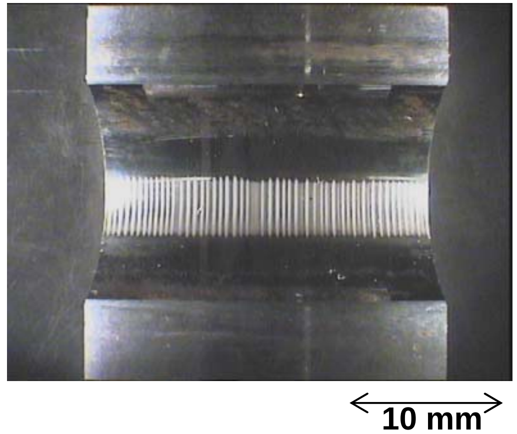


Photo: FOR 575
http://www.ew.e-technik.tu-darmstadt.de

1. Common-mode (CM) stator ground current
2. Circulating bearing (CB) currents
3. EDM bearing currents
4. Capacitive bearing currents - small amplitudes: (5-10) mA
5. Rotor ground currents - only for coupled loads at the motor shaft

Machine Capacitances and Their Influence on Parasitic HF Currents

- Stator winding-to-stator frame capacitance C_{WS}:
  - fundamental reason for the high frequency **CM current**

$$i_{\mathrm{CM}} \cong \frac{V_{\mathrm{DC}}}{Z_0} \cdot e^{-\xi \cdot \omega_{\mathrm{n}} \cdot t} \cdot \sin(\omega_{\mathrm{n}} \cdot t)$$

Where: $Z_0 = \sqrt{\frac{L_{\mathrm{CM}}}{C_{\mathrm{WS}}}}$; $\omega_{\mathrm{n}} = \frac{1}{\sqrt{L_{\mathrm{CM}} C_{\mathrm{WS}}}}$; $\xi = \frac{R_{\mathrm{CM}}}{2} \cdot \sqrt{\frac{C_{\mathrm{WS}}}{L_{\mathrm{CM}}}}$

- Rotor-to-stator winding capacitance C_{WR}, rotor-to stator frame capacitance C_{RS} and bearing capacitances C_{b}:
  - important role in the occurrence of the **EDM current**

$$\hat{i}_{\mathrm{EDM}} \cong \frac{\hat{v}_{\mathrm{b}}}{R_{\mathrm{b}}}$$

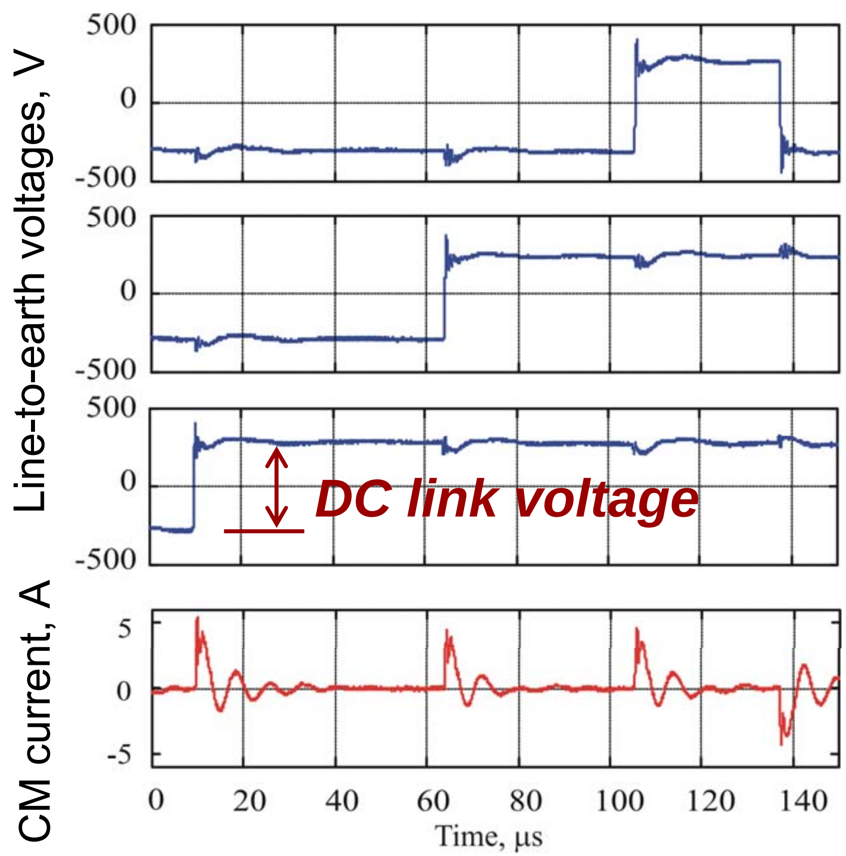
Where: $v_b = v_{CM} \cdot BVR = v_{CM} \cdot \frac{C_{WR}}{C_{WR} + C_{RS} + 2 \cdot C_b}$

R_{b} – bearing resistance after breakdown

Overview

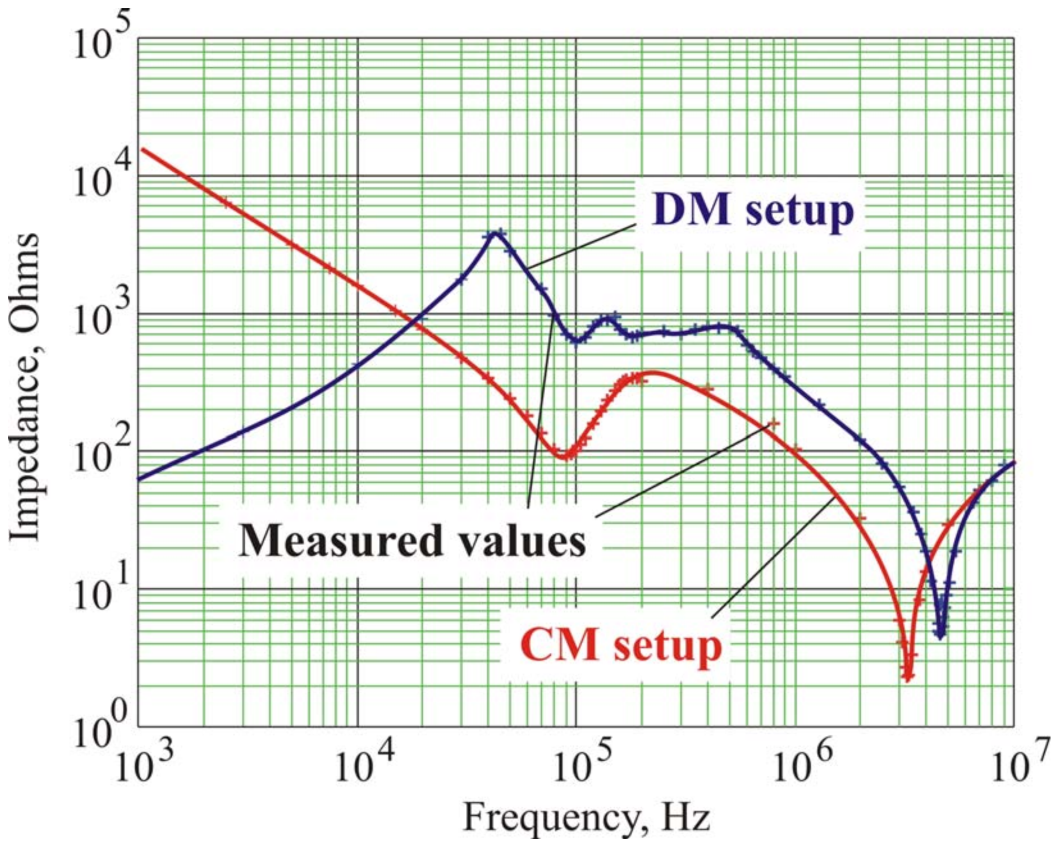
- **Introduction**
- **Common-Mode Stator Ground Currents**
  - **- Measurements of CM current**
  - **- Behaviour of AC Motors at High Frequencies**
  - **- Calculation of CM current**
    - **- Simple High Frequency Equivalent Circuits**
    - **- Transmission Line Equivalent Circuits**
- **Circulating Bearing Currents**
- **EDM Bearing Currents**
- **Conclusion**

Common Mode Currents

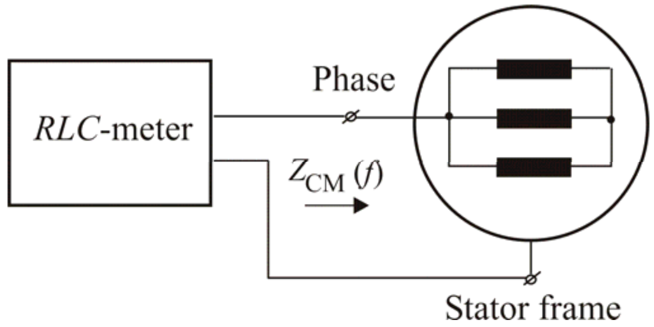


Test bench for measurements of CM currents at a 240 kW induction motor

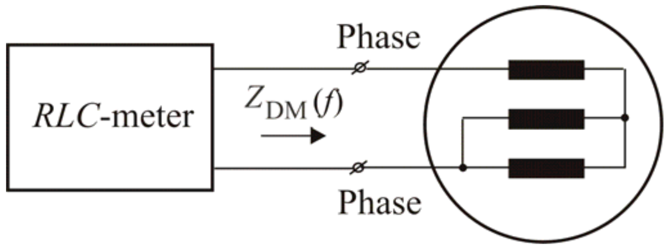
Behaviour of Induction Motors at HF



CM impedance measurement



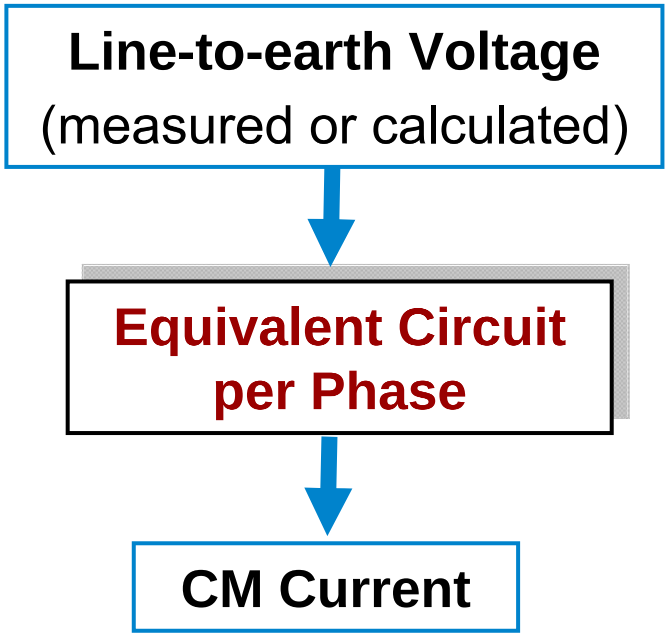
DM impedance measurement



Measured CM and DM winding impedance characteristics for a
7.5 kW, 4 pole cage induction machine
(oval shape semi-closed stator slots, single layer wound wire winding)

Calculation of CM Currents

At each voltage step of the DC link voltage at the motor terminals, a ground current impulse is generated. The CM current is constituted by the superposition of all the generated impulses.



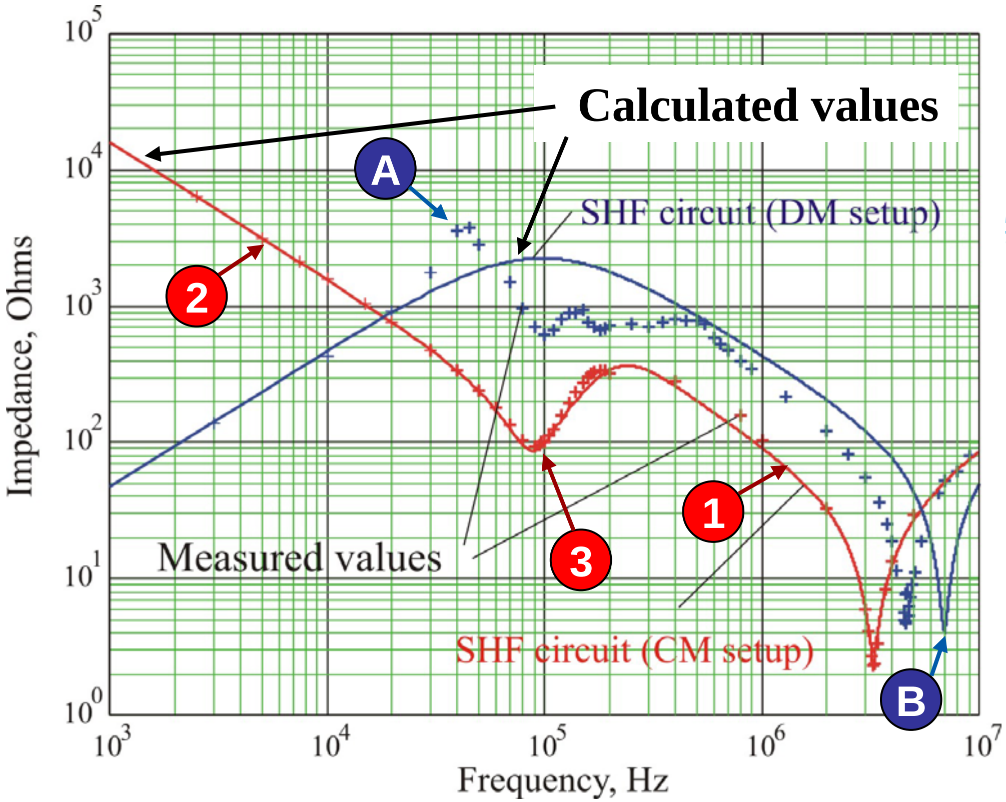
Equivalent circuits:

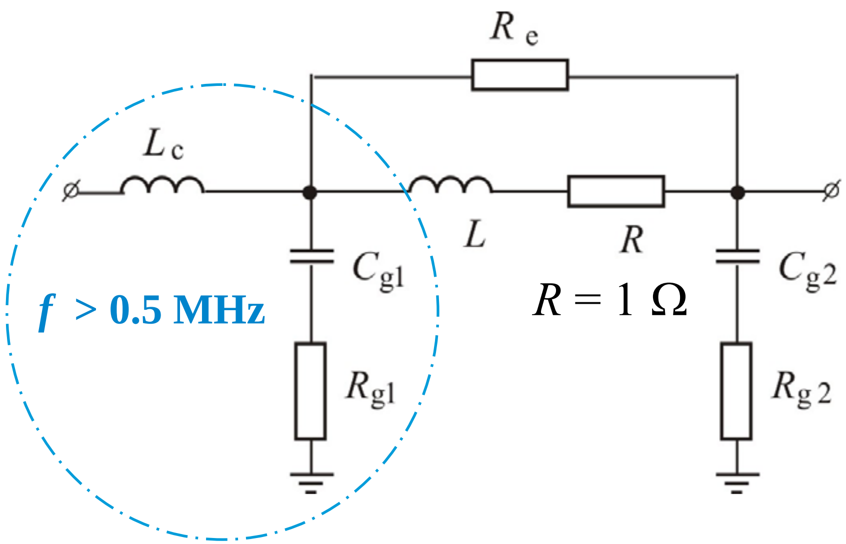
a) Simplified HF (SHF) equivalent circuits models - constant parameters determined by experiments;

b) Transmission line (TL) equivalent circuit models - parameters, which are calculated analytically or by FEM

SHF Equivalent Circuit

7.5 kW, 4-pole cage induction machine





M. Schinkel, **IEEE-2006**

1 $C_{HF} = \frac{1}{2\pi \cdot f \cdot Z} \rightarrow C_{g1} = \frac{1}{3} \cdot C_{HF}$

2 $C_{tot} = \frac{1}{2\pi \cdot f \cdot Z} \rightarrow C_{g2} = \frac{1}{3} \cdot C_{tot} - C_{g1}$

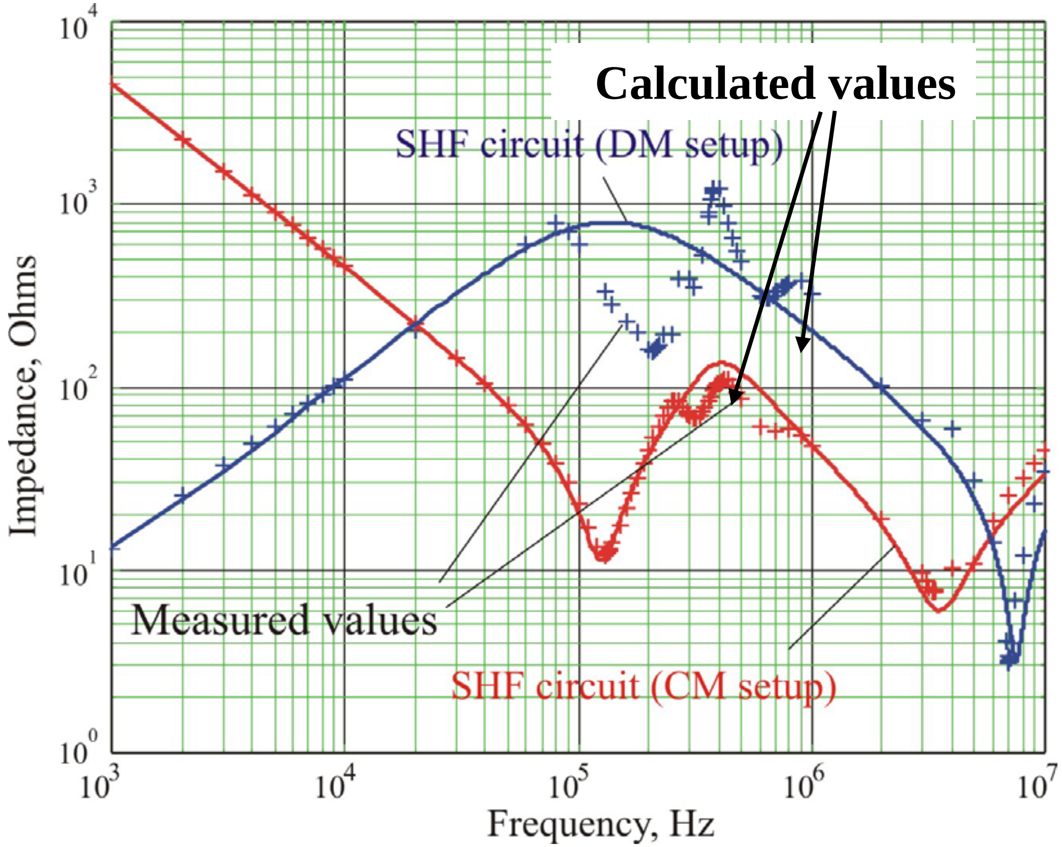
A $R_e = \frac{2}{3} \cdot Z_{\max}$

B $R_{g1} = \frac{2}{3} \cdot Z_{\min 2}$

3 $R_{g2} = \frac{1}{3} \cdot Z_{\min 1}$

Tests for a Big Machine

240 kW, 4-pole cage induction machine, rectangular open stator slots, two-layer profile copper winding



Several resonances between: 100 kHz …1 MHz

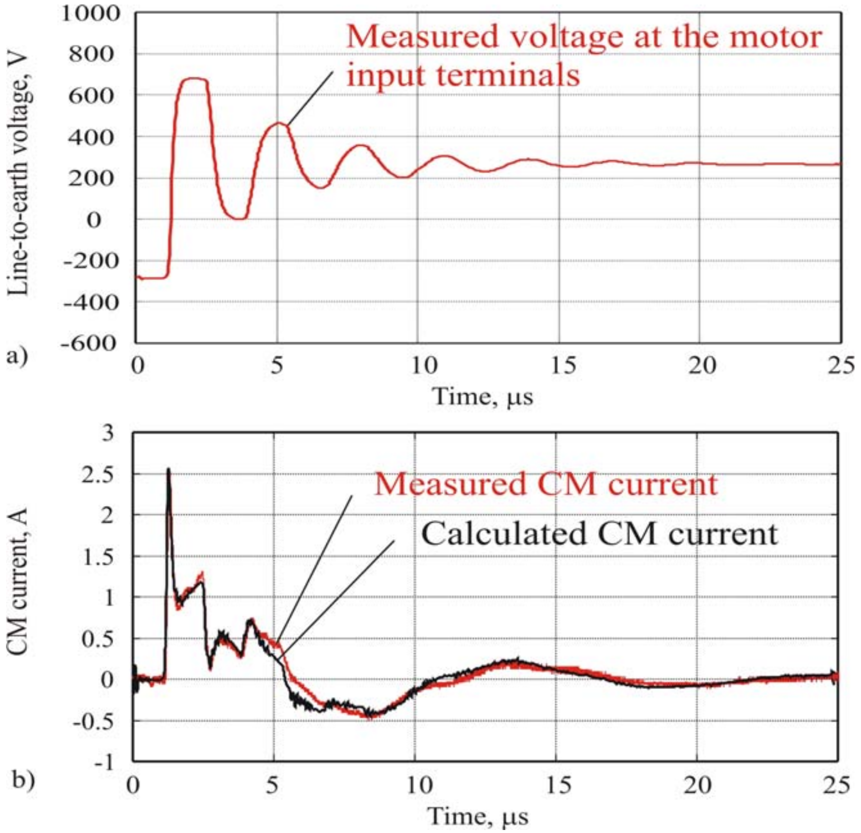
The model has to be improved!

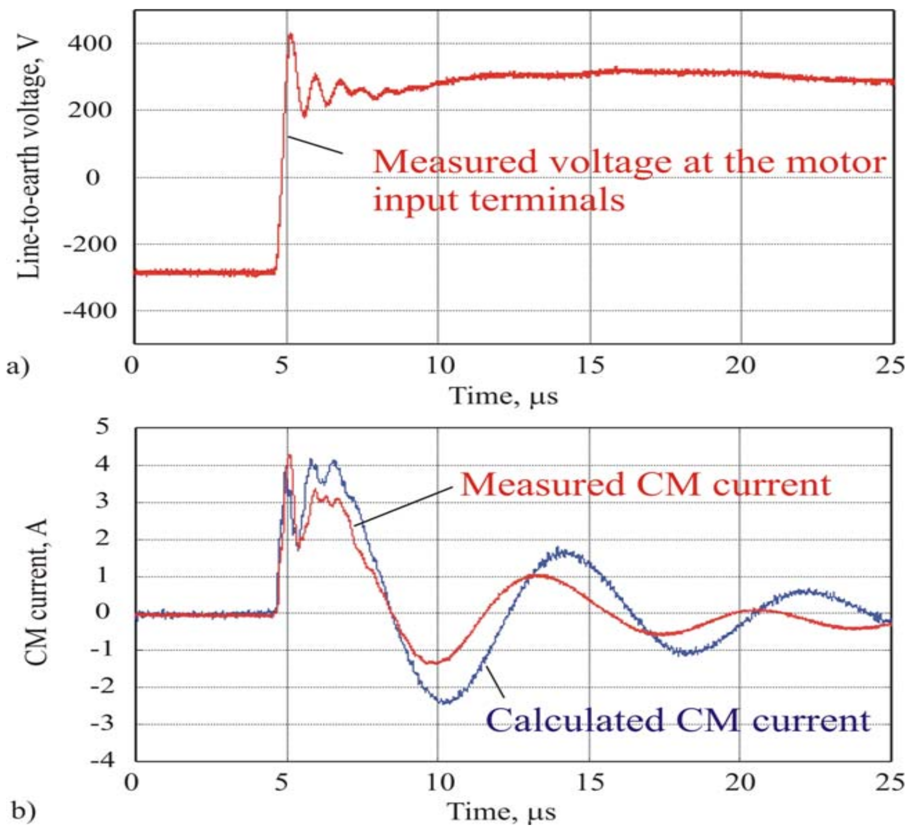
It has a good representation for:

f < 100 kHz

f > 1 MHz

Comparative Results





7.5 kW induction motor, motor cable length 100 m, DC link voltage 560V, 3 kHz switching frequency

240 kW induction motor, motor cable length 2 m, DC link voltage 560V, 4 kHz switching frequency

Modeling of Stator Winding at HF

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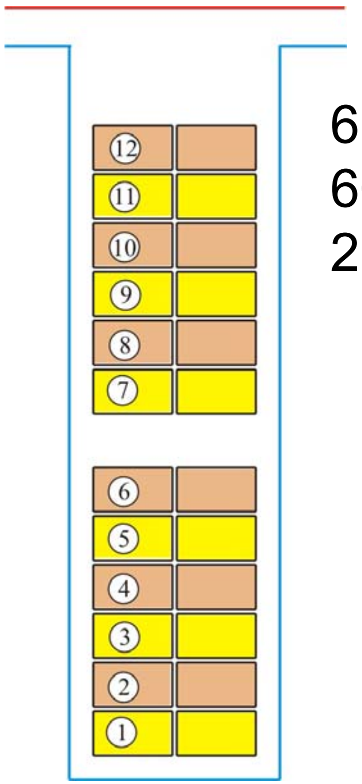
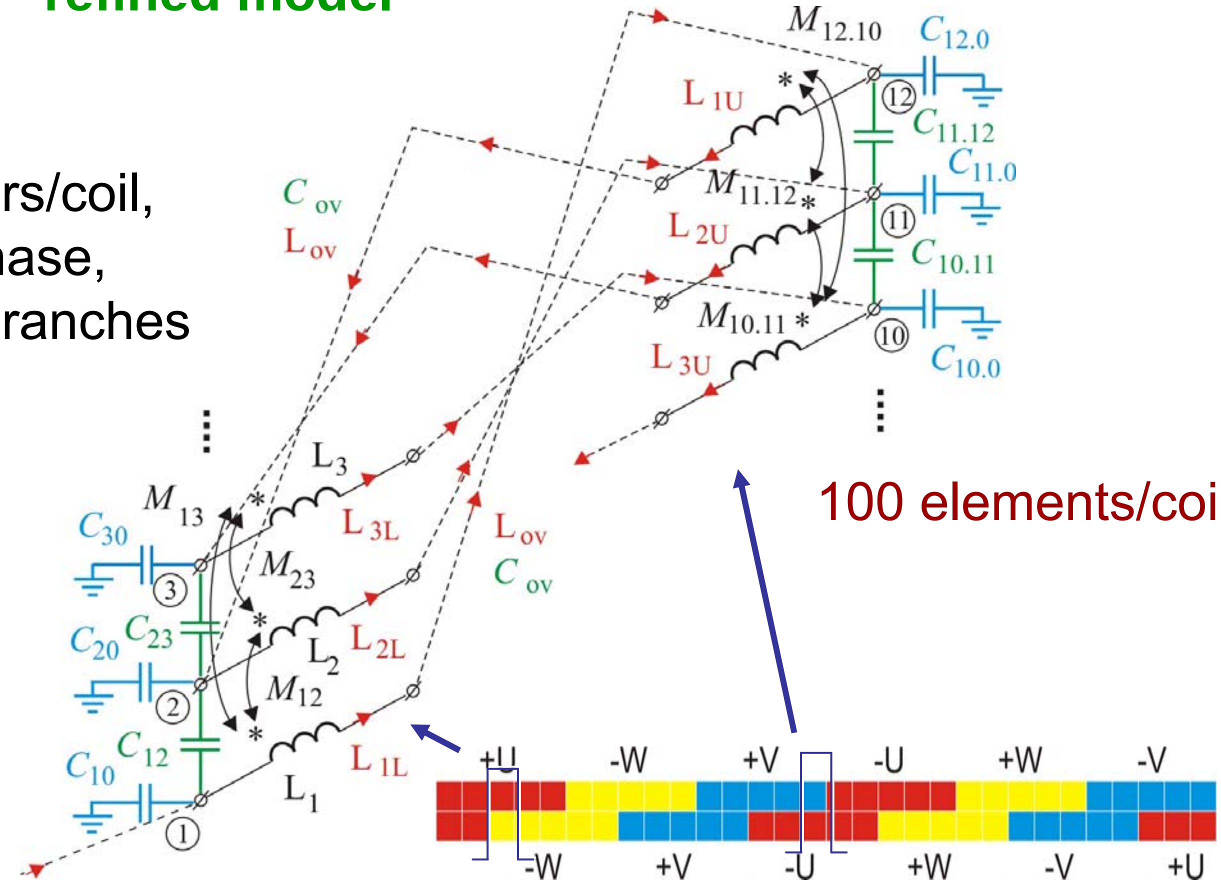
240 kW induction motor – **refined model**



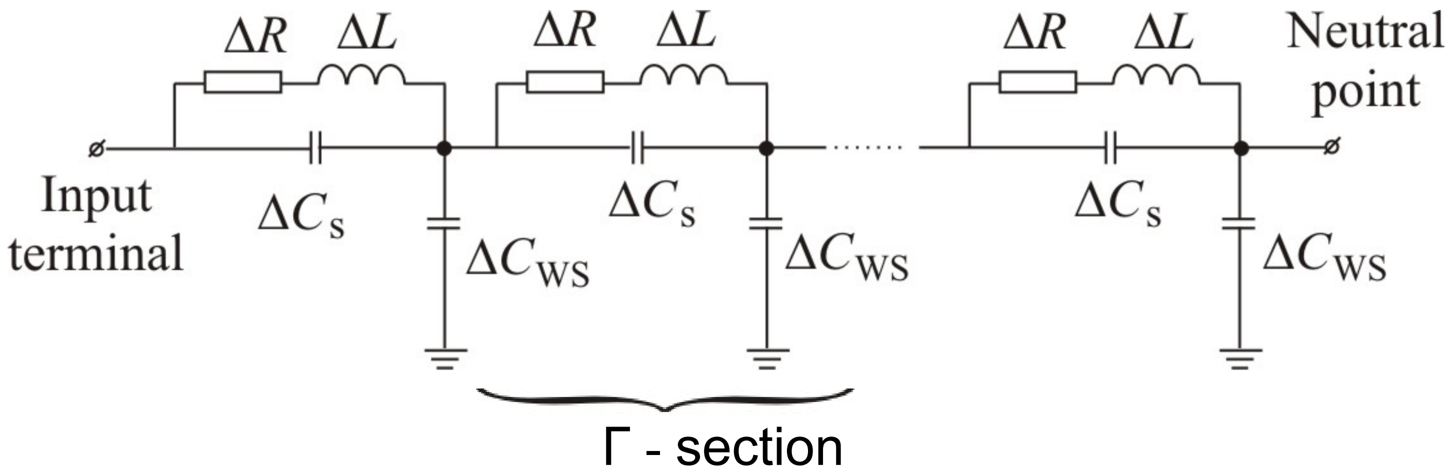
6 conductors/coil,
60 turns/phase,
2 parallel branches



100 elements/coil

Very big number of elements, time consuming! – need simplifications

TL Equivalent Circuits



Equivalent circuit per phase of a stator winding

- ΔR, ΔL are the resistance and inductance per turn,
- ΔC_{WS} is the stator winding – frame capacitance per turn of one stator phase
- ΔC_S is the capacitance between two turns (may be neglected for CM current calculation)

Calculation of TL Circuit Parameters

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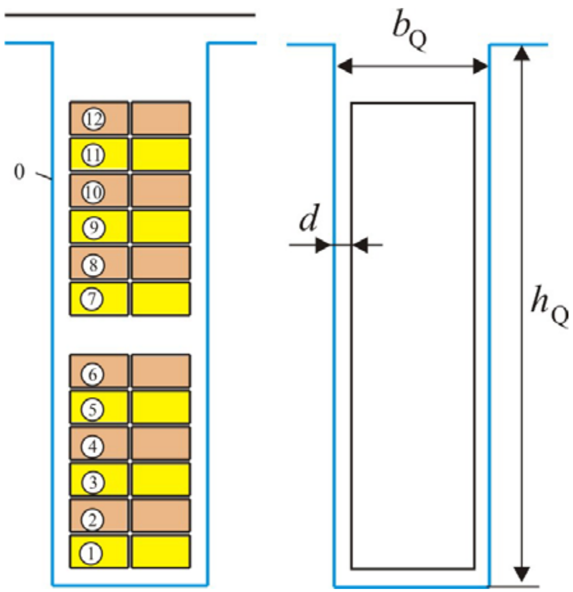
Assumptions from the transmission line theory :

-the electric field energy is enclosed inside the slots and the air gap

- the magnetic field does not penetrate the stator and rotor iron core

Capacitance per turn:



$$\Delta C_{WS} = \frac{2}{a_L \cdot N_C} \cdot \frac{C_{WS}}{Q_S}$$

N_C: number of conductors per coil in the slot

a_L: number of stator winding layers

where:

$$C_{WS} = \varepsilon_0 \cdot \varepsilon_r \cdot \frac{l_{Fe} \cdot u_Q \cdot 0.9}{d} \cdot Q_S$$

Calculation of TL Circuit Parameters

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Inductance per turn:

Due to the skin effects in the iron sheets, the leakage inductance per phase decreases considerable at HF.

Roughly, it can be estimated as 30% of the leakage winding overhang calculated at low frequency:

$$\Delta L \cong 0.3 \cdot \left(\mu_0 N_{\mathrm{s}}^{\;2} \cdot (2/p) \cdot \lambda_{\mathrm{b}} \cdot l_{\mathrm{b}}\right)$$

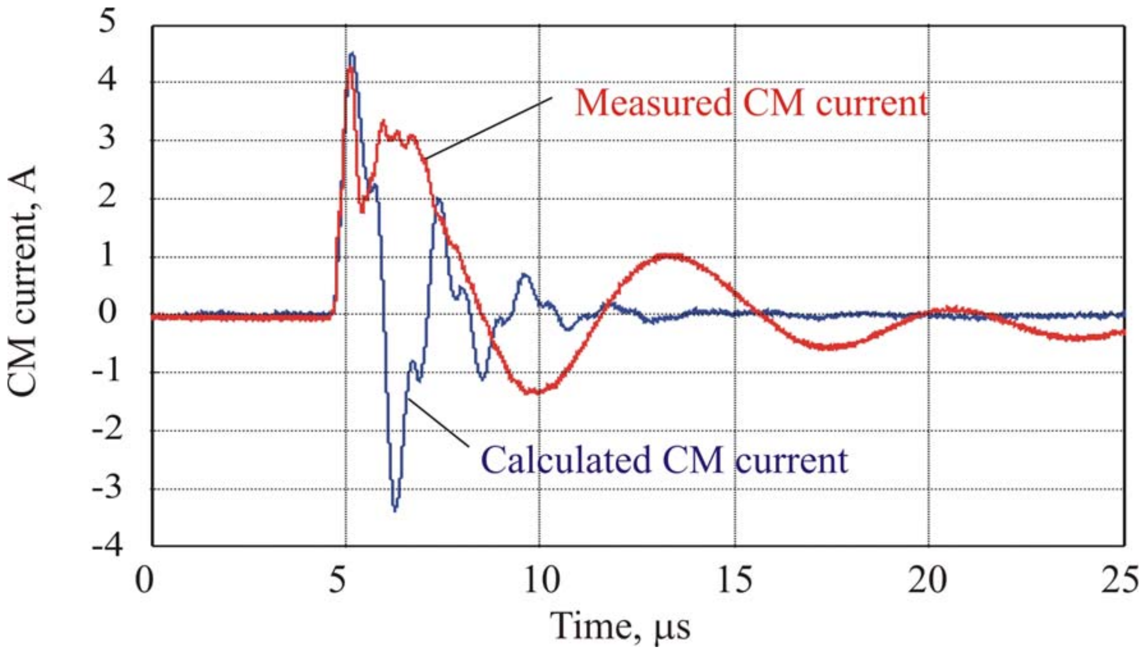
Resistance per turn:

The stator winding resistance increases strongly at HF because of the current displacement effect!

For rectangular-shaped wires the *Field* formula may be applied.

Comparative Results

Calculated CM current with a TL circuit (ΔR, ΔL, ΔC_{WS}) for a 240 kW induction motor fed by a PWM inverter (DC link voltage V_{DC} = 560 V)



Good results for bigger machines, but only peak values can be calculated!

For smaller machines, the TL circuit needs improvement! **– *R-L* ladder circuits** (proposed for cable modeling at HF)

Overview

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- **Introduction**
- **Circulating Bearing Currents**
    - **Calculation of CB Currents with Equivalent Transformer Circuits**
    - **Measurements and Comparative Results**
- **EDM Bearing Currents**
- **Conclusion**

Circulating Bearing Currents

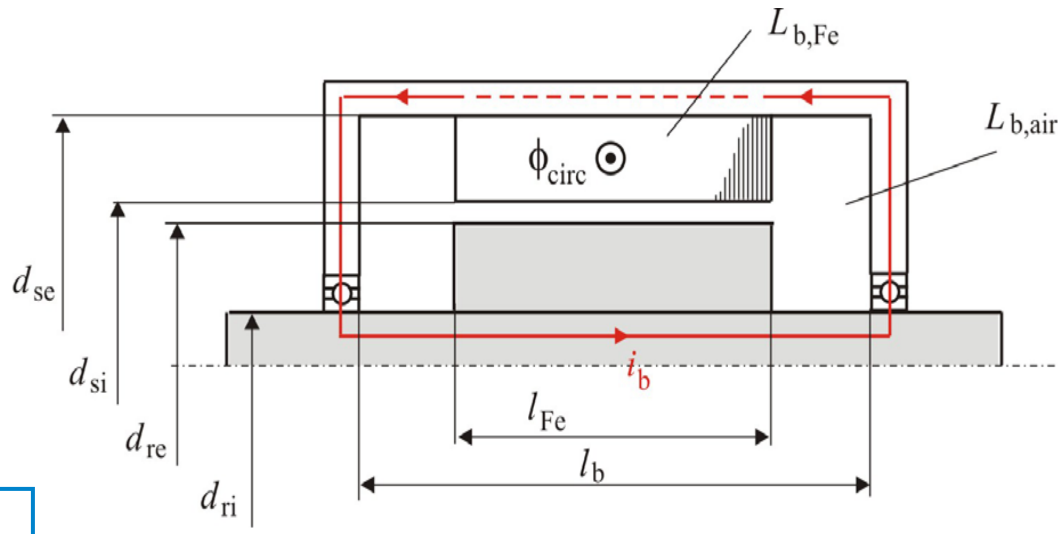
Common Mode Current
(measured or calculated)

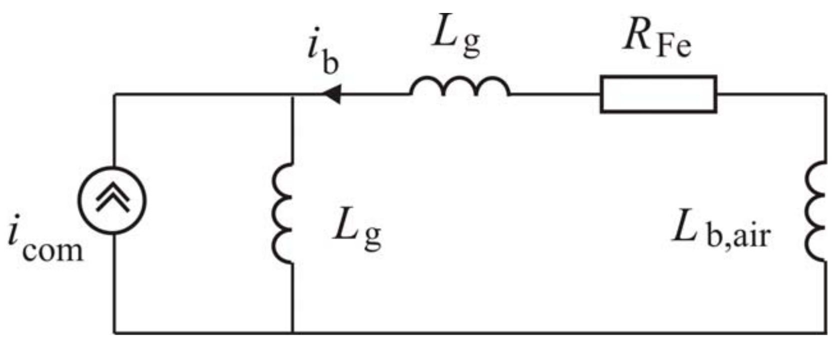
↓

Equivalent Circuit

↓

Circulating Bearing Current





Muetze, **IEEE-2004**

$2L_g = L_{b,Fe}$ - mutual inductance;

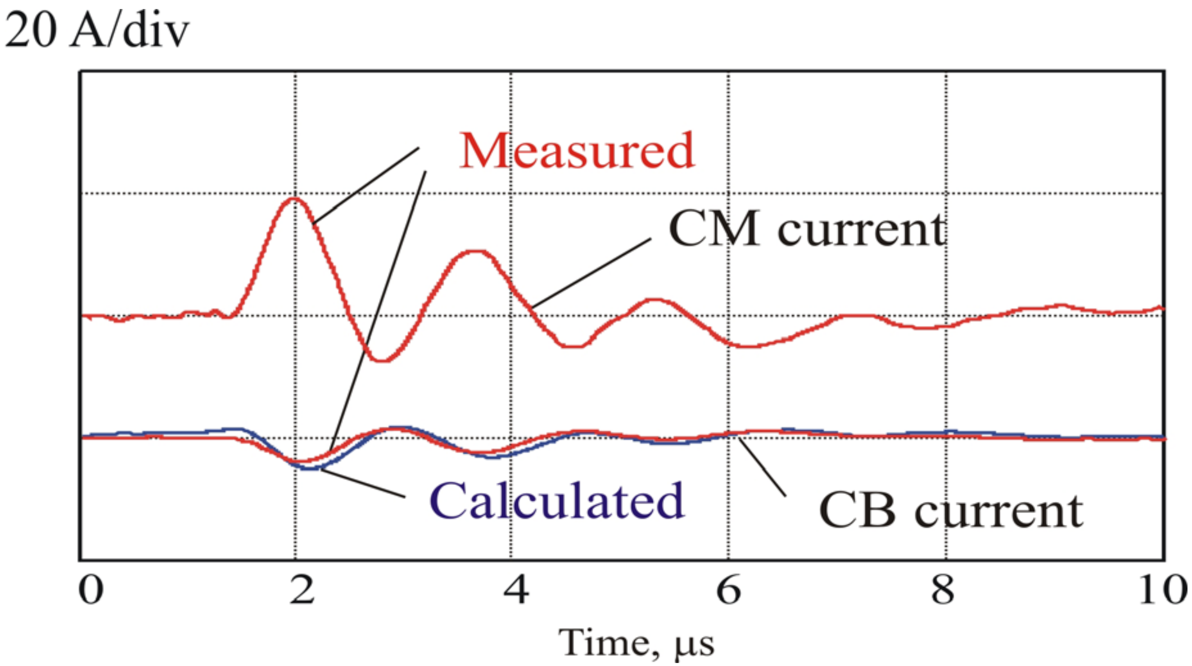
$L_{b,air}$ - self-inductance of the magnetic flux of the area enclosed by the the airgap and the end-winding cavity air;

R_{Fe} - resistance corresponding to the iron losses

Comparative Results

560 kW, 2 poles induction motor

$d_{se} = 680$ mm, $d_{si} = 360$ mm, $d_{re} = 353$ mm, $d_{ri} = 150$ mm, $l_{Fe} = 490$ mm



The *equivalent transformer circuit* is a harmonic circuit.

Thus, the Fourier analysis of the CM current waveforms is required!

Measured and calculated CB current with the *equivalent transformer circuit!*

Overview

- **Introduction**
- **Circulating Bearing Currents**
- **EDM Bearing Currents**
  - **Measurements of EDM Bearing Currents**
  - **Calculation of Bearing Capacitances**
  - **Modeling of Bearings**
  - **Prediction of EDM Currents and Bearing Voltages**
  - **Influence of Operating Parameters on EDM Currents**
- **Conclusion**

EDM Bearing Currents

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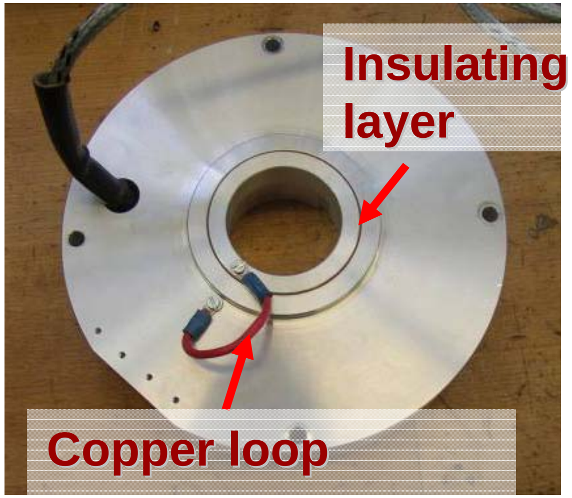
Measurement setup

An insulating layer is built in the end shield and a copper conductor loop is used to create a bridge over insulation.

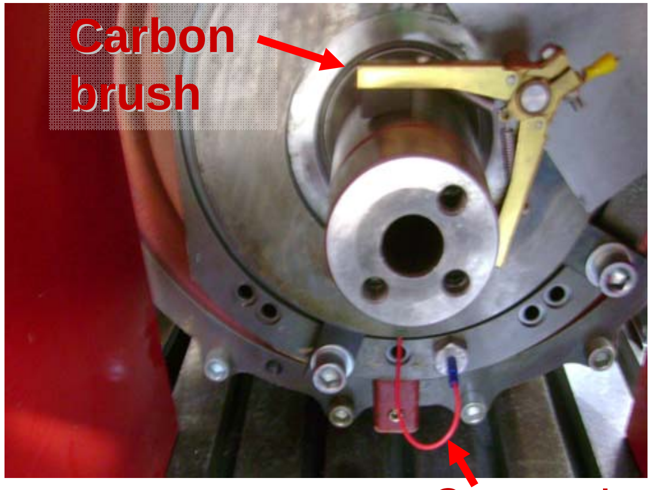
1.5 kW induction motor

Bearings type: 6205 C3 for both DE and NDE:



240 kW induction motor

Bearings type: NU228 at DE, 6316 at NDE



Copper loop

Measurements on EDM current – 1.5 kW

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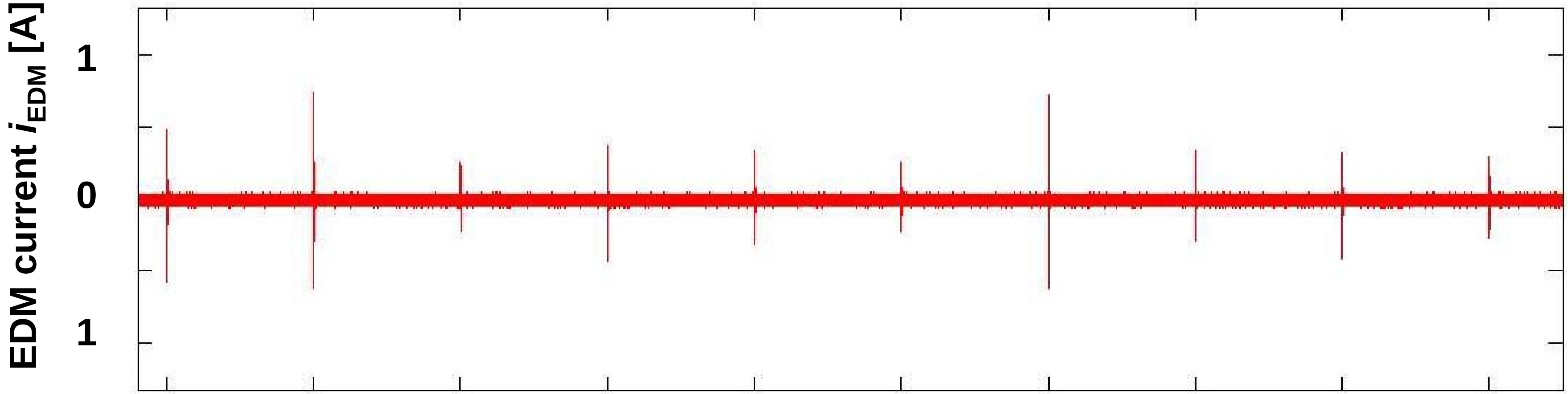
EDM current measured at **300 rpm, f_{sw} = 4 kHz** for a **1.5 kW induction motor**



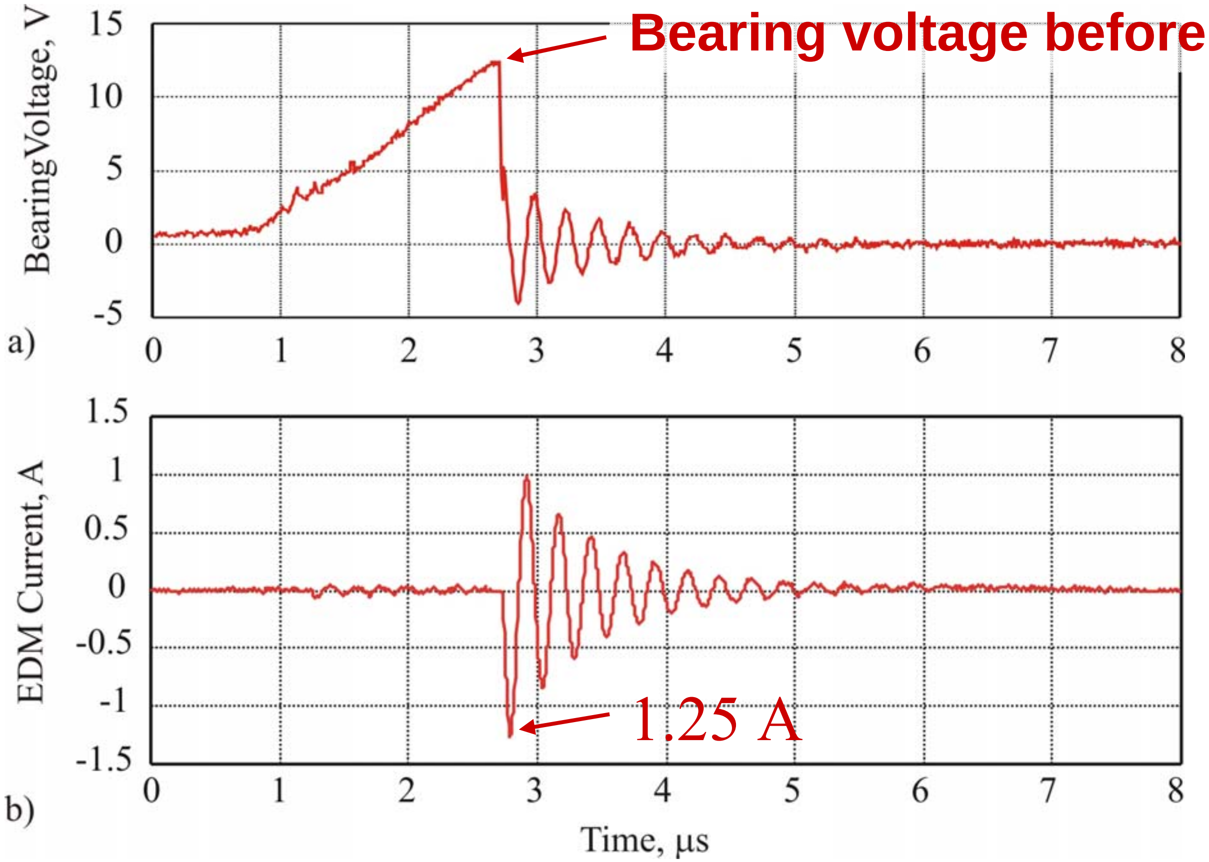
Puncture Sequence	1 - 2	2 - 3	3 - 4	4 - 5	5 - 6	6 - 7	7 - 8	8 – 9	9 – 10
Time, sec	1.76	10.79	5.29	3.41	0.21	7.43	3.81	3.81	$124 \cdot 10^{-6}$

Measurements on EDM currents show:

- Different amplitudes of the EDM currents
- Different intervals of time between two punctures

Measurements on EDM current – 240 kW

Bearing voltage (a) and EDM current (b) at a speed of **300 rpm** of the **240 kW induction motor, f_{sw} = 4 kHz**



Bearing voltage before breakdown:

$$\hat{v}_b = 12.5\,\text{V}$$

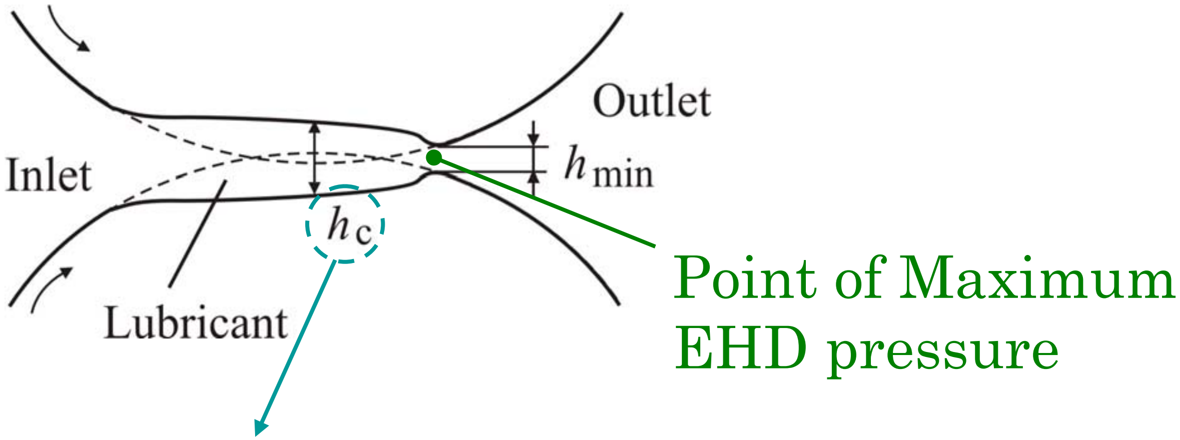
Lubricant thickness:

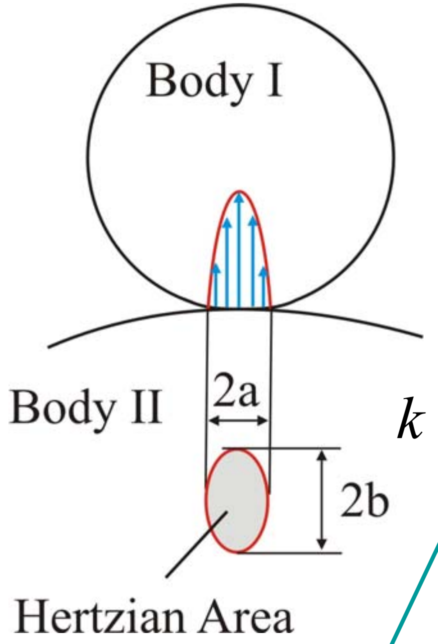
$$h_c \cong 0.8\ \mu\text{m}$$

estimated for a typical threshold value of
15 kV/mm

Calculation of Lubricant Thickness

Elastohydrodynamic (EHD) Theory





$$k = \frac{b}{a}$$

- <u>*Pan* and *Hamrock*'s equation</u> (roller bearings):

$$h_c[\text{mm}] = 2.922 \cdot R_{eq}[\text{mm}] \cdot U_r^{0.694} \cdot G^{0.47} \cdot W^{-0.166}$$

- <u>*Hamrock* and *Dowson*'s equation</u> (ball bearings):

$$h_c[\text{mm}] = 2.69 \cdot R_{eq}[\text{mm}] \cdot U_r^{0.67} \cdot G^{0.53} \cdot W^{-0.067} \cdot \left(1 - e^{-0.73 \cdot k}\right)$$

Lubricant Thickness: Roller Bearing

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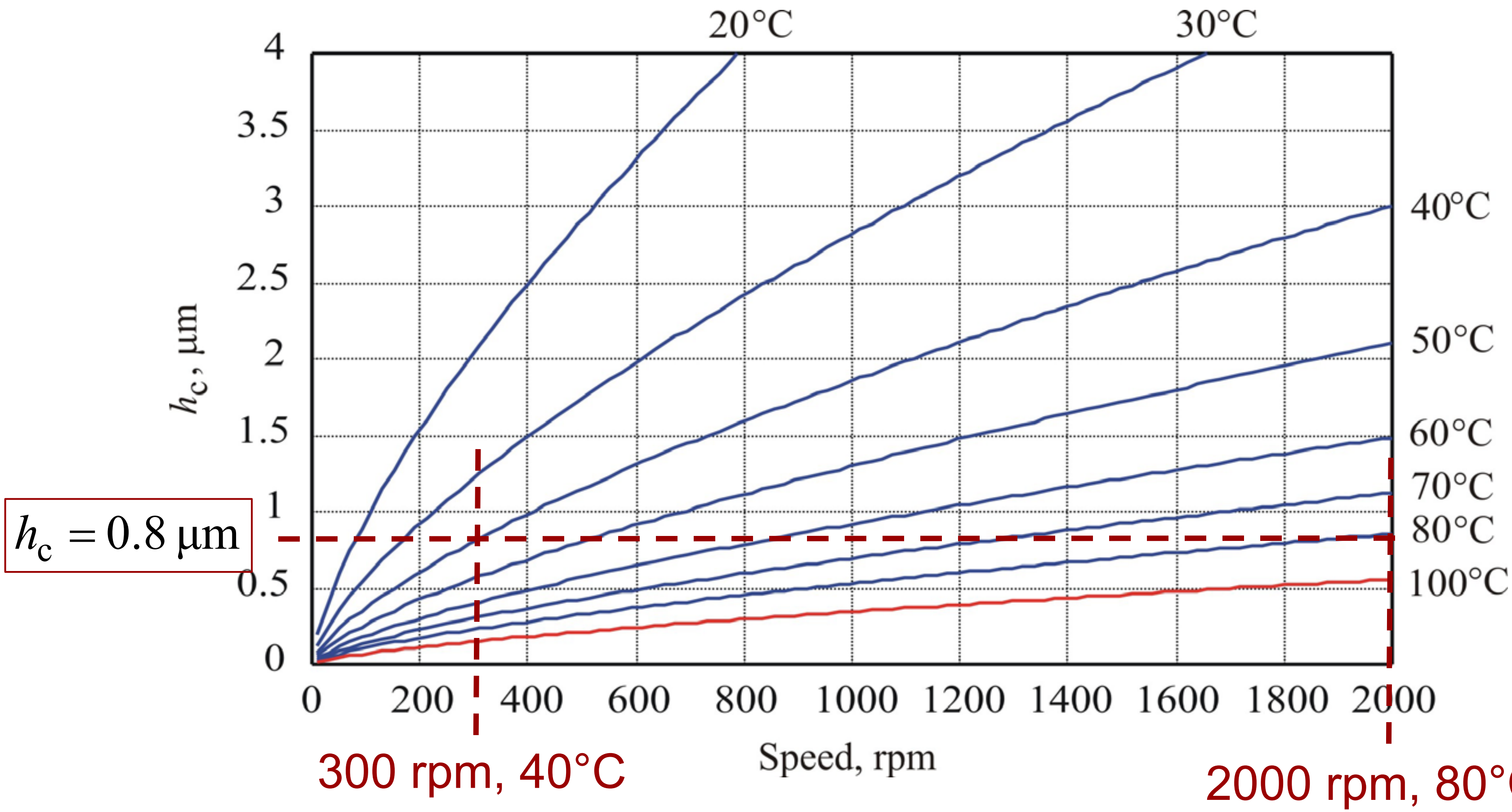
DE bearing for **240 kW induction motor**: **NU228**



Calculation of Bearing Capacitance

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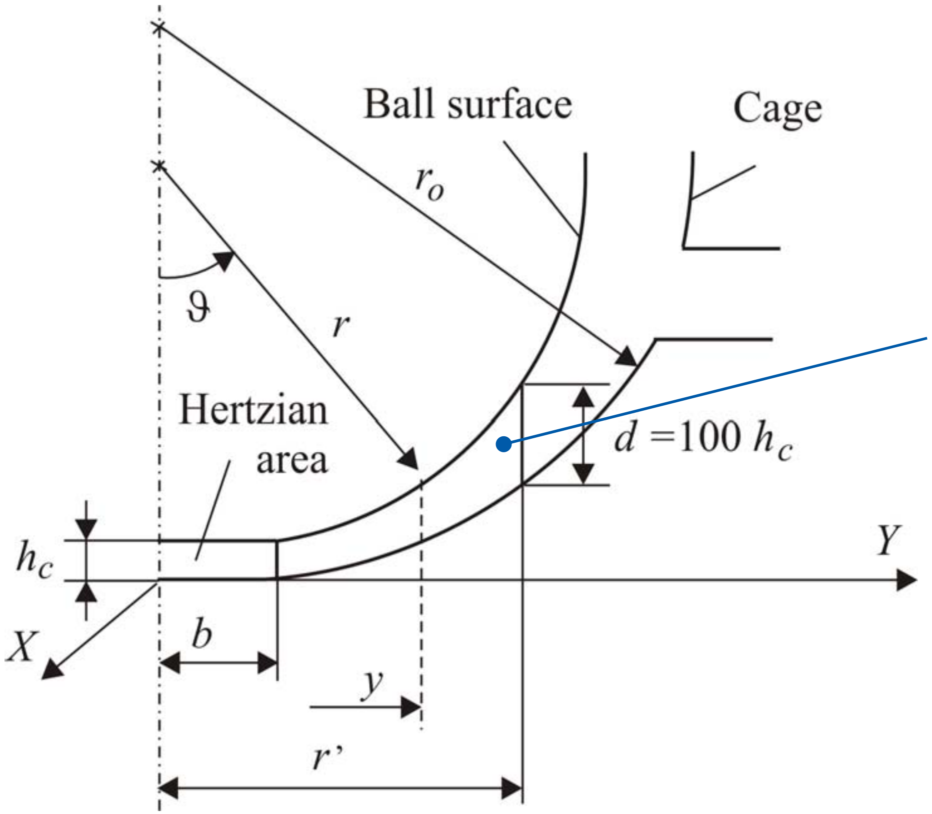
Model of a ball bearing in a radial section



For the *Hertz*'ian area:

$$C_{\mathrm{Hz}} = \varepsilon_0 \varepsilon_{\mathrm{r}} \cdot \frac{\pi \cdot a \cdot b}{h_c}$$

Close to the *Hertz*'ian area:

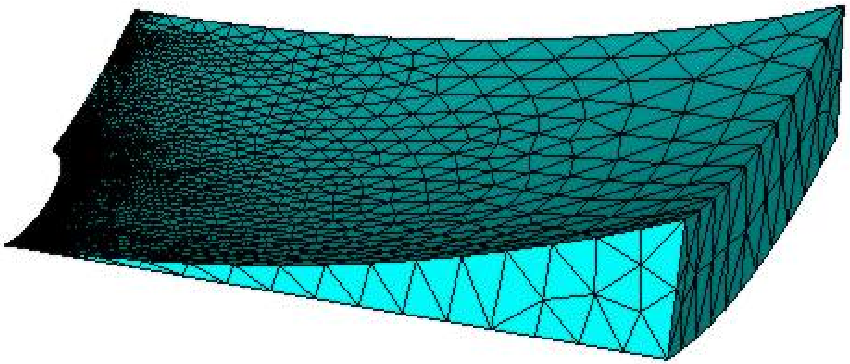
$$C_{\mathrm{air}} = 4 \cdot \varepsilon_0 \cdot \int_a^{r'} \frac{k_{\mathrm{xy}} \cdot x}{h_{\mathrm{c}} + \delta_{\mathrm{x}} \cdot x^2} \cdot dx$$

$$\delta_{\mathrm{x}} = \frac{1}{2 \cdot r}$$

$$\delta_{\mathrm{y}} = \frac{1}{2}\left(\frac{1}{r} - \frac{1}{r_0}\right) \qquad k_{\mathrm{xy}} = \sqrt{\frac{\delta_{\mathrm{x}}}{\delta_{\mathrm{y}}}}$$

Calculation of Bearing Capacitance

- 2D FEM methods (roller bearing capacitances)
- 3D FEM methods (ball bearing capacitances)



3D mesh (ANSYS) for calculation of the air capacitance C_{air} of the ball bearing type 6316

Example: 240 kW motor

300 rpm and 40°C

Roller bearing capacitance:

$$C_b = 428 \text{ pF}$$

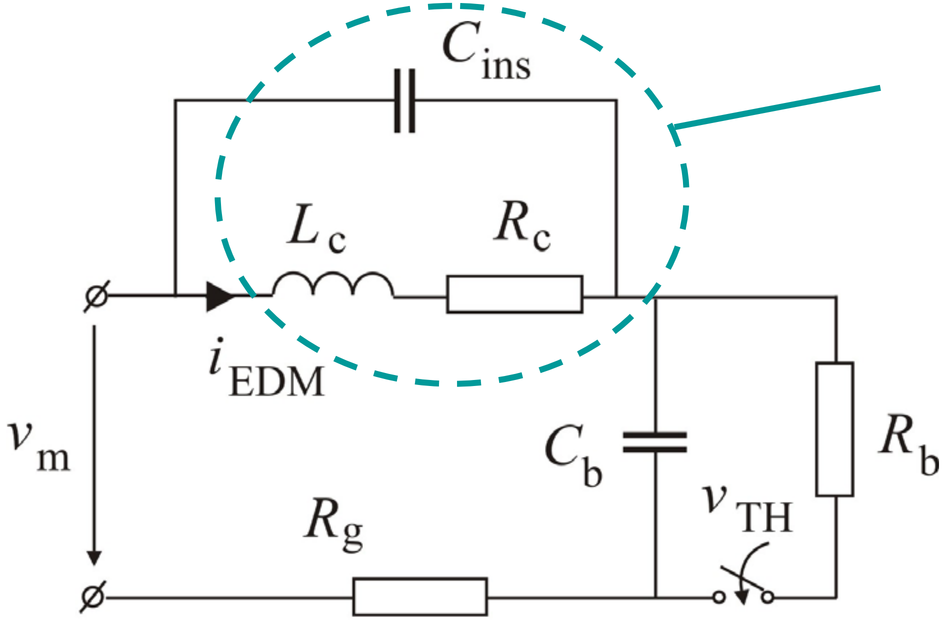
Ball bearing capacitance:

$$C_b = 159 \text{ pF}$$

Main problem: $\frac{r'}{h_c} = \frac{5.25\,\text{mm}}{0.4\,\mu\text{m}} = 13.1 \cdot 10^3$

Modeling of Bearings

The bearing parameters are dynamically dependent on the operating conditions of the machine.



Ceramic coating (insulating layer): - C_{ins}

Copper conductor: - R_c, L_c

- R_b - Bearing resistance and C_b - Bearing capacitance
- A switch models the behavior of the lubricant

Evaluation of Bearing Resistance

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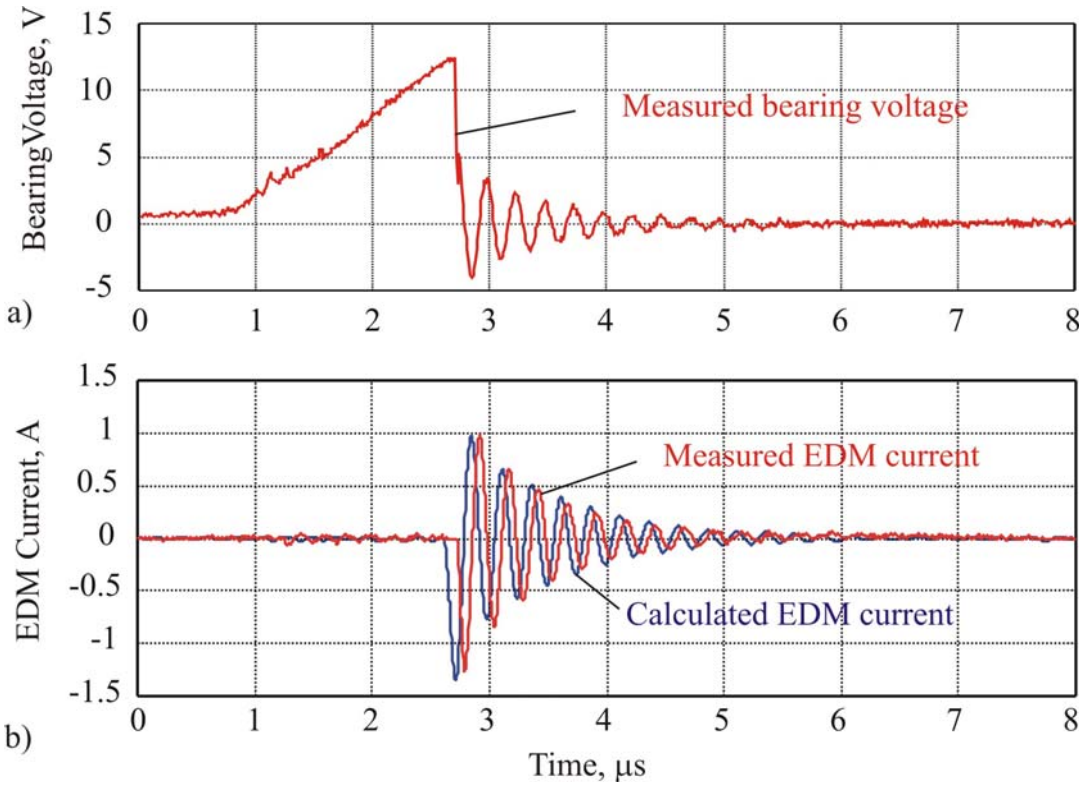
The evaluation is done indirectly considering:

- the bearing equivalent circuit,
- bearing voltage (a) and EDM current (b)



300 rpm, 40°C !

$R_b = 4.5\ \Omega$

(after breakdown)

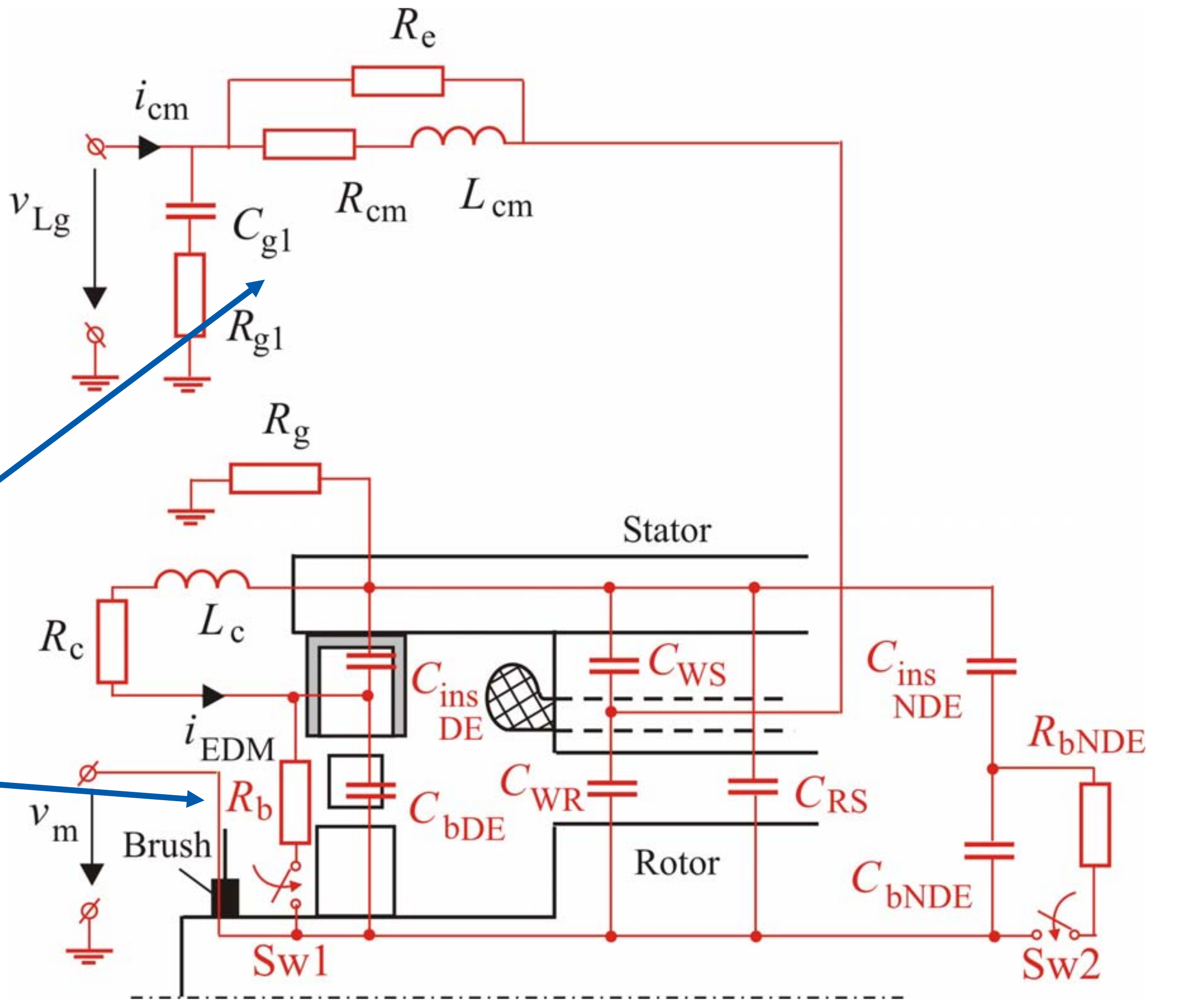
$C_b \leq 0.7\ \text{nF}$

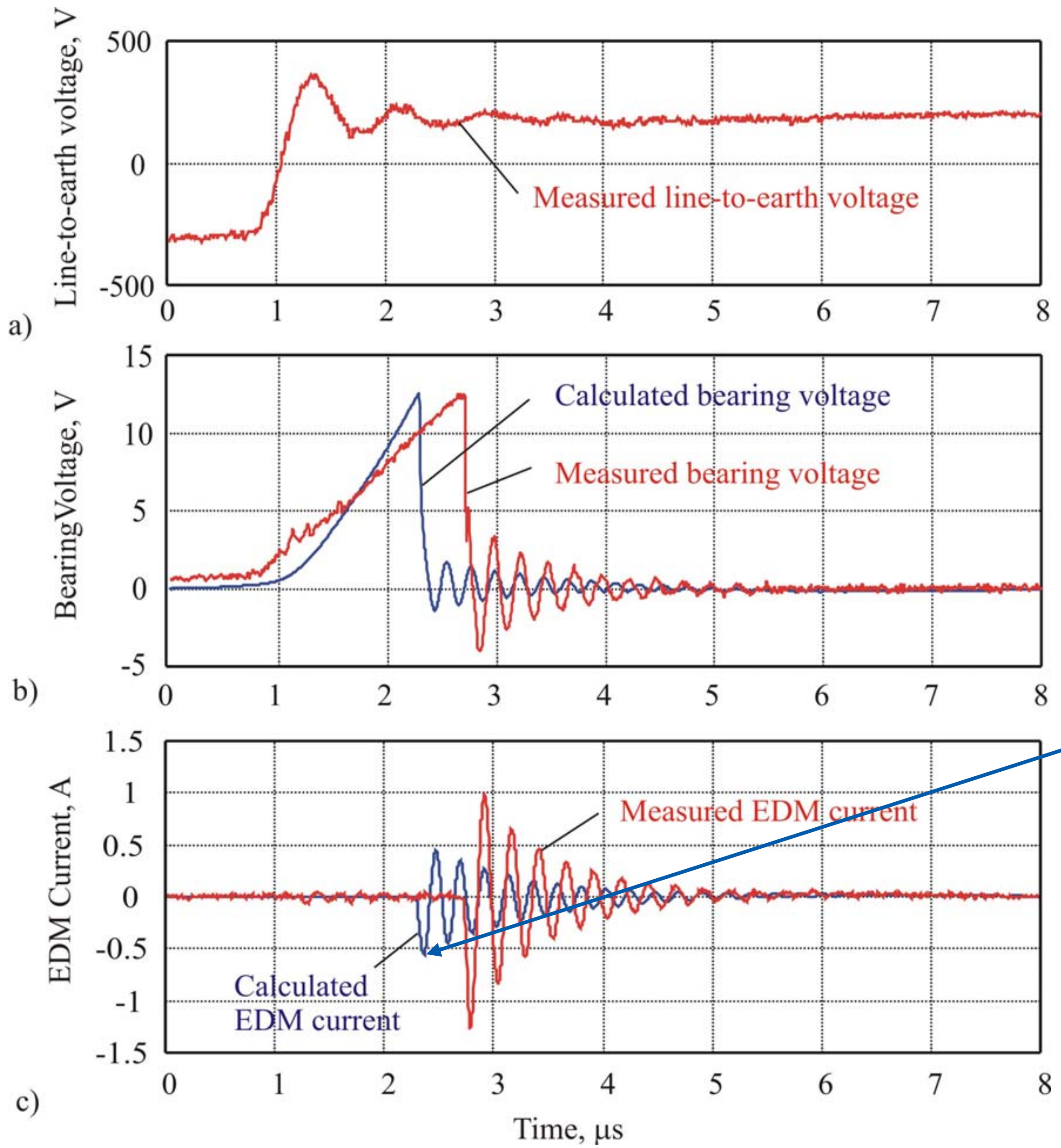
Obs: The results are very sensitive at the insulation capacitance!

Prediction of EDM Currents and Bearing Voltages

The representation of the motor capacitances suggests a:

- HF equivalent circuit of the induction motor
- Bearing model





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Measurements on the 240 kW induction motor
- switching frequency:
$f_{sw} = 4$ kHz,

- DC link voltage
$V_{DC} = 560$V

The model shows:
existence of a peak of the EDM current of 0.5 A

Related to the *Hertz'*ian area:
EDM peak current density
$J_B = 0.17$ A/mm^2

Influence of Temperature, Speed and Bearing Load on EDM Currents

Sometimes, the bearings are not destroyed by EDM currents. They may develop a stable gray bearing trace.

The reason has not been clarified yet!

Investigations on the influence of the operating parameters on the EDM currents and bearing wear are necessary.

1.5 kW, 4-pole, Squirrel Cage Induction Machine

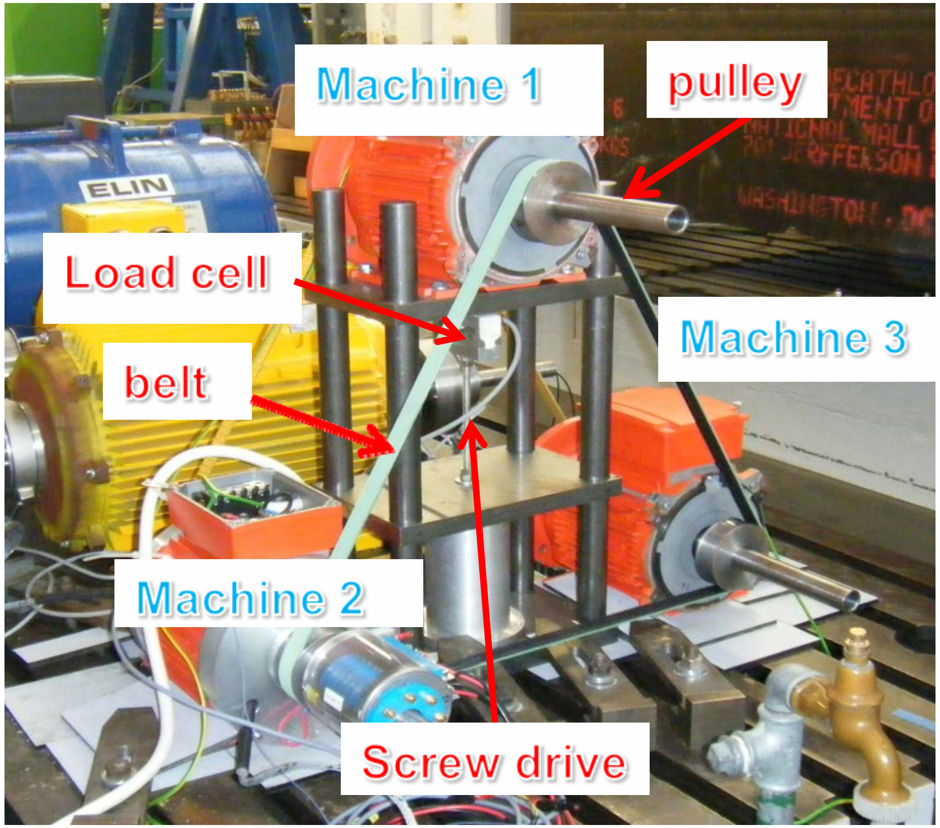
DE and NDE Bearings, type 6205 C3

4.2 kVA Inverter, 560 V DC link voltage, 3-5 kHz switching frequency

- **Speed**: 150 rpm – 1500 rpm (1950 rpm) in 150 rpm steps
- **Temperature**: 40°C – 80°C in 10°C steps
- **Load**: radial bearing forces with up to 270 N

Bearing Loading and Measurement System

Test bench with 3 identical 1.5 kW squirrel-cage induction machines and force measurement system



Advantages:

- Only radial forces
- High bearing loading
- Good insulation
- Less complexity and less components
- Easier adjusting
- Long lifetime

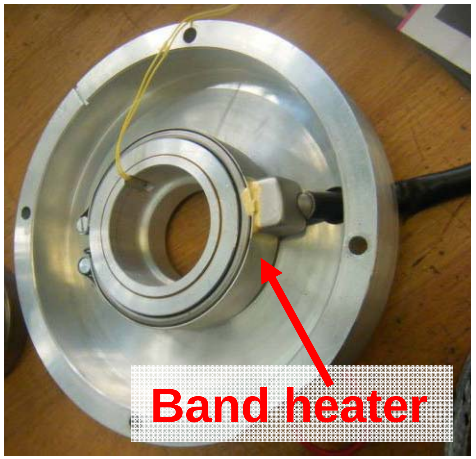
Disadvantages:

- Big initial force for belt

Bearing Heating System

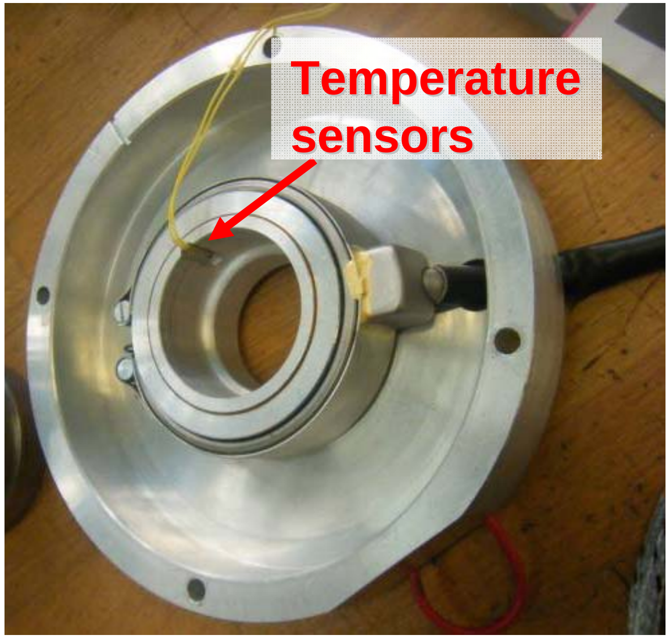
Heating with band heaters – normally used for extruders

Advantages:
- Symmetrical heating – symmetrical bearing temperature
- Isolated system
- Good controlling
- Less built space
- High lifetime
- Available at different sizes and power levels



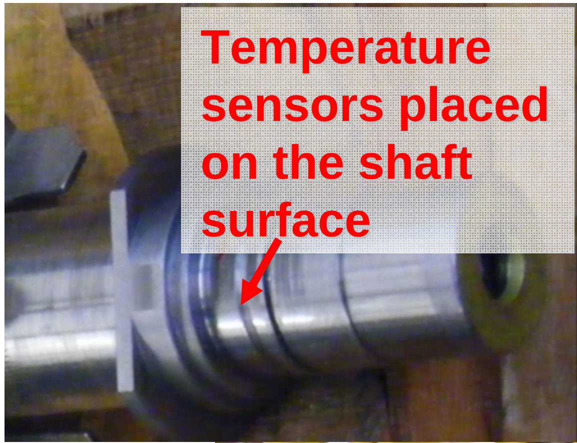
Temperature Measurement System

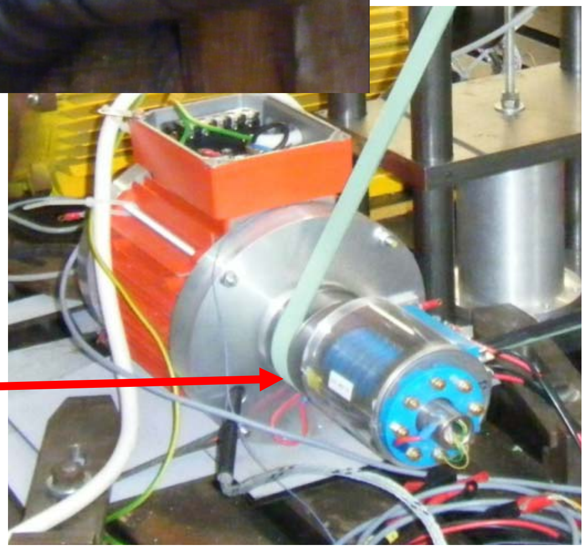
Temperature measurement at the outer bearing surface:



The bearing temperature should not differ, at the inner and outer bearing surface, with more than 10°C !

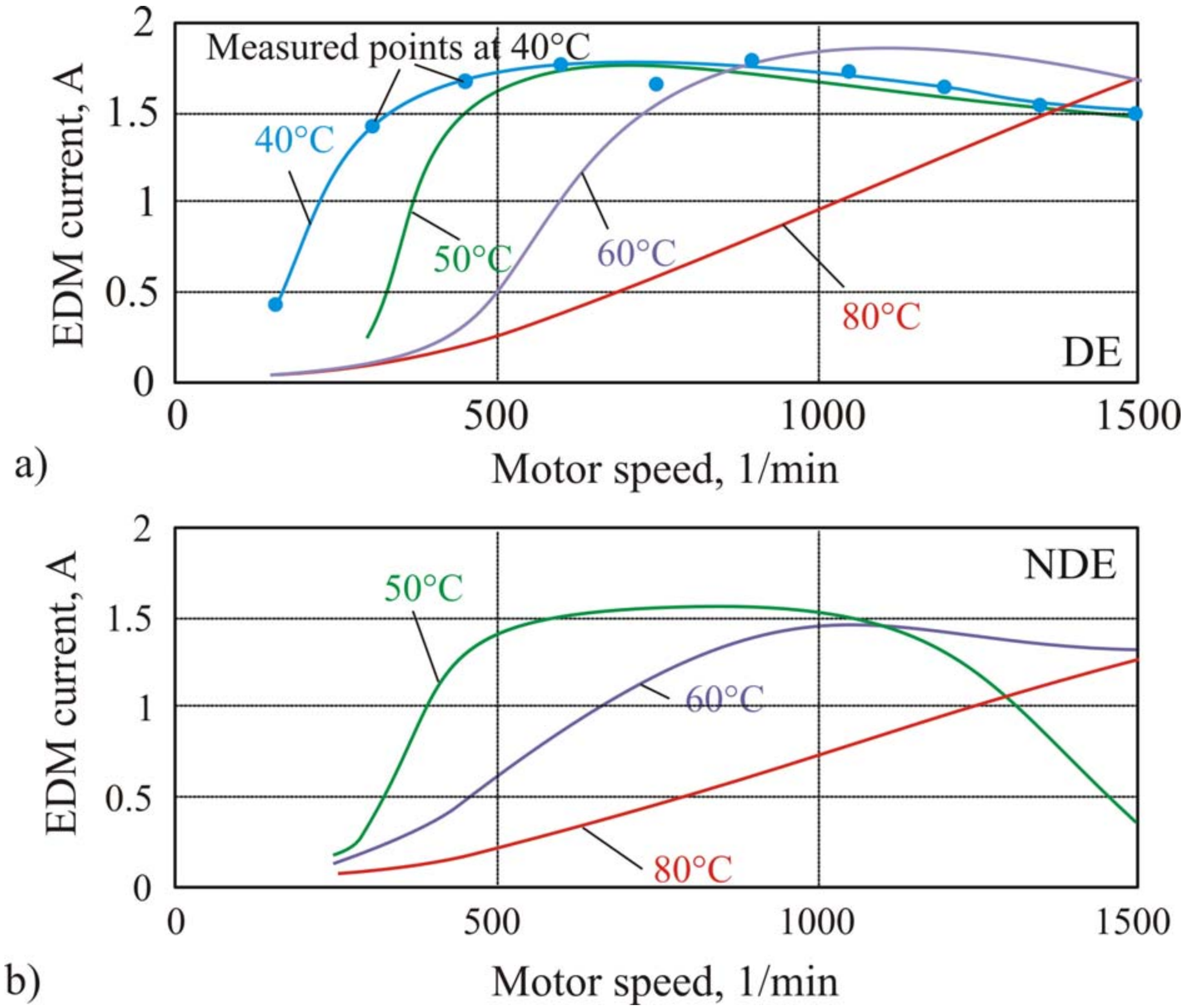
Temperature measurement at the inner surface:





Slip rings for temperature measurement

Temperature Influence on EDM Currents – Radial Load per Bearing of 60 Nm



Induction Motor:
1.5 kW

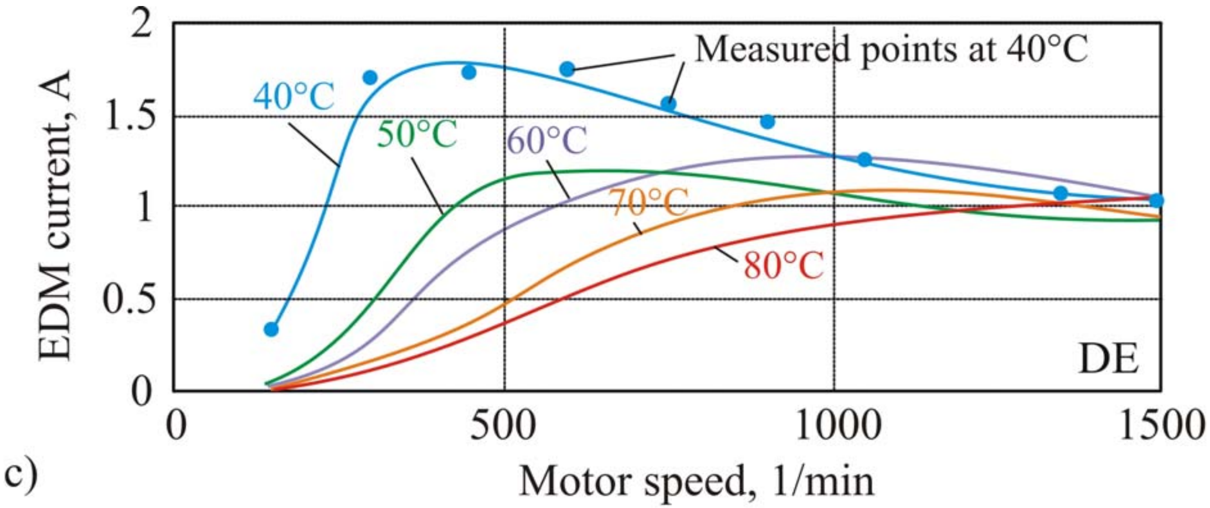
Bearing:
6205 C3

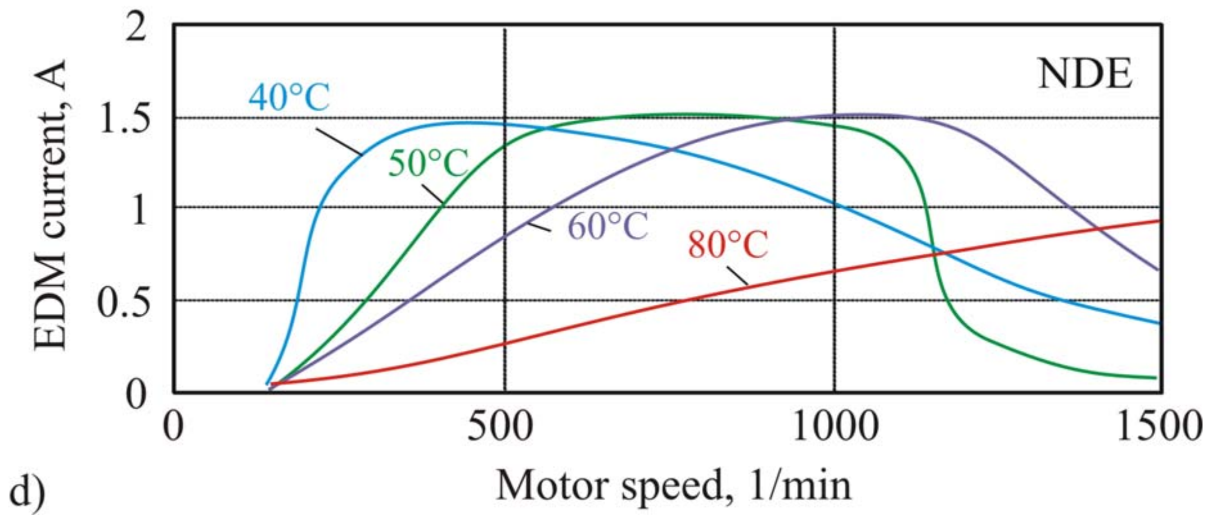
Lubricant:
oil: - mineral
soap: - diurea complex

Inverter switching frequency:
4 kHz

Cable:
2m, unshielded

Temperature Influence on EDM Currents – Radial Load per Bearing of 160 Nm





Induction Motor:
1.5 kW

Bearing:
6205 C3

Lubricant:
oil: - mineral
soap: - diurea complex

Inverter switching frequency:
4 kHz

Cable:
2m, unshielded

Bearing Load Influence on EDM Currents - Bearing Temperature of 60°C

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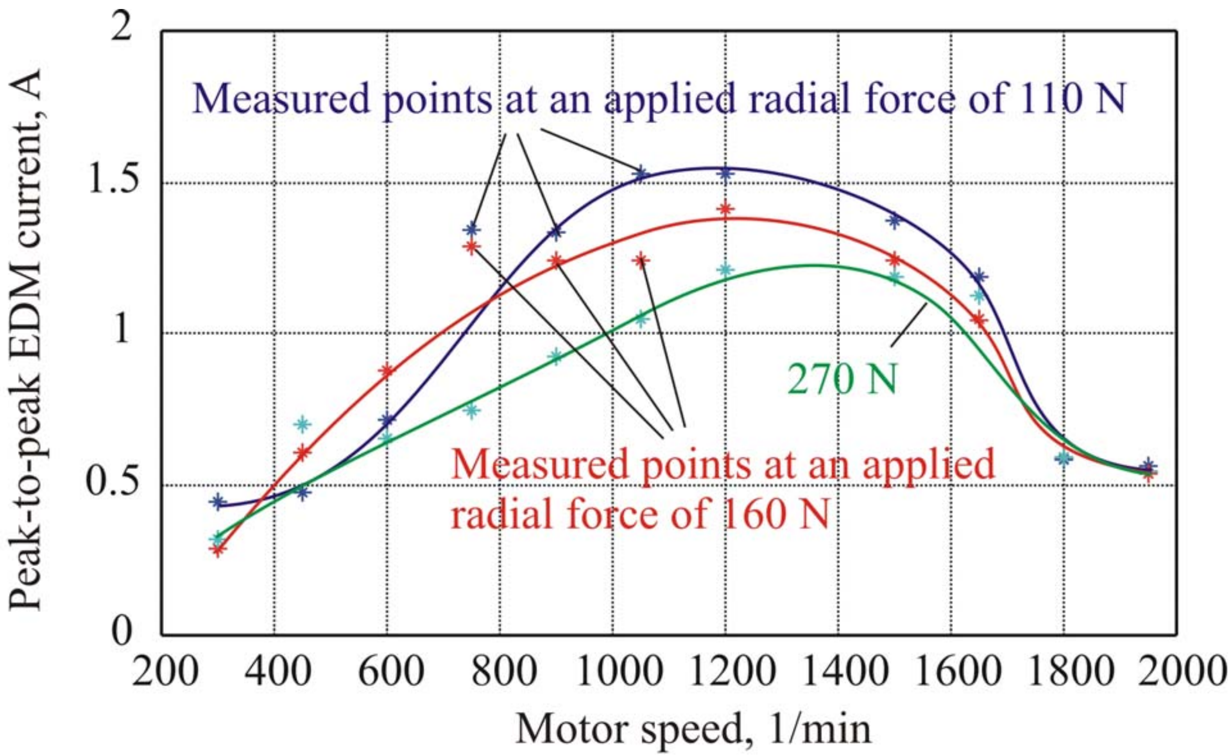

The larger the bearing load, the smaller the EDM current!

Induction Motor:
1.5 kW

Bearing:
6205 C3

Lubricant:
oil: - mineral
soap: - diurea complex

Inverter switching frequency:
4 kHz

Cable:
2m, unshielded

Evaluation During Time of EDM Currents

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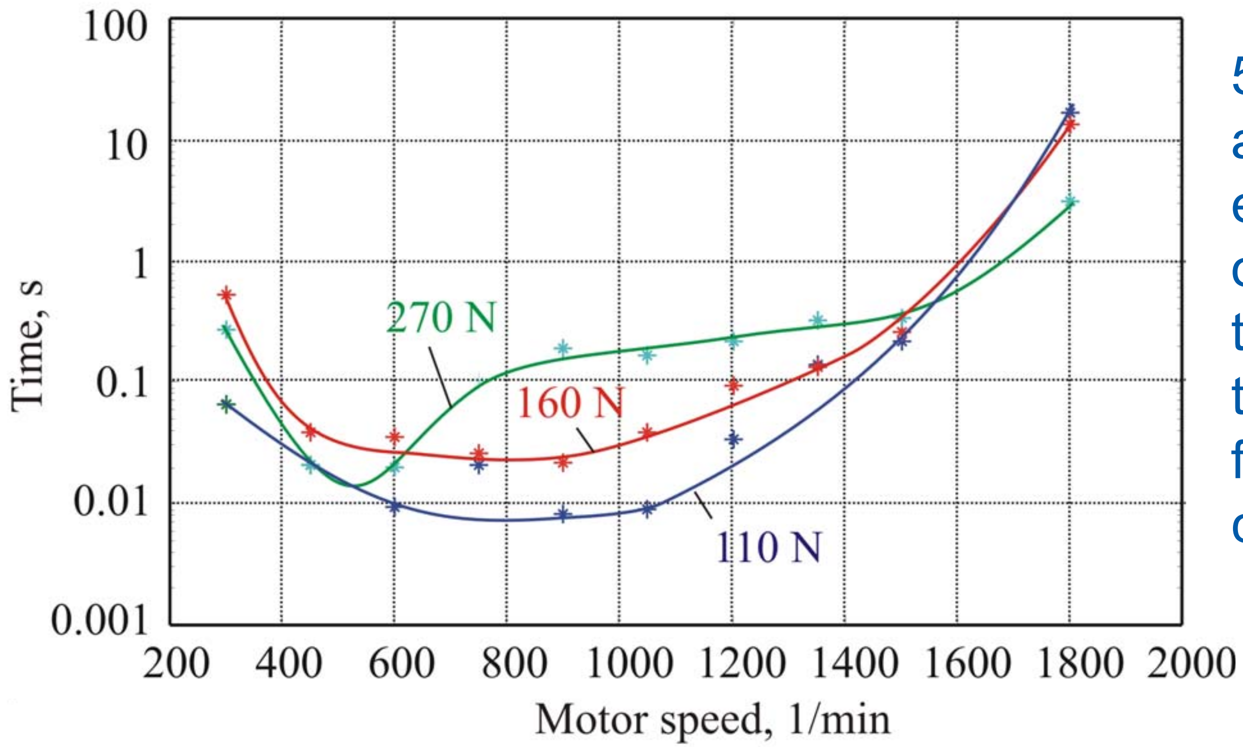
Non Drive End: EDM currents for different bearing loads versus speed at 60°C bearing temperature



50 EDM currents are measured at each speed with an oscilloscope for a trigger of 0.1 A, and the time between the first and the last EDM current is counted !

Frequently occurrence of EDM currents: 500 rpm - 1000 rpm

Conclusions

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1. The SHF circuit may be used for an exact preliminary calculation of CM currents for motors, which are already manufactured. The TL circuits are recommended only for a prediction of the peak value of the CM currents in the design stage.

2. The CB current can be evaluated using transformer equivalent circuits using the CM current as an input current source. A *Fourier Analysis* is required in this case.

3. The EDM current can be well predicted with models, which considers only the bearing circuit. Unfortunately, the bearing voltage has to be measured in this case. A different model, which considers all motor capacitances, may be also used. It needs only the CM voltage at the input, but the prediction of EDM currents may be underestimated.

Conclusions

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4. The bearing load and bearing temperature affected strongly the peak-to-peak values of the EDM currents and the frequency of electric discharges. For a longer life, the bearings have to operate under load.

5. The artificial temperature rise has reduced the magnitude of EDM currents, independently by bearing loading, but only at lower speeds. Only for the NDE bearings and at higher speeds, the lower bearing temperatures kept the magnitude of EDM currents at smaller values.

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Thank you for your attention!