# Scaling Issues for Common Mode Chokes to Mitigate Ground Currents in Inverter-Based Drive Systems

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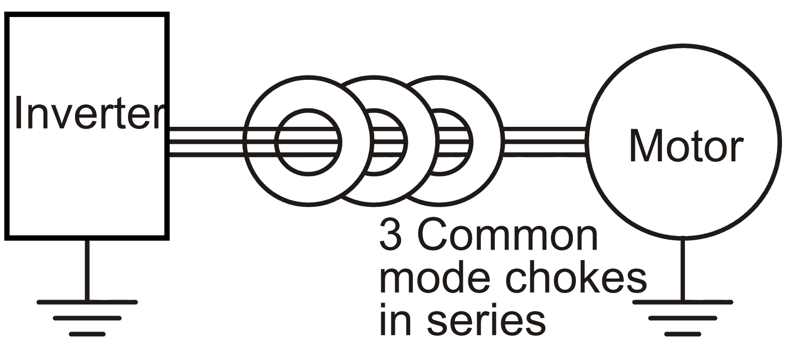


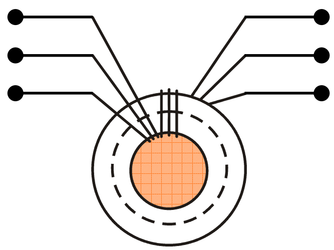

Source: Magnetec GmbH

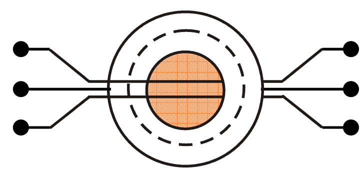
# Outline

- Motivation

  …to use common mode chokes in the inverter-output → requirements?

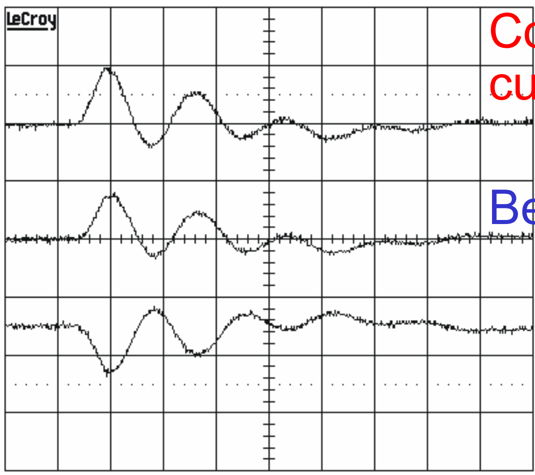
- Influence of the Inductance Value on the Current Reduction
  - Equivalent circuit, general case and un-damped case
- Physics of Common Mode Chokes
  - Fundamentals, wound and feed-through chokes





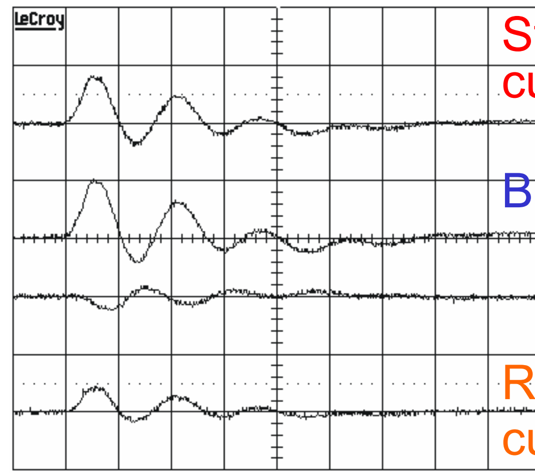
- Design Criteria
  - Window area, current-to-diameter ratio, minimum diameter,…
- Measurement Results
- Summary

# Motivation



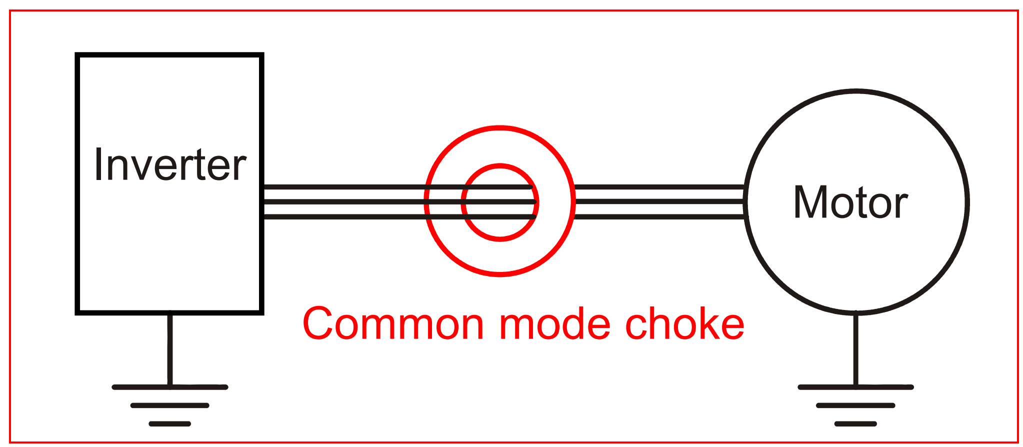

1 μs/Div

Circulating bearing currents
motor speed $n$ = 3000 /min




1 μs/Div

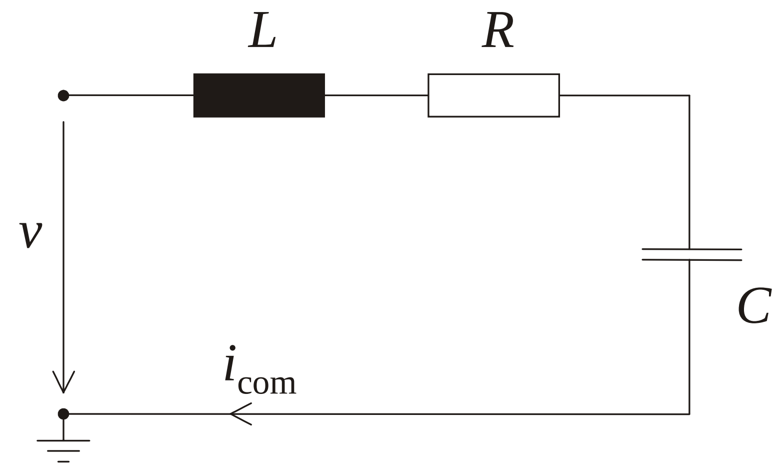
Bearing currents due to rotor ground currents,
motor speed $n$ = 15 /min, rotor grounded on DE-side




Squirrel-cage induction motor, frame size 400 mm, 500 kW rated power, bearing temperature $T_b \approx 70°C$ (Measurements were obtained in the frame of a research project at Darmstadt University of Technology, Institute of Prof. Binder)

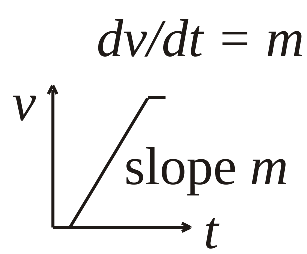
# Modeling: Lumped Parameter Circuit

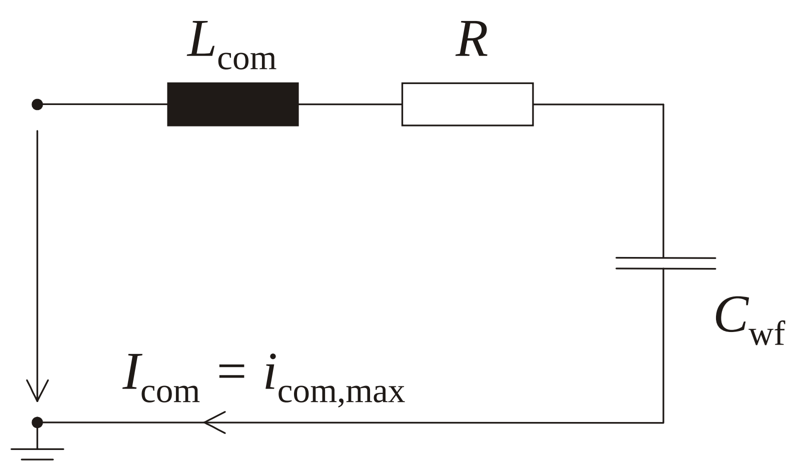
▷ Approach:
$RLC$-Circuit ($L$: function of cable, $R$ and $C$: function of motor)
[Ogasawara, Akagi, 1996]




▷ The peak HF common mode current amplitude is searched for:

$$I_{\text{com}} = f(\frac{v_{\text{Lg}}}{dt}, L_{\text{com}}, C_{\text{wf}}) = f(m, L_{\text{com}}, C_{\text{wf}})$$

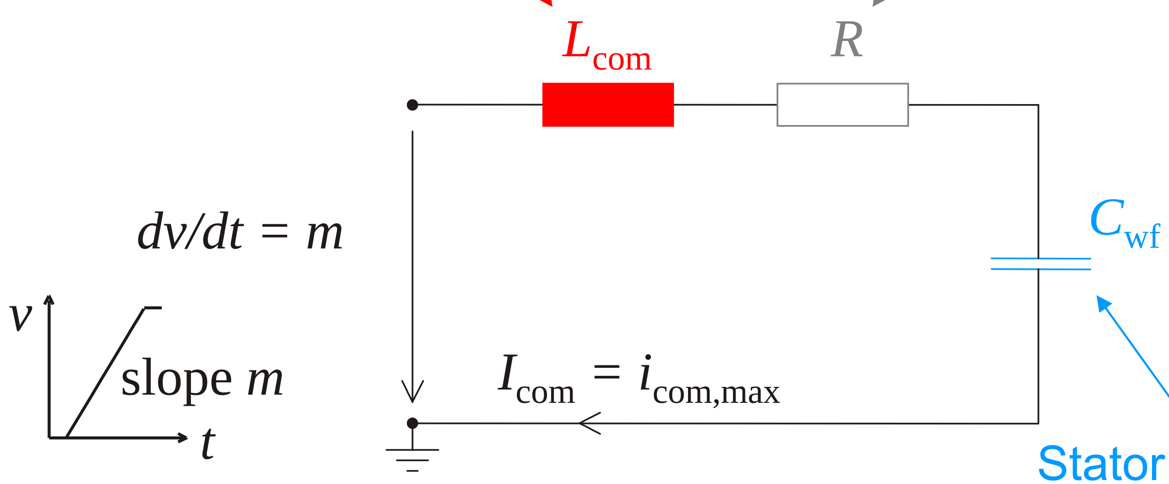


# Lumped Parameter Circuit: Parameters

Related to the motor only
Damping due to motor frame resistance including skin effect;
…up to some tens of Ω

Common mode inductance
… required value …???




Stator winding to frame capacitance

▹ Assumptions:

- short motor leads ($L_{cable} \approx 0$)
- $I_{com} = i_{com,max}$ occurs during rise time $t_r$

All values are per phase values.

# Influence of $L_{com}$ on the Current Reduction: Problem Formulation

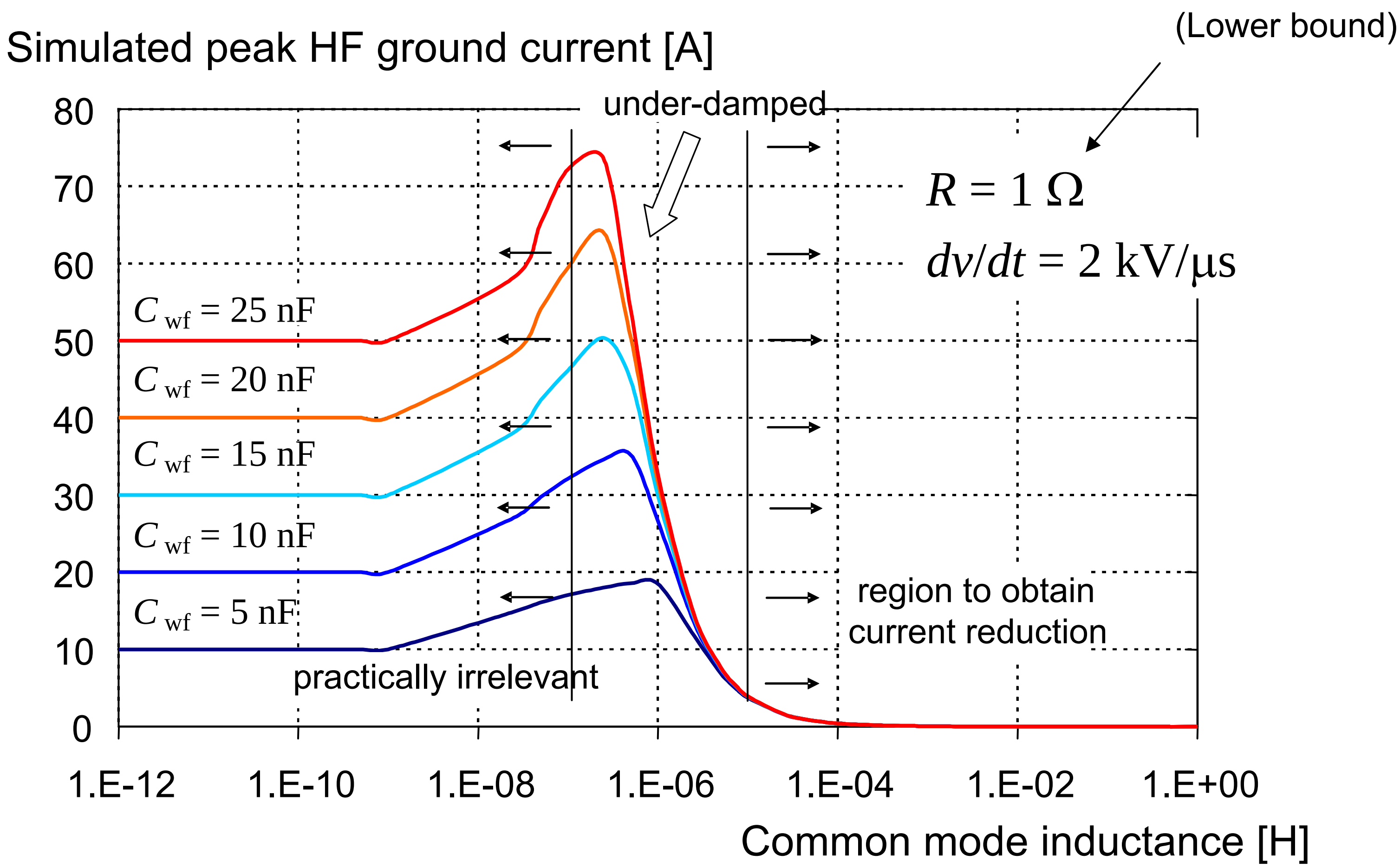
- $i_{\text{com}}(t) = f(m, L_{\text{com}}, C_{\text{wf}})$
- $i_{\text{com}}(t) = f(\omega_0, Z_0, \xi)$

where $\omega_0 = \sqrt{\dfrac{1}{L_{\text{com}}C_{\text{wf}}}}$ $\quad Z_0 = \sqrt{\dfrac{L_{\text{com}}}{C_{\text{wf}}}}$ $\quad \xi = \dfrac{R}{2}\sqrt{\dfrac{C_{\text{wf}}}{L_{\text{com}}}}$

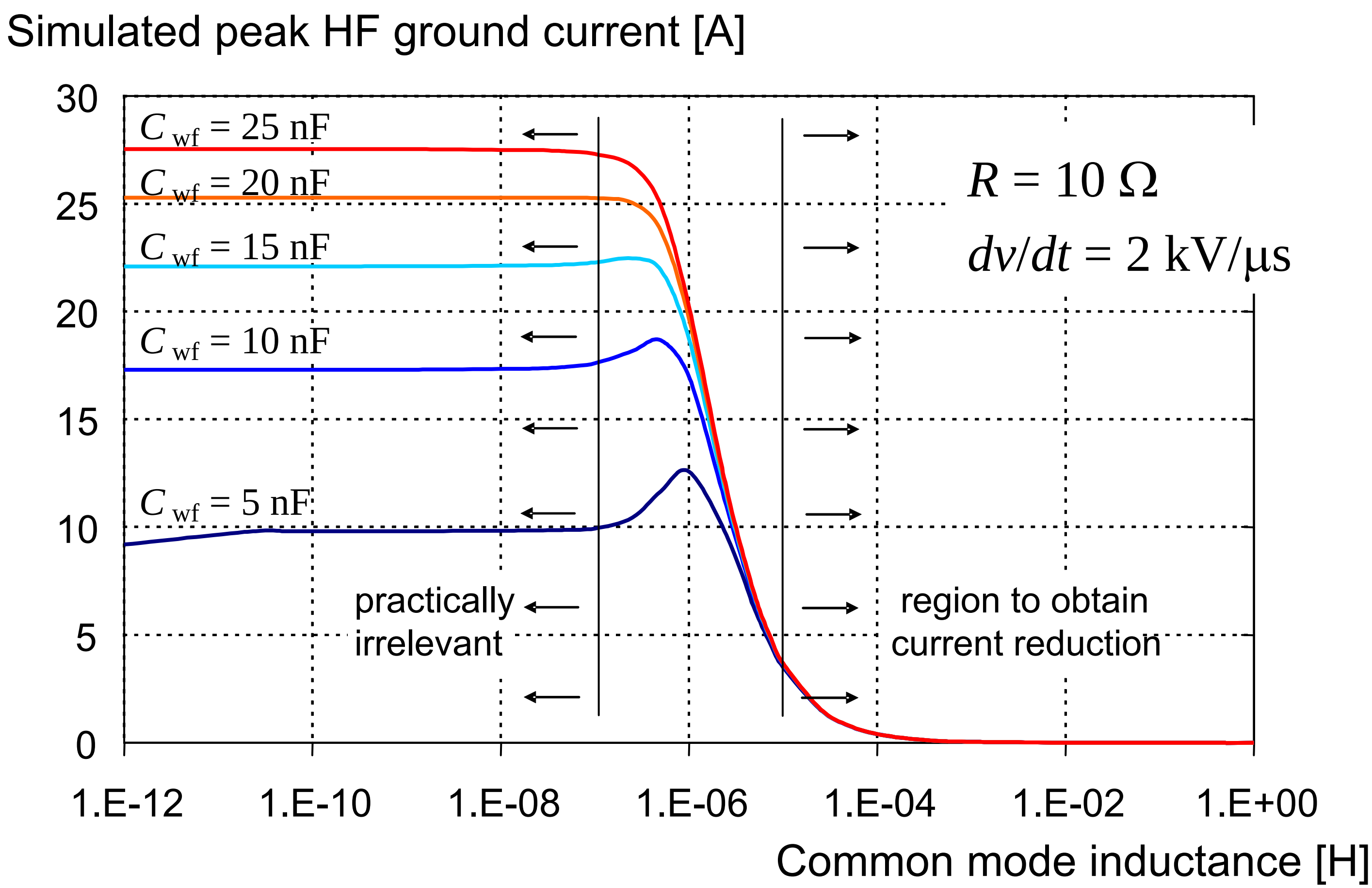
1. Under-damped case
2. Critically-damped case
3. Over-damped case

$$i_{\text{com}}(t) = \ldots \quad \rightarrow \quad I_{\text{com}} = f(m, L_{\text{com}}, C_{\text{wf}}) = f(\omega_0, Z_0, \xi)\ldots$$

# Influence of $L_{com}$ on the Current Reduction: General Case



# Influence of $L_{com}$ on the Current Reduction: General Case cont.



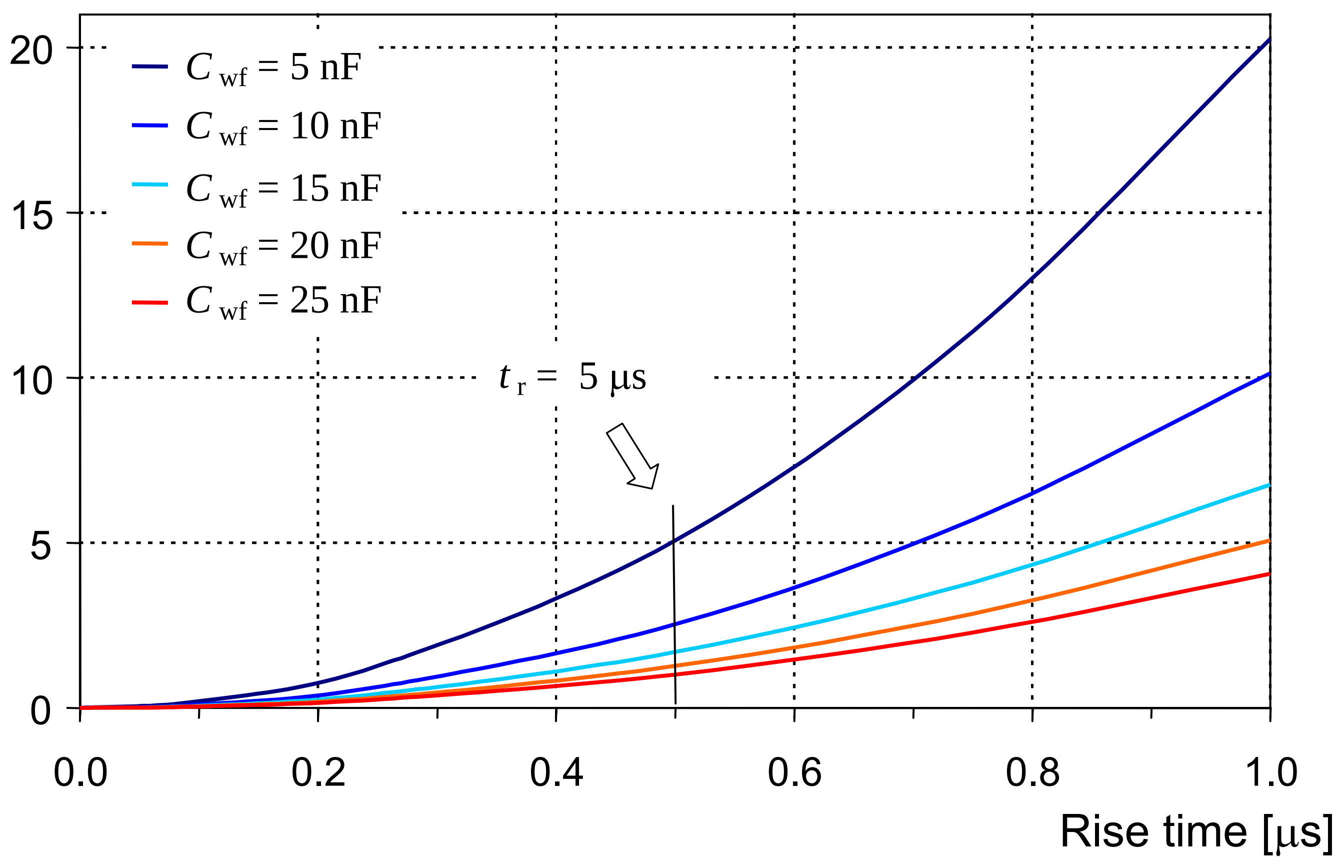
# Influence of $L_{com}$ on the Current Reduction: Un-damped Case

- $i_{\mathrm{com}} = mC_{\mathrm{wf}}\{1 - cos(\omega_e t)\}$
- $I_{\mathrm{com}} = 2mC_{\mathrm{wf}}$

$$L_{\mathrm{com}} \geq L_{\mathrm{com,min}} = \frac{1}{C_{\mathrm{wf}}}\left(\frac{t_{\mathrm{r}}}{\pi}\right)^2$$

$$t_{\mathrm{r}} = \frac{T}{2}$$

Minimum value of common mode inductance [uH]



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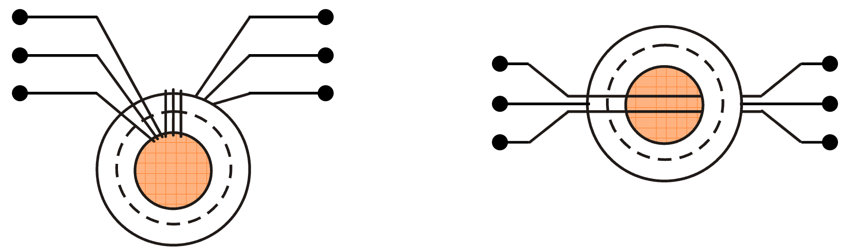

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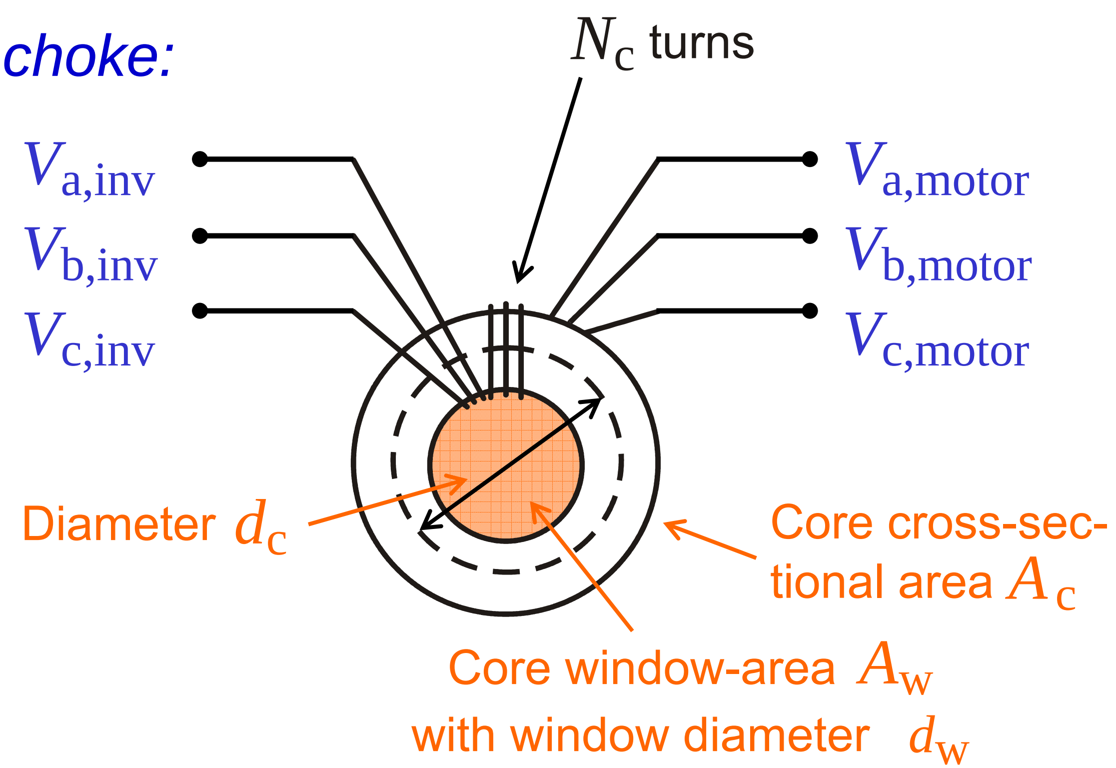
# Physics of Common Mode Chokes

*Wound choke:*



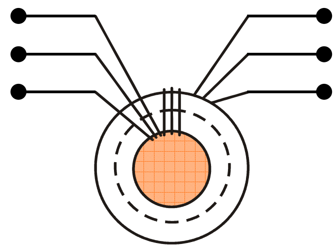

*Inductance value:*

$$L_{com} = \frac{N_c^2 \mu A_c}{\pi d_c}$$

(Un-gapped cores)

# Physics of Common Mode Chokes cont.

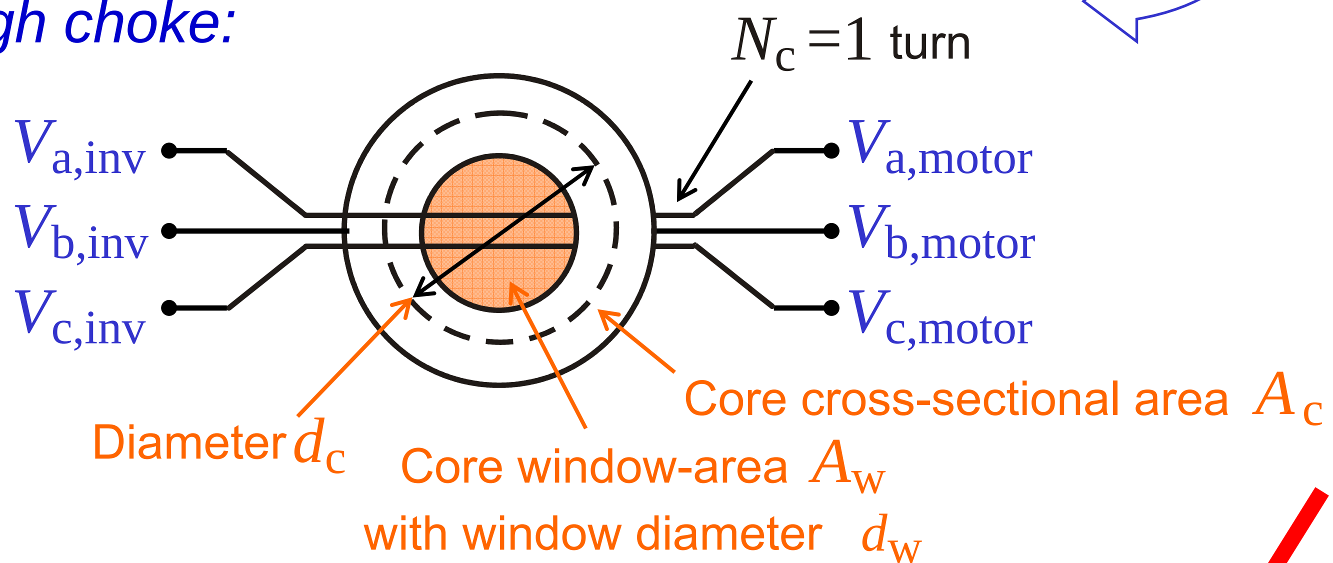
*Wound choke:*



$$L_{\mathrm{com}} = \frac{N_{\mathrm{c}}^2 \mu A_{\mathrm{c}}}{\pi d_{\mathrm{c}}}$$

$$N_{\mathrm{c}} = 1$$

*Feed-through choke:*




*Inductance value:*

$$L_{\mathrm{com}} = \frac{\mu A_{\mathrm{c}}}{\pi d_{\mathrm{c}}}$$

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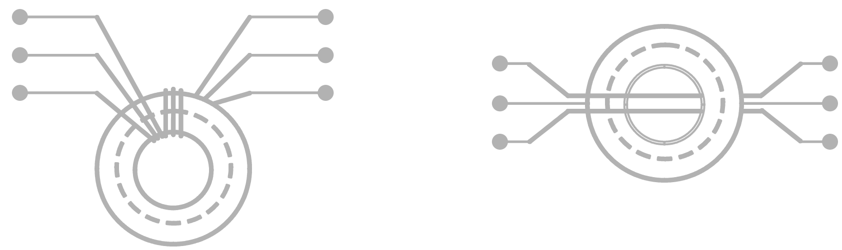

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# Accommodation of the Motor Leads

Minimum core window area and bore of feed-through toroidal cores for different cable cross-sectional areas:

$N_c = 1, k_w = 0.4$

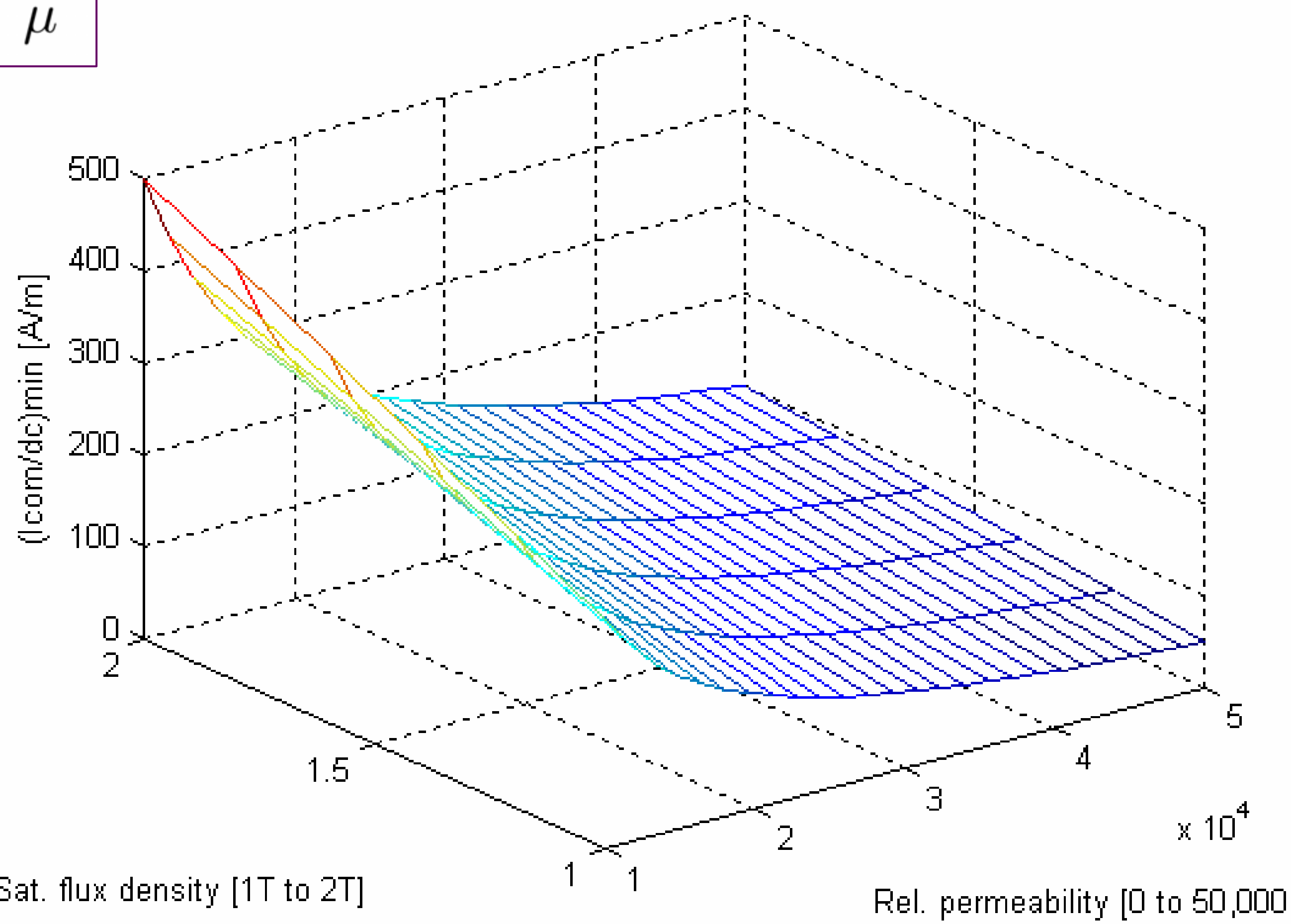
| Cable cross-sectional area | Current carrying capability per individual cable*) | Core minimum window area | Core minimum bore diameter |
|---|---|---|---|
| 70 mm² | 207 A | 525 mm² | 26 mm |
| 150 mm² | 335 A | 1125 mm² | 38 mm |
| 300 mm² | 523 A | 2250 mm² | 54 mm |

More than a factor of 2 smaller than the minimum bore diameter to avoid saturation! – Already at 1 turn!

*) At 30°C ambient temperature, according to DIN VDE 0276 Part 1000

# Maximum $d_c/I_{com}$ – Ratio for Avoiding Core Saturation

$$\left\{\frac{I_{\mathrm{com}}}{d_{\mathrm{c}}}\right\}_{\mathrm{max}} = \frac{\pi}{N_{\mathrm{c}}}\frac{B_{\mathrm{s}}}{\mu}$$

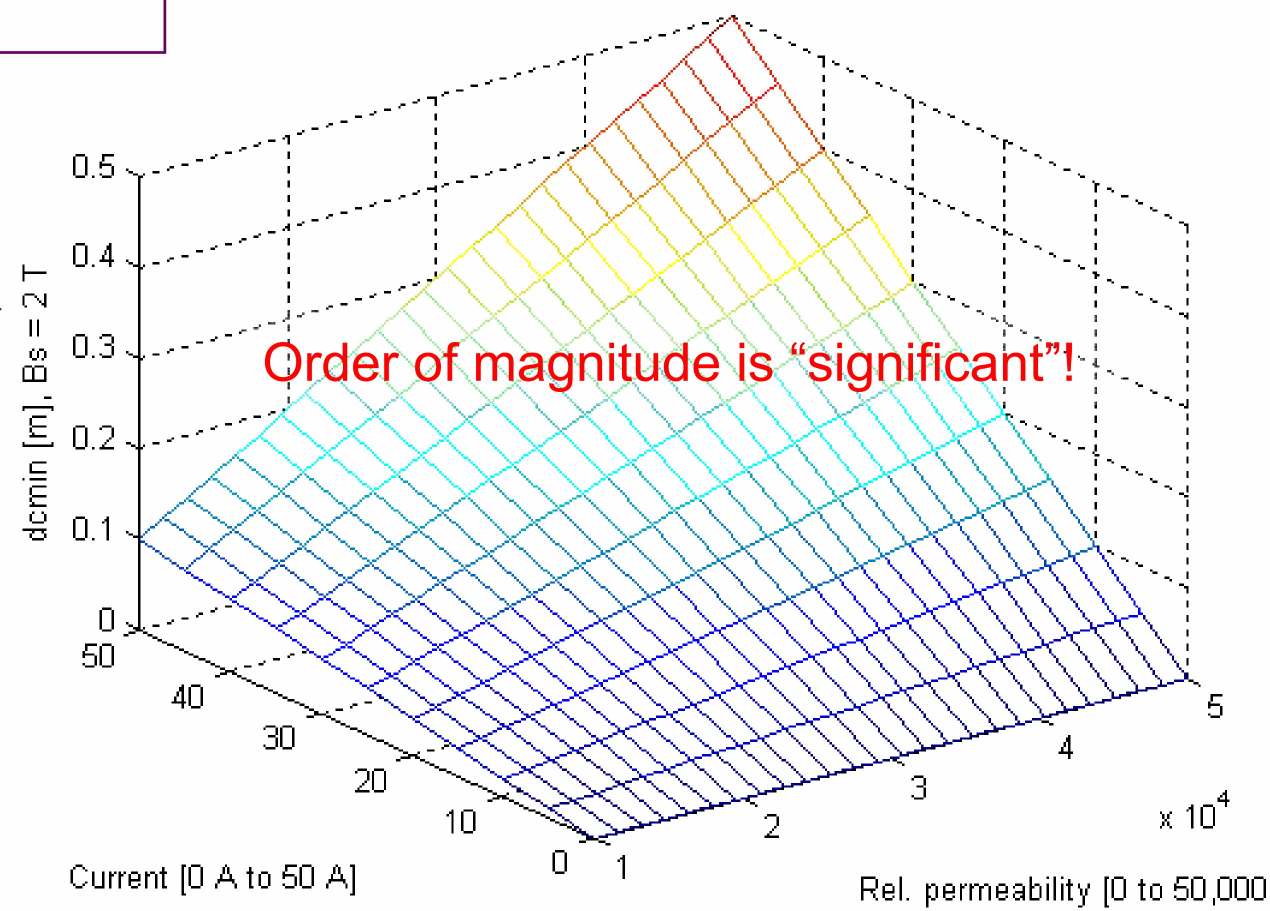



(Un-gapped cores)

# Minimum Core Diameter for Avoiding Core Saturation

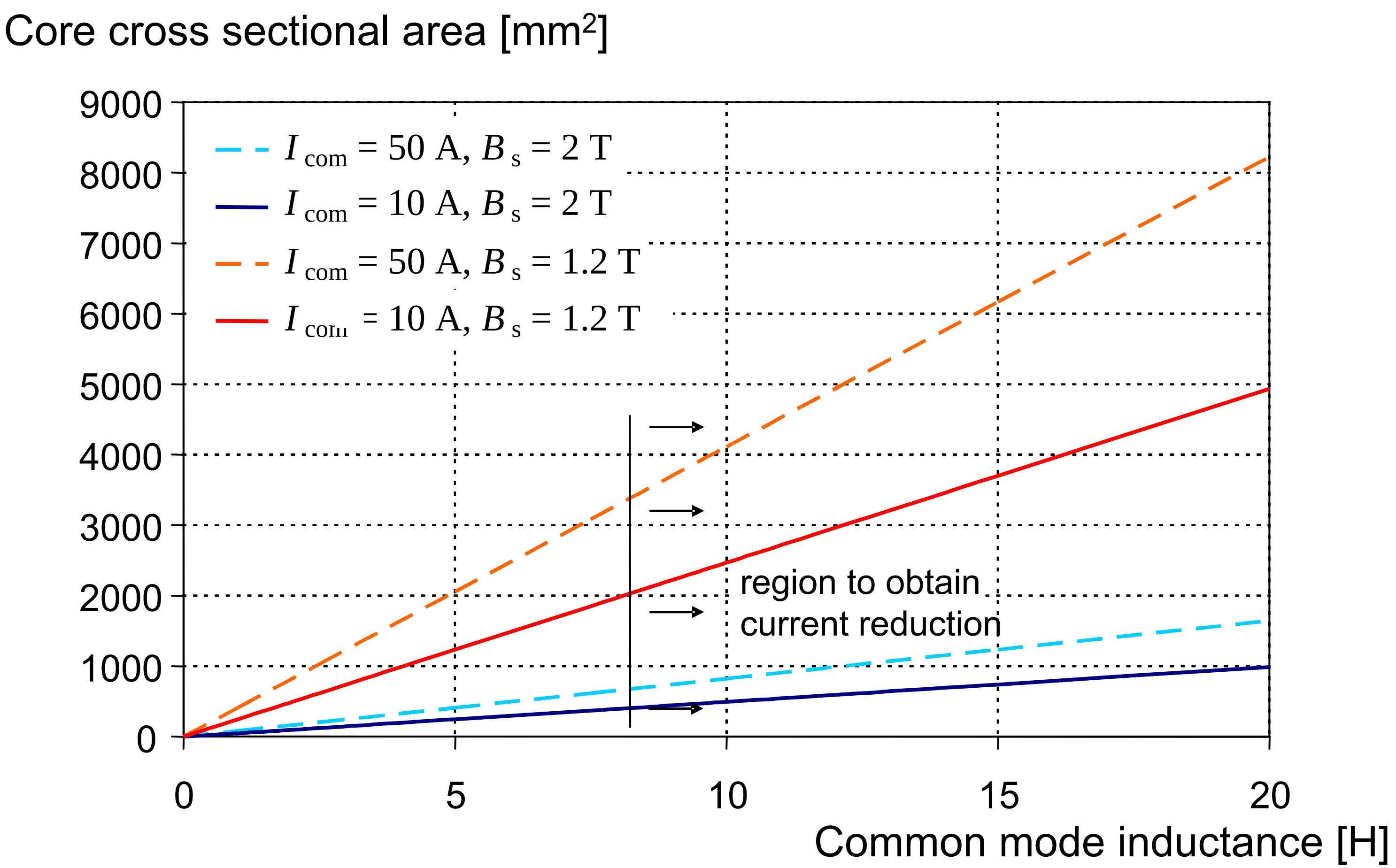
$$d_{\mathrm{c,min}} = \frac{I_{\mathrm{com}} 4\pi 10^{-7} \mu_{\mathrm{r}}}{B_{\mathrm{s}}}$$

High value by intention




(Un-gapped cores)

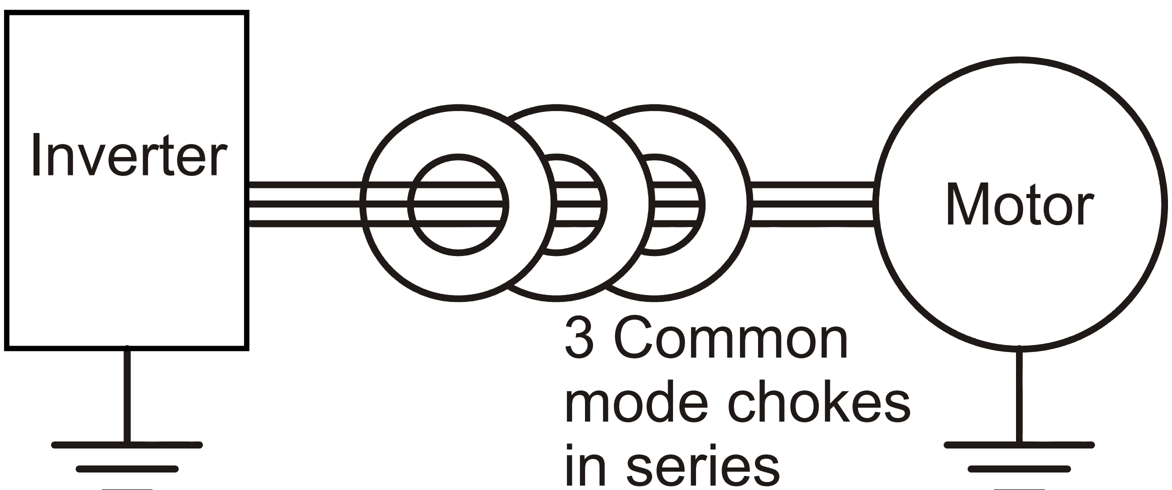
# Cross Sectional Area as Function of $L_{com}$




(Un-gapped chores, constant $\mu$)

# Use of Several Feed-Through Cores in Series

- Large cross sectional area required to achieve $L_{com}$
- Increase of the $N_c$ not an option because of saturation
  - Use several cores in series



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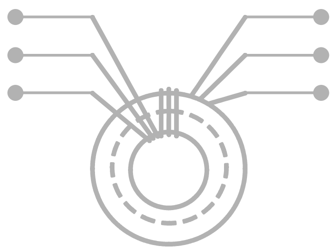

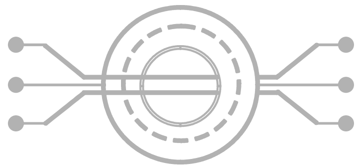

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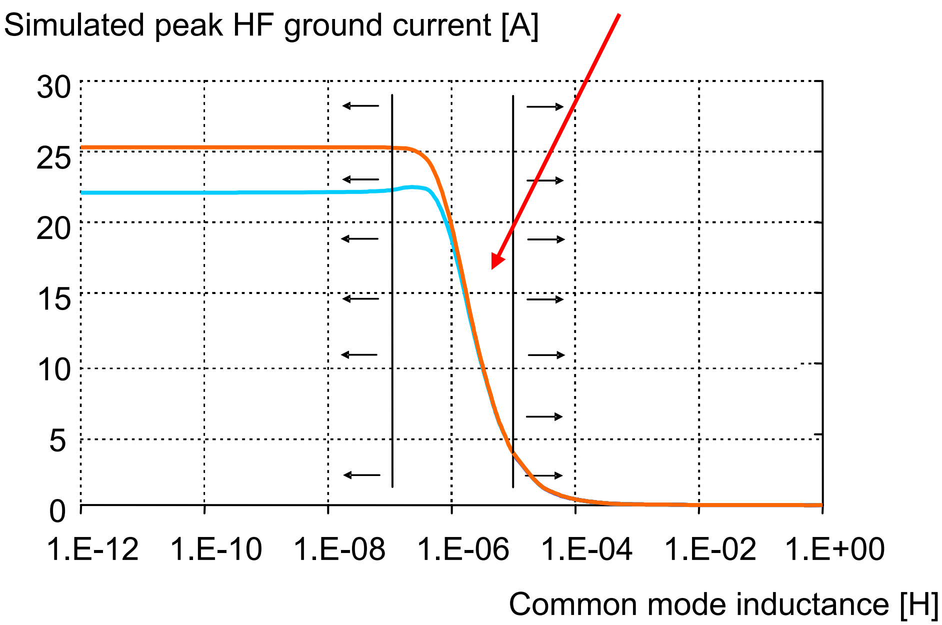
# Measurement Results

- Commercially available un-gapped toroidal core ("Cool Blue®" of Magnetec GmbH)
  - Nano-crystalline material with $\mu_r$ = 30,000 (10 kHz)
  - Tabulated inductance (20…30)μH
- Drive with $C_{wf}$ = 8 nF, $dv_{Lg}/dt$ = 2 kV/μs
  - Reduction of $I_{com}$ = 28 A
  - 1 core: by 15%
  - 2 cores: by 36%
- Minimum $d_c$ = 280 mm ≈ twice actual value
  - Reduction of the choke performance by ≈ 50%
  - Compares well with above Figures



# Summary

1. Minimum inductance value of the chokes: in the order of 10 μH
2. Rather large values of $I_{com}$ require a minimum bore diameter for avoiding saturation that results in a core window area large enough to accommodate the motor leads
3. Any number of turns > 1 will likely result in increased saturation (→ not improve the choke performance) (Un-gapped cores)
4. Aiming for a higher value of relative permeability than 10,000 is arguable (Un-gapped cores)
5. Use of several cores in series