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

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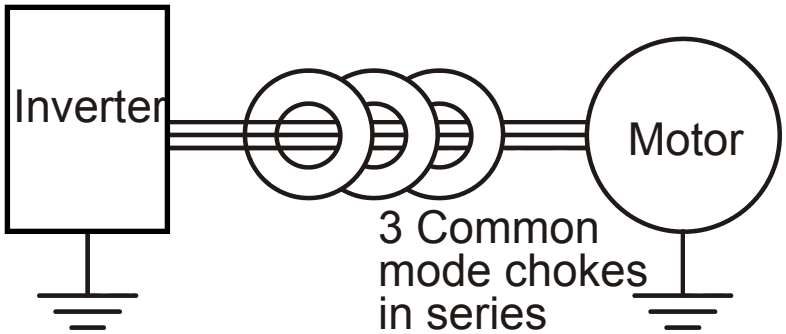
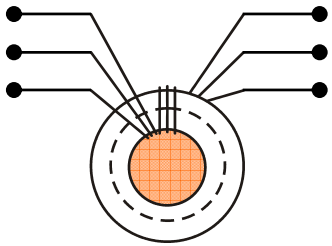
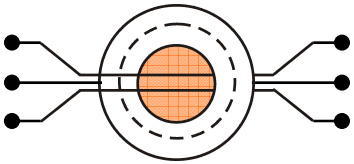


Source: Magnetec GmbH

Outline

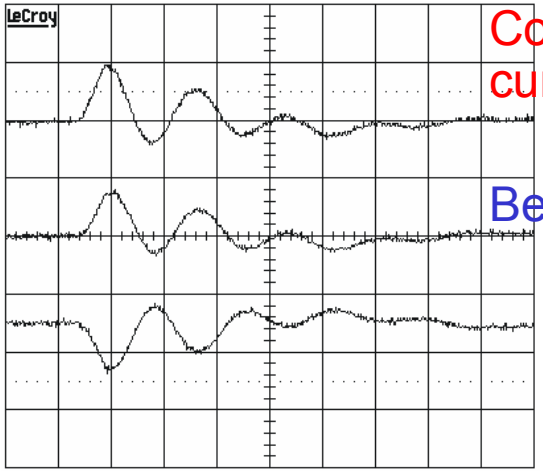
- Motivation
  …to use common mode chokes in the inverter-output → requirements?
- Influence of the Inductance Value on the Current Reduction
  – Equivalent circuit, general case and un-damped case
- Physics of Common Mode Chokes
  – Fundamentals, wound and feed-through chokes



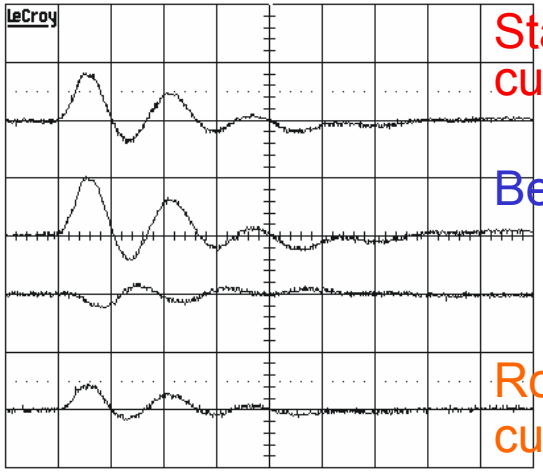


- Design Criteria
  – Window area, current-to-diameter ratio, minimum diameter,…
- Measurement Results
- Summary

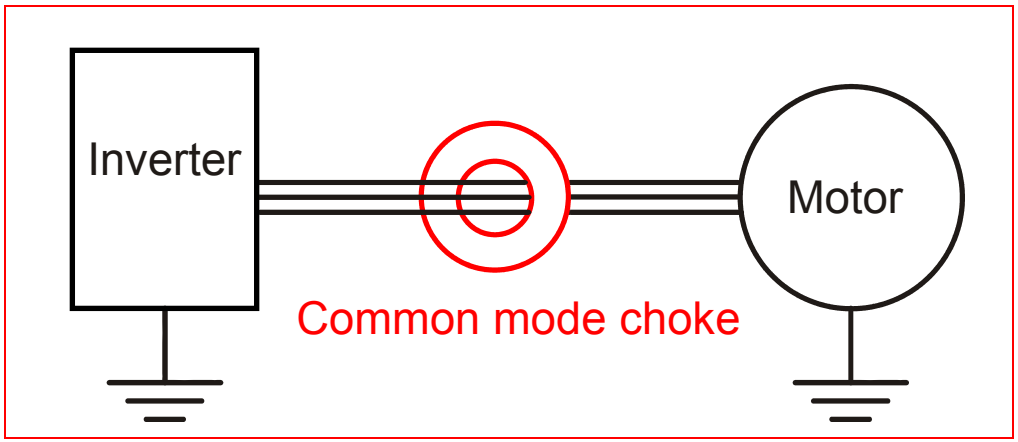
Motivation



Circulating bearing currents
motor speed n = 3000 /min



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

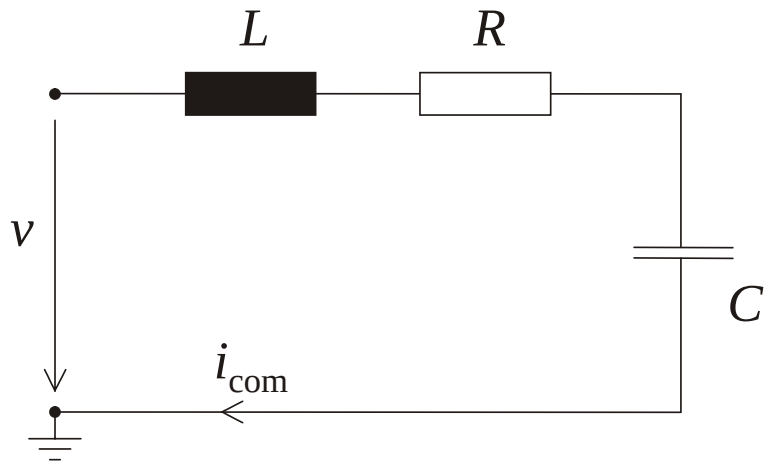


Squirrel-cage induction motor, frame size 400 mm,
500 kW rated power, bearing temperature $T_b \approx 70°C$
(Measurements were obtained in the frame of a
research project at Darmstadt University of
Technology, Institute of Prof. Binder)

Modeling: Lumped Parameter Circuit

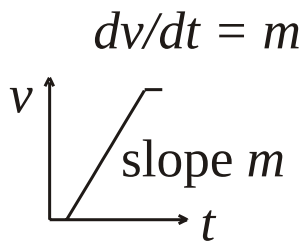
▹ Approach:

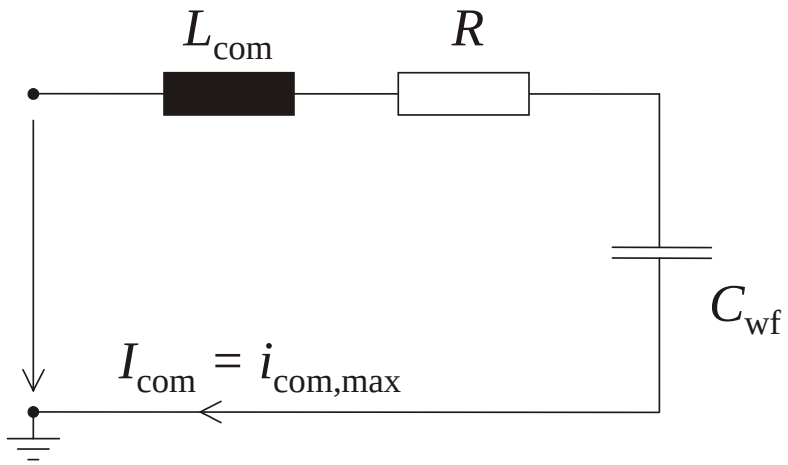
RLC-Circuit (L: function of cable, R and C: function of motor) [Ogasawara, Akagi, 1996]



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

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

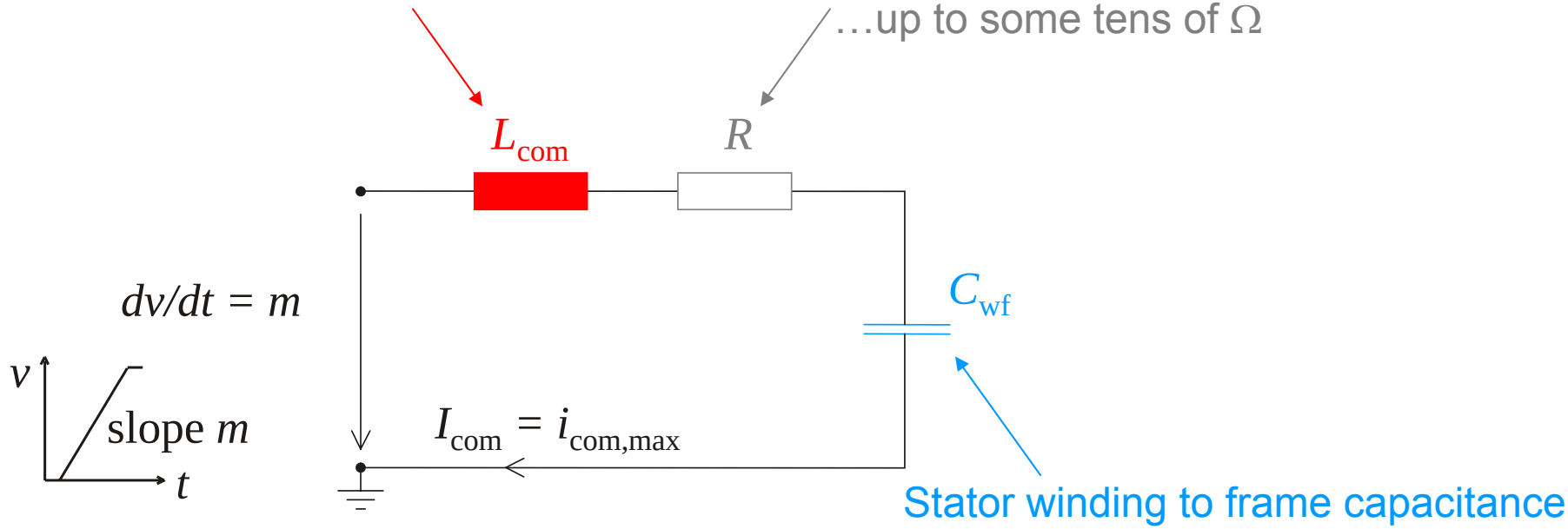




Lumped Parameter Circuit: Parameters

Common mode inductance
… required value …???

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



▹ 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

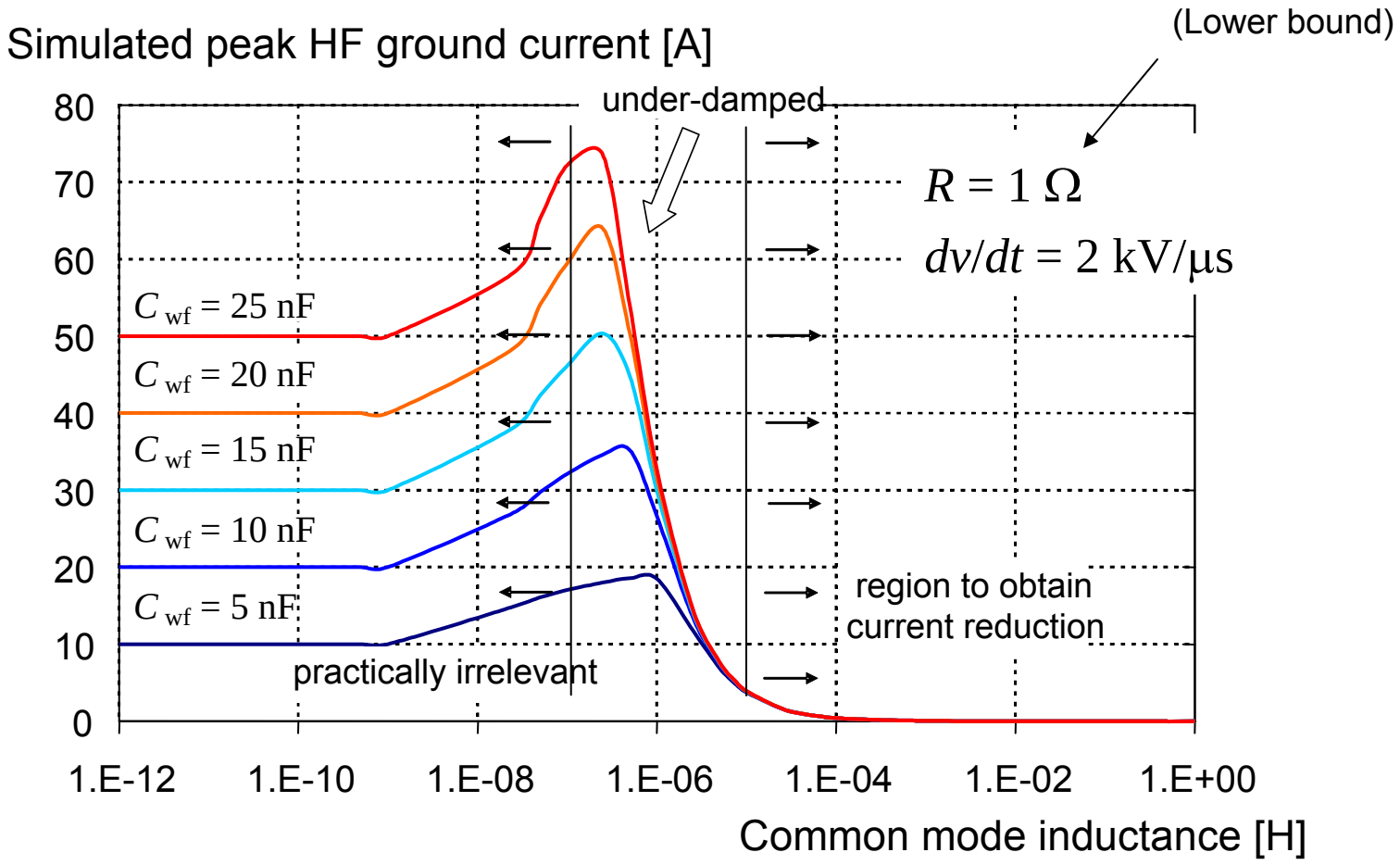
- $i_{com}(t) = f(m, L_{com}, C_{wf})$
- $i_{com}(t) = f(\omega_0, Z_0, \xi)$

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

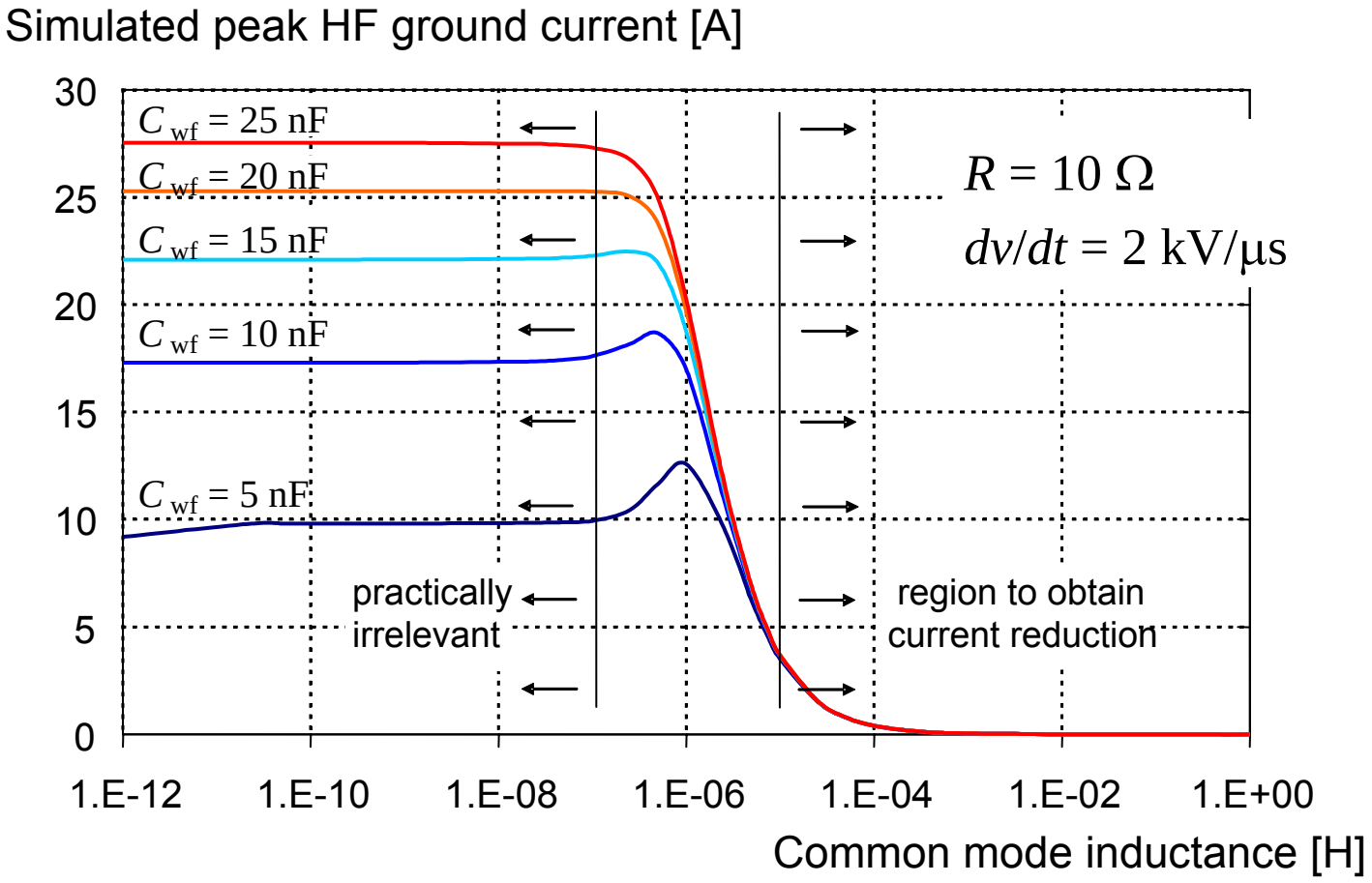
1. Under-damped case
2. Critically-damped case
3. Over-damped case

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

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



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

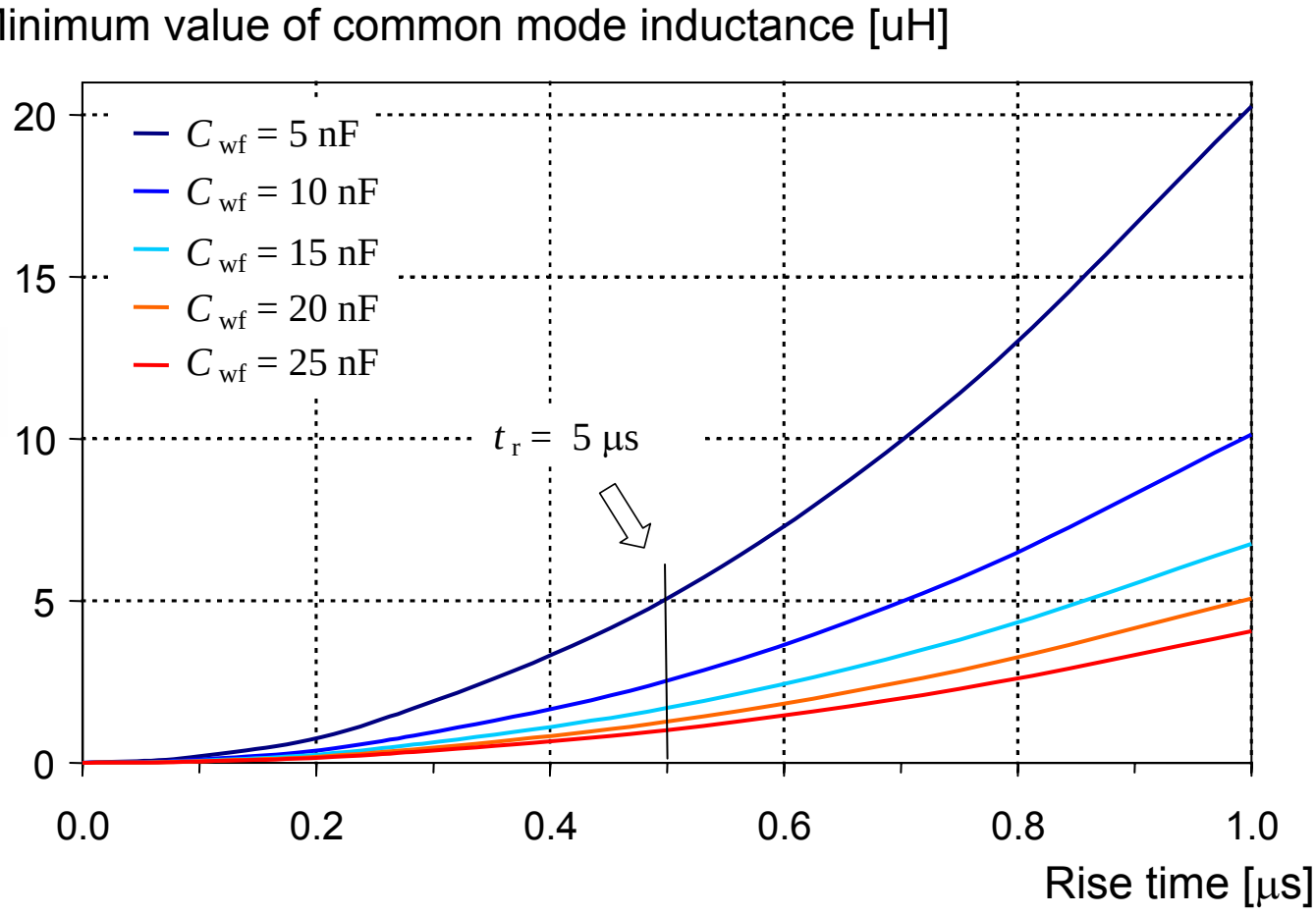


Influence of L_{com} on the Current Reduction: Un-damped Case

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

$$L_{com} \geq L_{com,min} = \frac{1}{C_{wf}}(\frac{t_r}{\pi})^2$$

$$t_r = \frac{T}{2}$$



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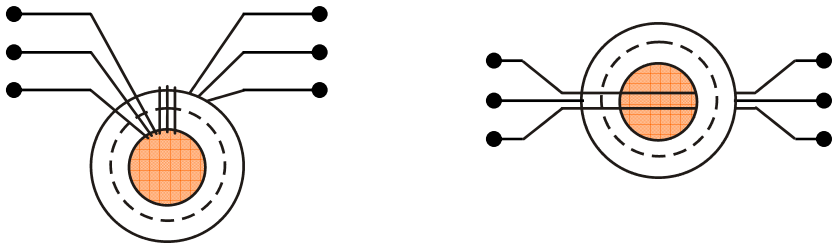

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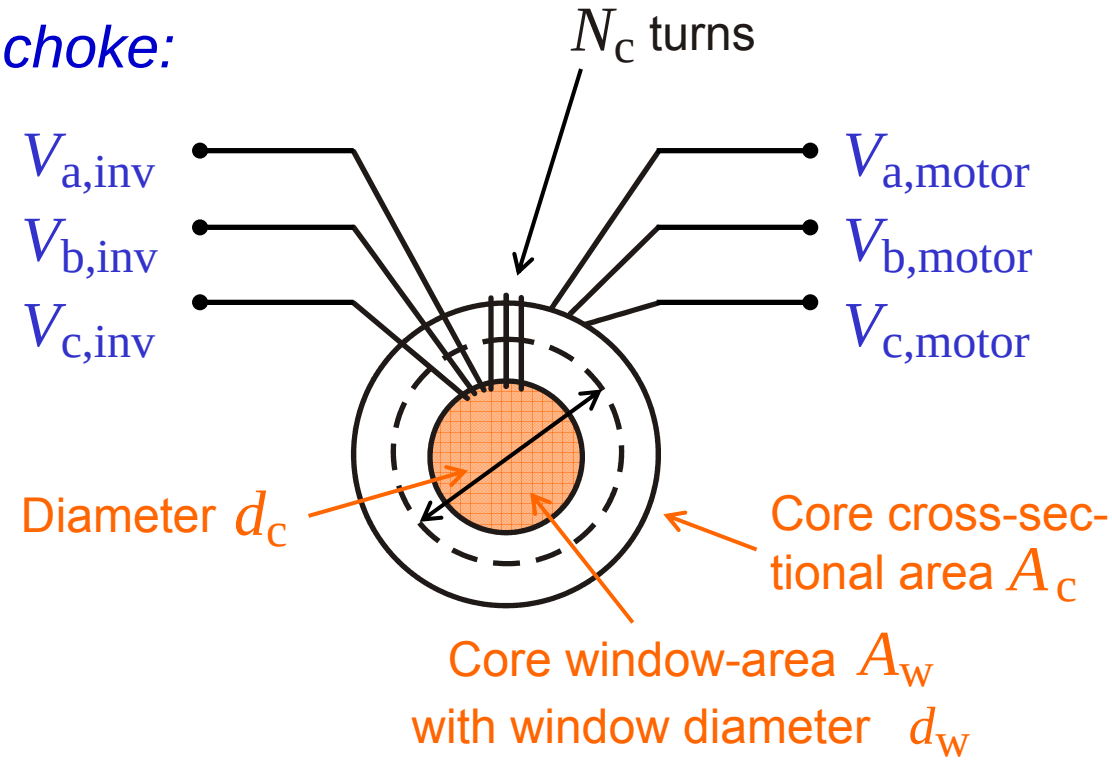
Physics of Common Mode Chokes

Wound choke:



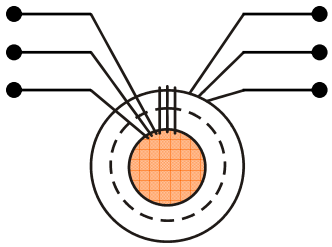
Inductance value:

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

(Un-gapped cores)

Physics of Common Mode Chokes cont.

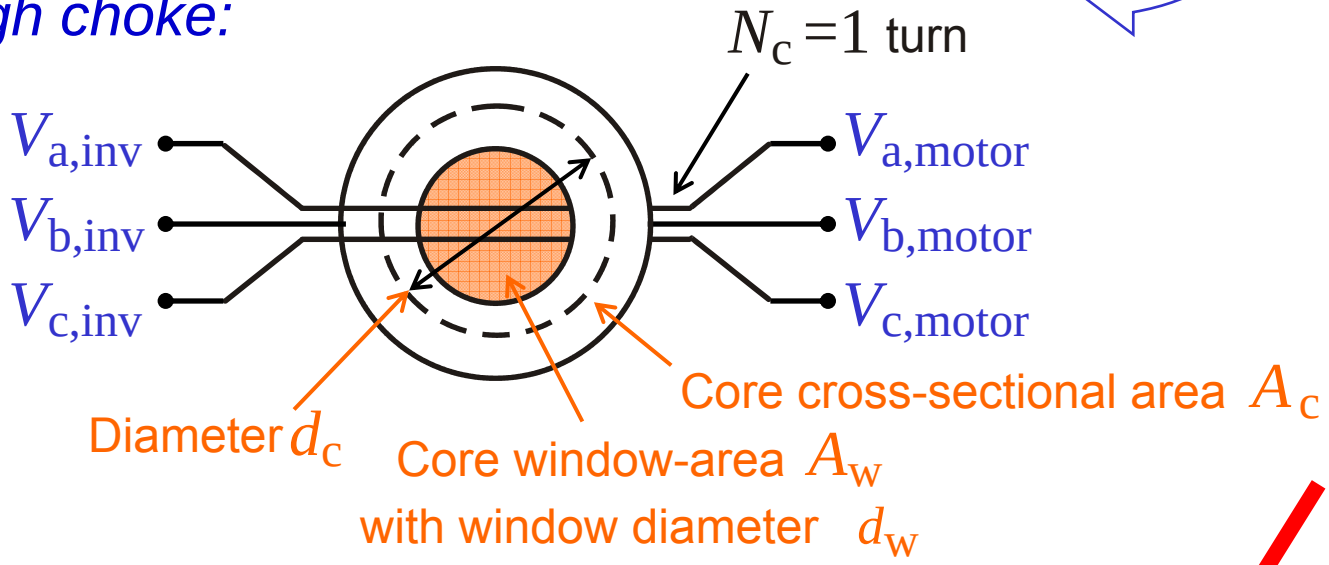
Wound choke:



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

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

Feed-through choke:



Inductance value:

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

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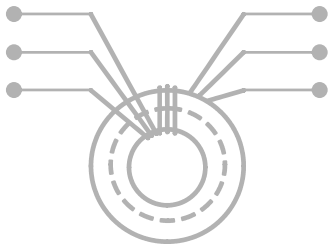

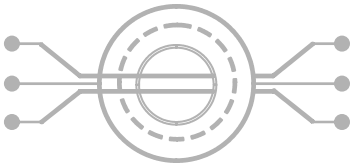

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Accommodation of the Motor Leads

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

$N_c = 1,\ k_w = 0.4$

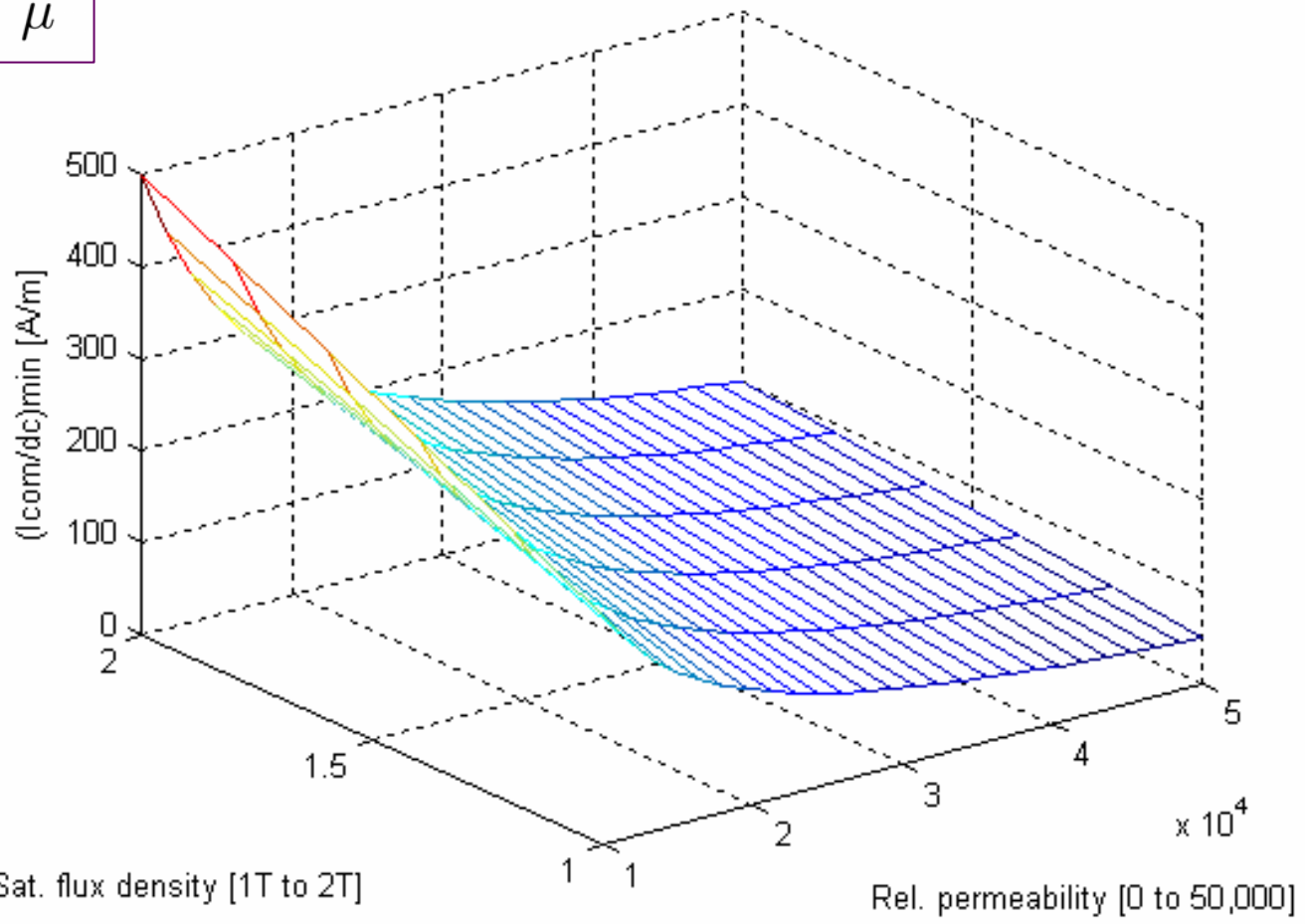
Cable cross-sectional area	Current carrying capability per individual cable*)	Core minimum window area	Core minimum bore diameter
70 mm²	207 A	525 mm²	26 mm
150 mm²	335 A	1125 mm²	38 mm
300 mm²	523 A	2250 mm²	54 mm

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

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

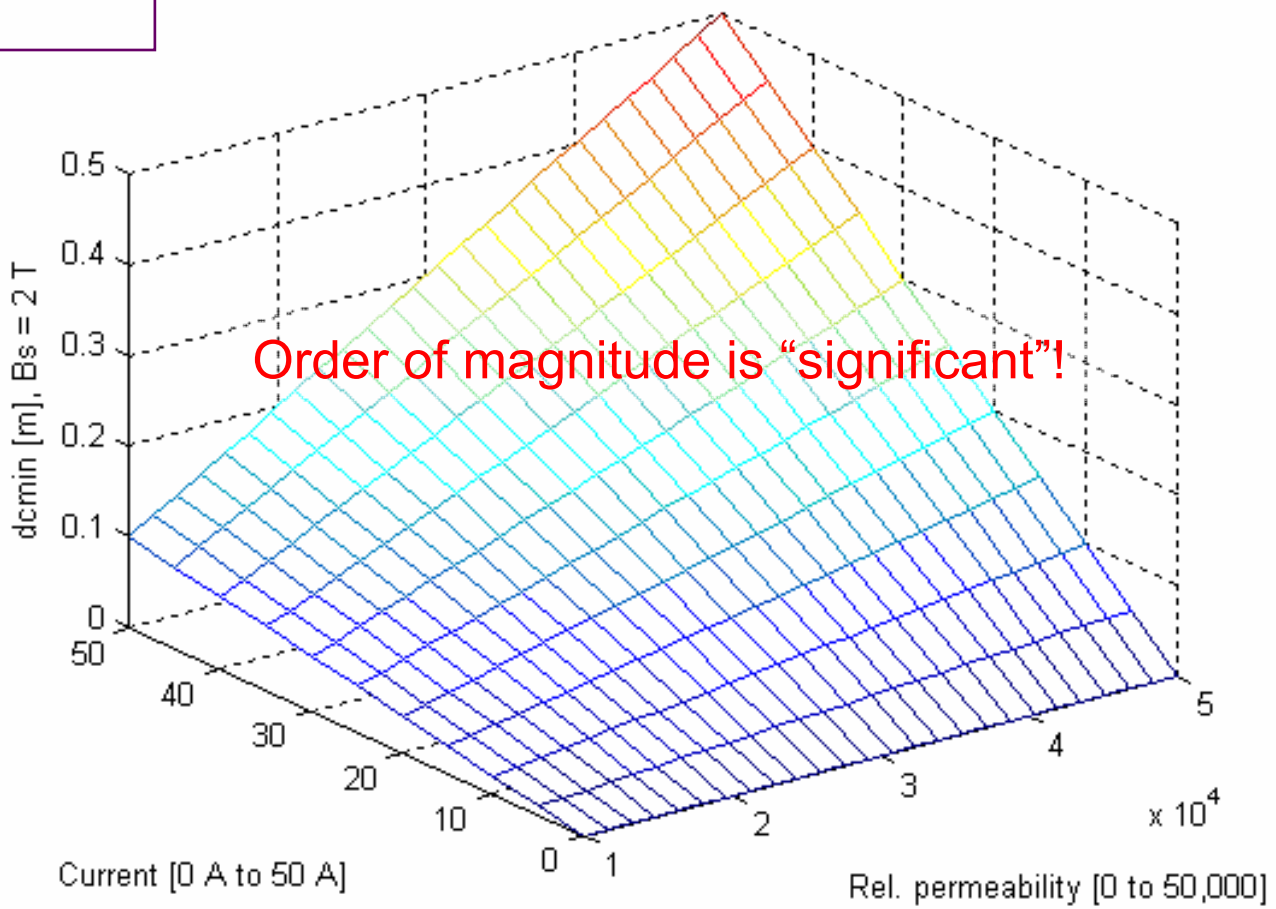


(Un-gapped cores)

Minimum Core Diameter for Avoiding Core Saturation

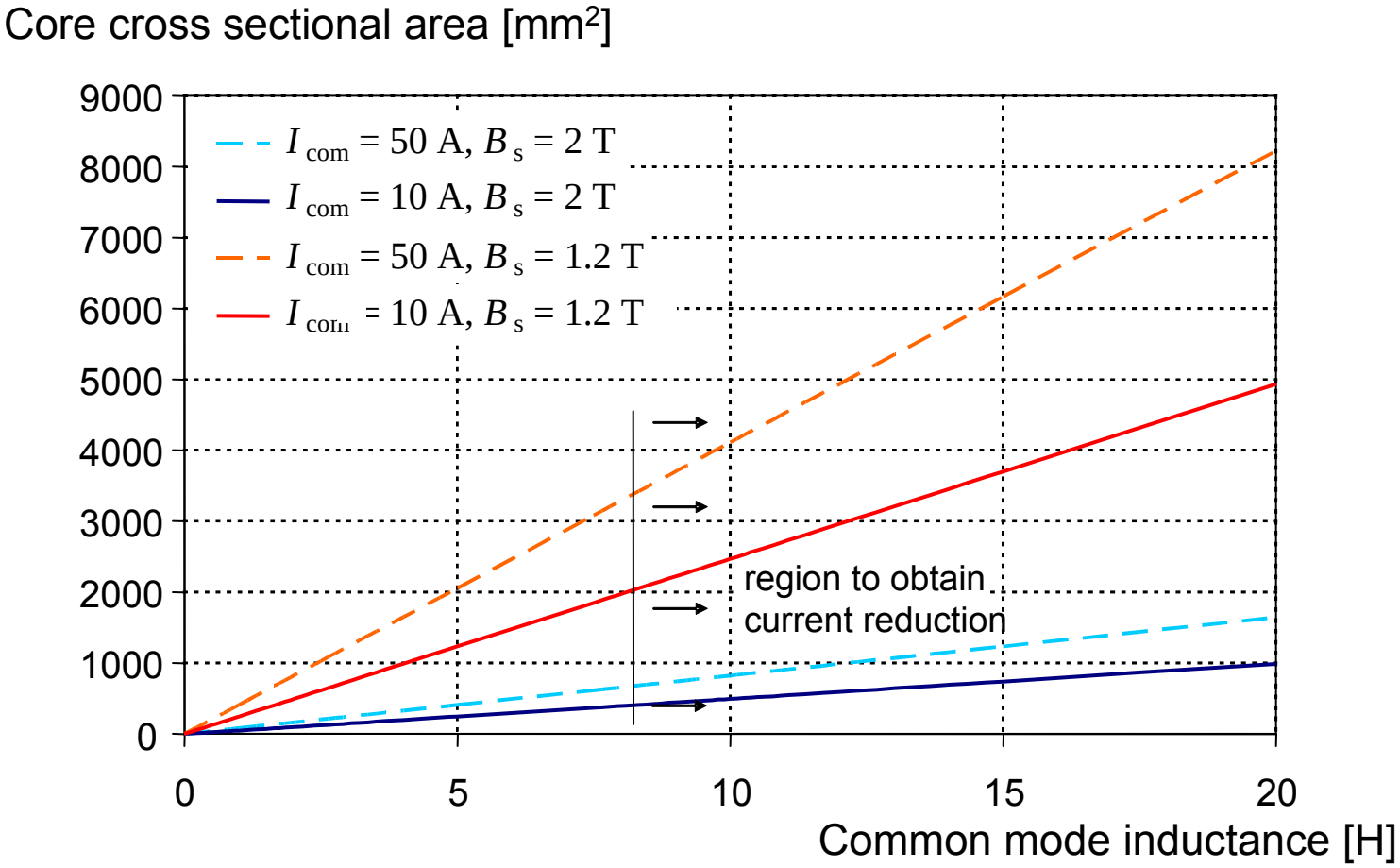
$$d_{\mathrm{c,min}} = \frac{I_{\mathrm{com}} 4\pi 10^{-7} \mu_{\mathrm{r}}}{B_{\mathrm{s}}}$$

High value by intention



(Un-gapped cores)

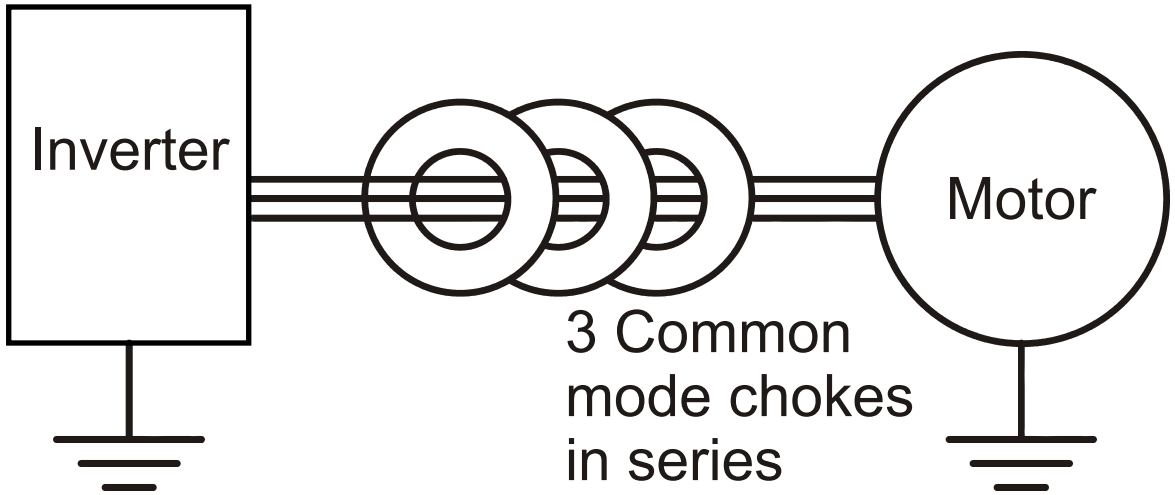
Cross Sectional Area as Function of L_{com}



(Un-gapped chores, constant μ)

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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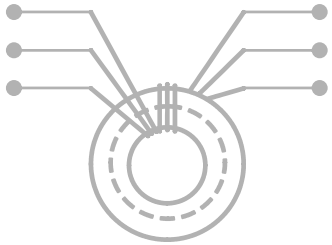

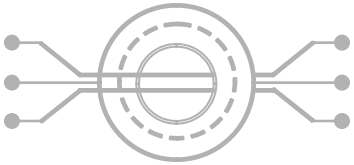

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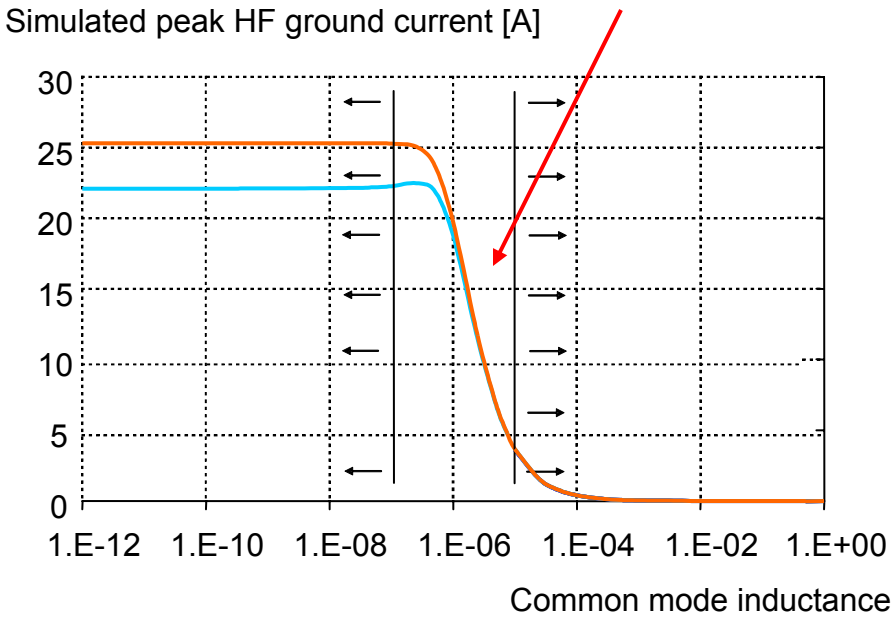
Measurement Results

- Commercially available un-gapped toroidal core
  ("Cool Blue®" of Magnetec GmbH)
  - Nano-crystalline material with μ_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 ($\rightarrow$ 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