High frequency effects in inverter-fed AC electric machinery

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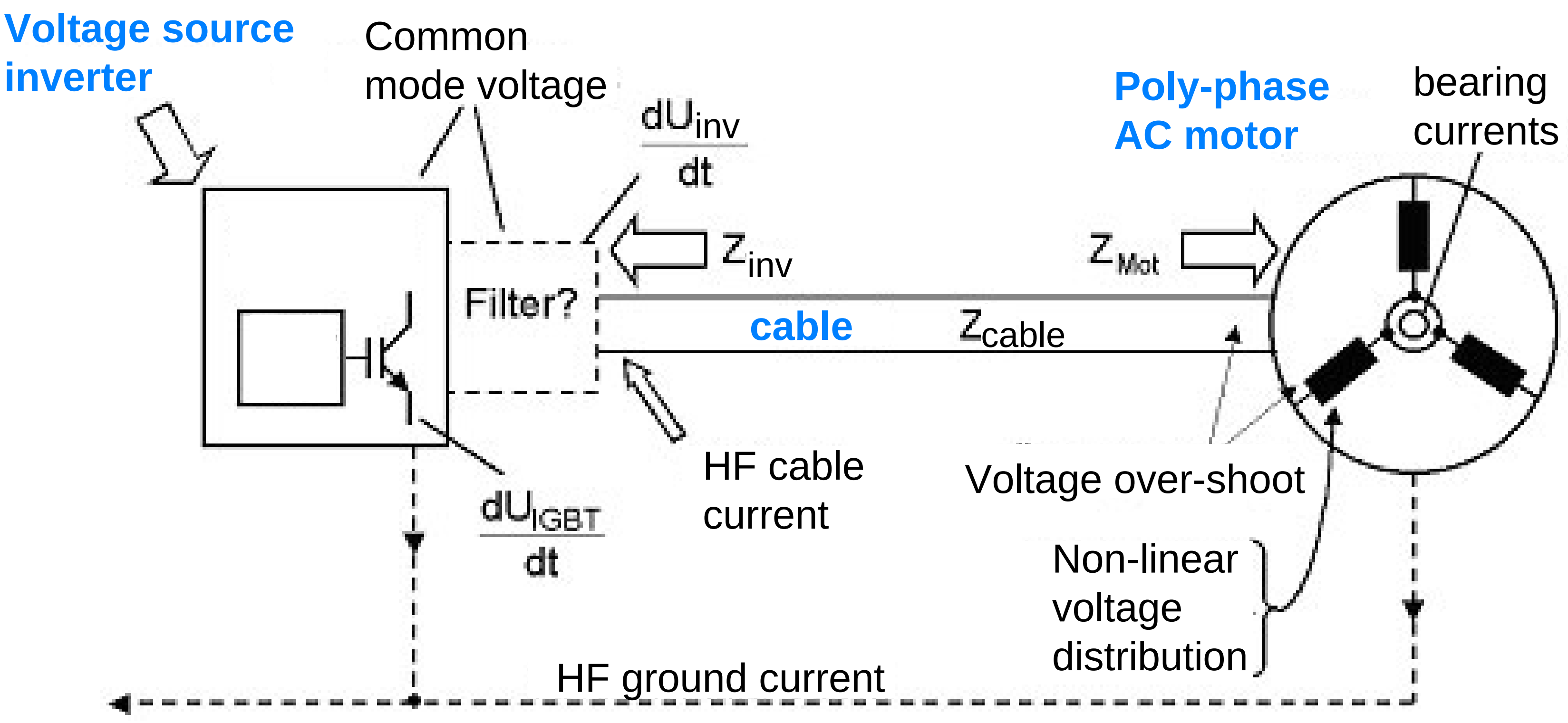
Fast voltage change rates du/dt

- Fast switching IGBT inverters: short **voltage rise time** t_r between zero and DC link voltage 100 ns: $\mathrm{d}u/\mathrm{d}t \cong U_d / t_r$

Line supply	*dc link voltage*	$\mathrm{d}u/\mathrm{d}t \cong U_d / t_r$
Single phase 230 V 50 Hz	310 V	3.1 kV/µs
Three phase 400 V 50 Hz	560 V	5.6 kV/µs
Three phase 500 V 50 Hz	700 V	7.0 kV/µs

- “Steep voltage pulses” means, that the wave propagation time between inverter and motor on the motor cable is in THE SAME ORDER OF MAGNITUDE as the time for voltage build up.
- **So wave propagation effects (= wave reflection) become significant!**

Inverter-fed electrical machines as drive system



Source: DFG research group FOR575: Binder/Mutschler, TU Darmstadt

High frequency effects in inverter-fed AC electric machinery

High d*u* / d*t* = steep inverter voltage front:

- Voltage overshoot at motor winding terminals
- Non-linear voltage distribution per phase leads to voltage stress

HF common mode inverter output voltage:

- HF ground currents via motor main insulation
- Cable loading due to HF capacitive cable current
- HF parasitic bearing currents
- HF electromagnetic interference via cable and radiation

High frequency effects in inverter-fed AC electric machinery

1 Voltage wave reflections at motor terminals

2 HF voltage distribution in armature winding

3 Insulation stress of AC winding at inverter supply

4 Parasitic HF currents

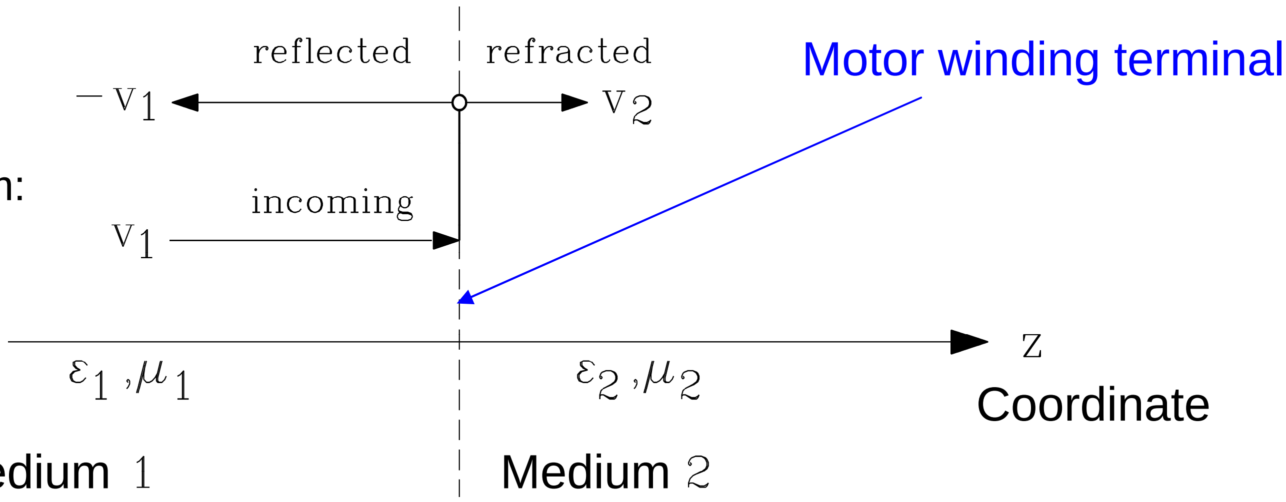
5 System design of inverter drives coping with big d*u*/d*t*

Voltage wave reflection at motor terminals

Wave propagation velocity *v*

Permittivity & permeability of medium: ε, μ

Voltage wave amplitude: *u*



1: Motor cable:

low wave impedance Z_{cable}

2: Motor winding:

high wave impedance Z_{mot}

$$\frac{u_{reflected}}{u_{incom}} = r = \frac{Z - Z_{cable}}{Z + Z_{cable}}$$

Voltage wave reflection coefficient *r*

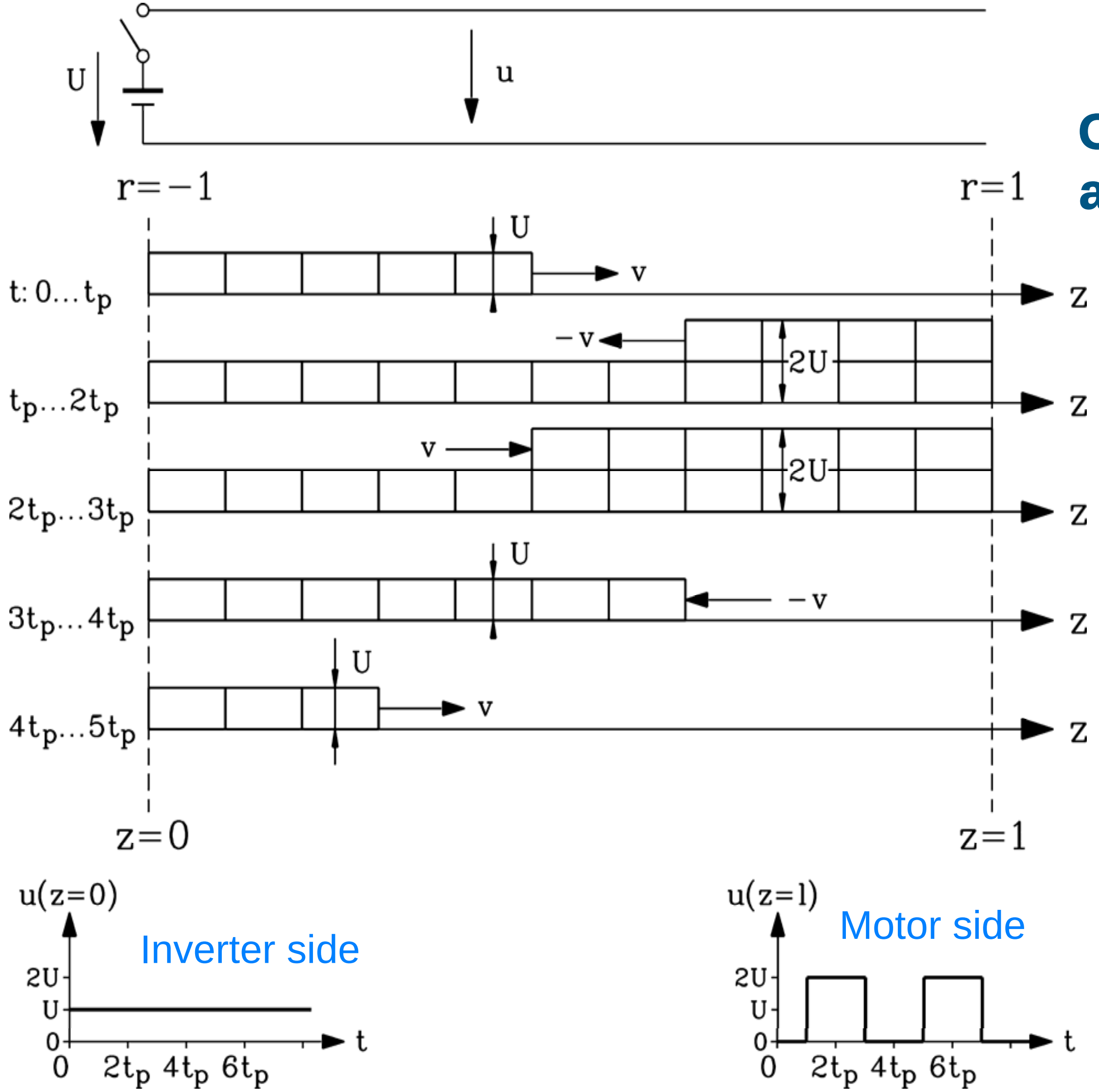
$$\frac{u_{\mathrm{reflected}}}{u_{\mathrm{incom}}} = r = \frac{Z - Z_{\mathrm{cable}}}{Z + Z_{\mathrm{cable}}}$$

Positive voltage wave reflection at motor terminals: voltage increased

$$r_{\mathrm{mot}} = \frac{Z_{\mathrm{mot}} - Z_{\mathrm{cable}}}{Z_{\mathrm{mot}} + Z_{\mathrm{cable}}} \quad Z_{\mathrm{mot}} \to \infty : \quad r_{\mathrm{mot}} = 1$$

Negative voltage wave reflection at inverter, because DC link capacitor is HF short circuit

$$r_{\mathrm{inv}} = \frac{Z_{\mathrm{inv}} - Z_{\mathrm{cable}}}{Z_{\mathrm{inv}} + Z_{\mathrm{cable}}} \quad Z_{\mathrm{inv}} \to 0 : \quad r_{\mathrm{inv}} = -1$$



Oscillation of voltage at motor terminal

- Motor side: “Open cable end”: $Z_{mot} \to \infty$, $r_{mot} = 1$
- Inverter: “Short-circuited cable end”: $Z_{inv} = 0$, $r_{inv} = -1$

Wave reflection at both ends of cable:

a) Motor side:
Voltage oscillation with twice dc link voltage

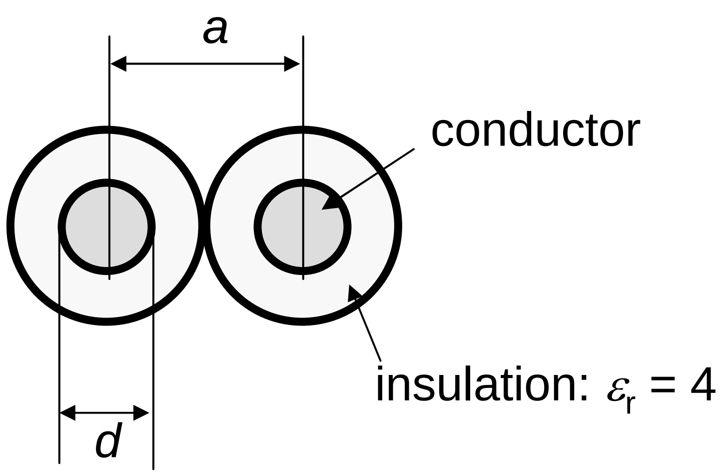
b) Inverter side:
No oscillation

Simple single phase motor cable

Example:

PVC-insulated cable H05VVF4G1.5: 4 x 1.5 mm²
conductor diameter d = 1.4 mm, $q = d^2\pi / 4 = 1.5\,\mathrm{mm}^2$
cable length l_c = 100 m
distance between conductor centres: a = 4.15 mm,
average relative permittivity: ε_r = 4

HF current flows on conductor surface, so no inner inductance occurs!



Motor cable parameters

Phase outer inductance per unit length: $L'_{\text{cable}} = \frac{\mu_0}{2\pi} \cdot \ln\left(\frac{2a}{d}\right) = 0.36\,\mu\text{H/m}$

Phase capacitance per unit length: $C'_{\text{cable}} = 2\pi \cdot \varepsilon_r \cdot \varepsilon_0 / \ln(2a/d) = 125\,\text{pF/m}$

Cable wave impedance (*R´* ≈ 0, *G´* ≈ 0) : $Z_{\text{cable}} = \sqrt{\frac{L'_{\text{cable}}}{C'_{\text{cable}}}} = \underline{\underline{53.7\,\Omega}}$ measured: $83\,\Omega$

Wave velocity : $v = \frac{1}{\sqrt{L'_{\text{cable}} C'_{\text{cable}}}} = \underline{\underline{149 \cdot 10^6\,\text{m/s}}} \approx 150\,000\,\text{km/s}$

$$v \cong \frac{c_0}{2} = 150\,000\,\text{km/s}$$

Motor cable voltage reflection

DC link voltage 560 V, motor reflection coefficient ("worst case"):

$$r_{\mathrm{mot}} = 1$$

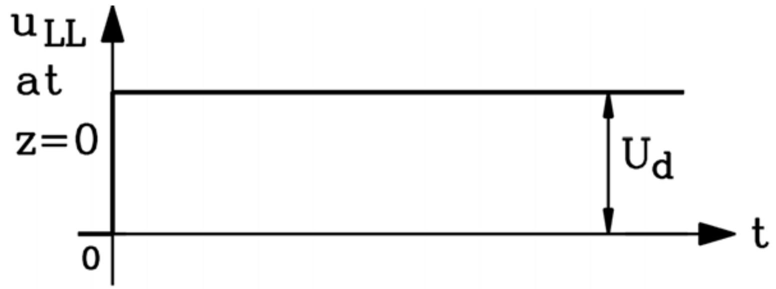
Line to line over-voltage at motor terminals:

$$\hat{U}_{\mathrm{LL,mot}} = (1 + r_{\mathrm{mot}}) \cdot U_{\mathrm{d}} = 2 \cdot 560 = \underline{\underline{1120\,\mathrm{V}}}$$

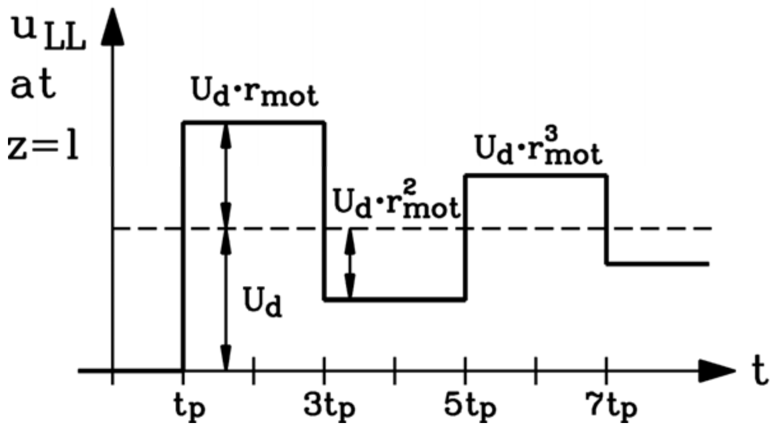
Wave propagation time: $t_{\mathrm{p}} = l_{\mathrm{c}} / v = 100 / (150 \cdot 10^6) = 0.67\,\mu\mathrm{s}$

$1/(4t_{\mathrm{p}})$ = **375 kHz**

Motor reflection coefficient r_{mot} = 0.75 < 1



Assumption:
Voltage rise time $t_r = 0$,
$du/dt \to \infty$



Oscillation of voltage at motor side end due to wave reflection at both ends of loss-free-cable:

Reflection coefficient: r_{mot} = 0.75 on motor side

r_{inv} = –1 at inverter side.

Influence of motor size on cable and motor wave impedance

Wave impedance of motor cables Z_{cable} is more or less independent from rated cable current!

Motor impedance is determined by $Z_{mot} = 2\pi \cdot f \cdot \sigma \cdot L_s$

Frequency f

Total motor flux leakage coefficient σ

Stator motor inductance per phase $L_s \sim (N_s)^2$

Number of turns per phase N_s

At a given rated voltage U_N the number of turns per phase N_s decreases with motor size.

Motor impedance Z_{mot} decreases with increased motor size!

Influence of motor size on reflection coefficient

Example:

Four pole induction motor 400 V, 50 Hz

a) Small 1.1 kW-motor:

2.1 A, frame size 90 mm, measured motor wave impedance Z_{mot} = 5000 Ohm.
Motor cable 4 x 1.5 mm^2, Type H05VVF4G1.5: current density: 1.4 A/mm^2,
Cable wave impedance Z_{mot} = 83 Ohm,

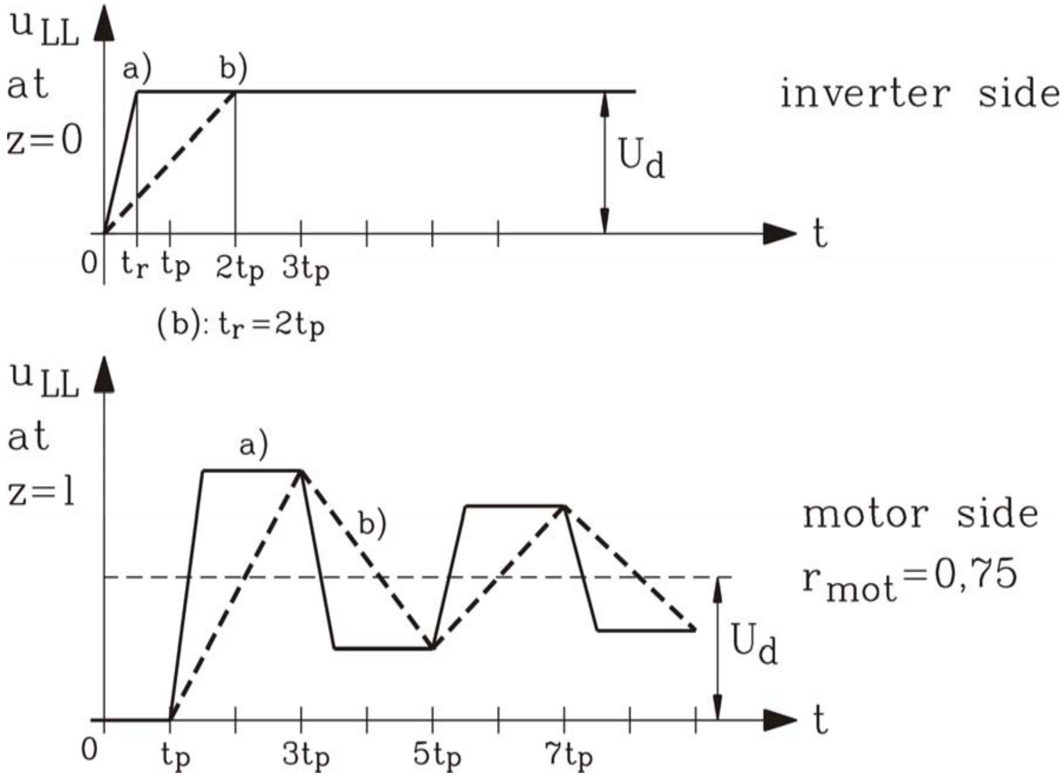
Motor reflection coefficient: $$r_{mot} = \frac{5000-83}{5000+83} = \underline{\underline{0.967}}$$

b) Bigger 18.5 kW-motor:

frame size 180 mm, wave impedance 570 Ohm.
Motor cable wave impedance 75 Ohm.

Motor reflection coefficient: $$r_{mot} = \frac{570-75}{570+75} = \underline{\underline{0.77}}$$

Critical cable length $l_{c,crit}$ at $du/dt \cong U_d / t_r$



- For a given voltage rise time t_r of the inverter, a **"critical cable length"** $l_{c,crit}$ exists, where $t_r = 2t_p$.
- Longer cables lead to full voltage overshoot, as $t_r < 2t_p$!
- Shorter cables lead to reduced voltage overshoot: as $t_r > 2t_p$.

$$t_r = 2t_p = 2 \cdot l_c / v \quad \Rightarrow \quad l_{c,crit} = v \cdot t_r / 2$$

Example: Critical cable length $l_{c,crit}$

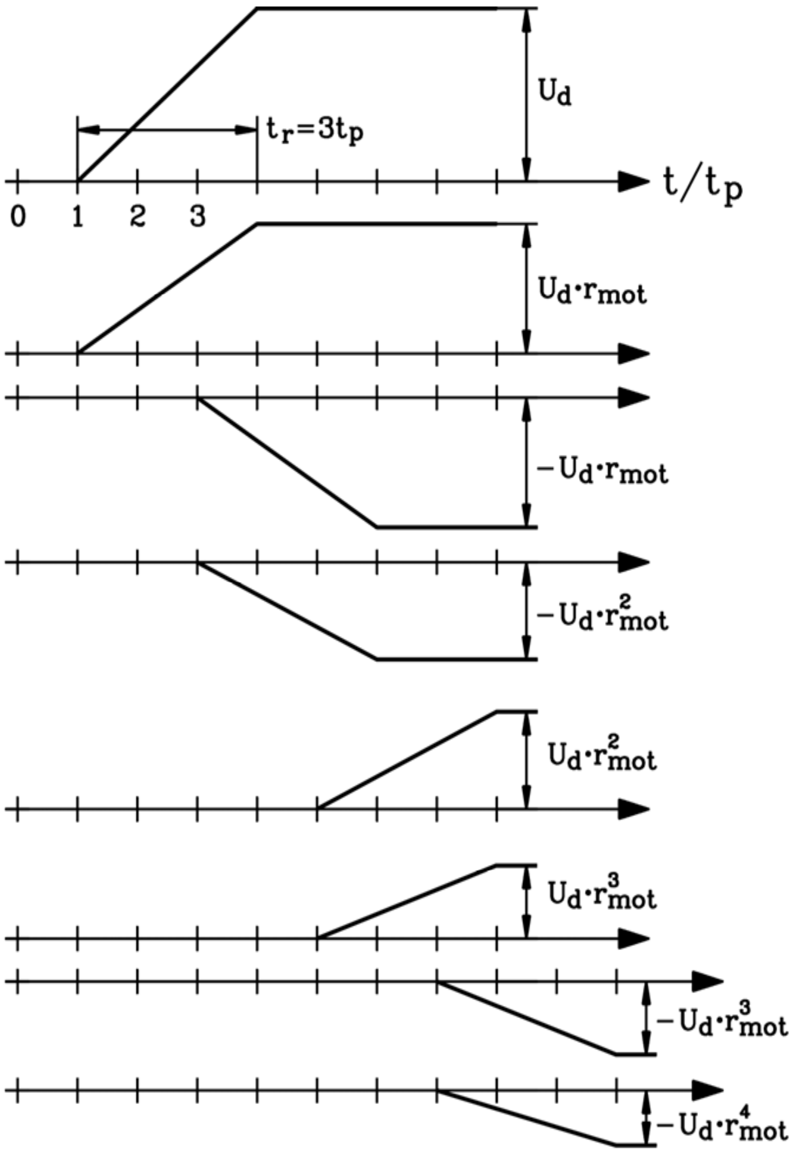
$$t_r = 2t_p = 2 \cdot l_c / v \quad \Rightarrow \quad l_{c,crit} = v \cdot t_r / 2$$

Voltage rise time t_r = 100 ns,

Voltage wave propagation velocity $v = c_0/2$ = 150 000 km/s

$$l_{c,crit} = v \cdot t_r / 2 = 150 \cdot 10^6 \cdot 100 \cdot 10^{-9} / 2 = 7.5\,\mathrm{m}$$

If the cable is longer than 7.5 m between inverter an motor, then full voltage wave reflection occurs at the motor terminals!

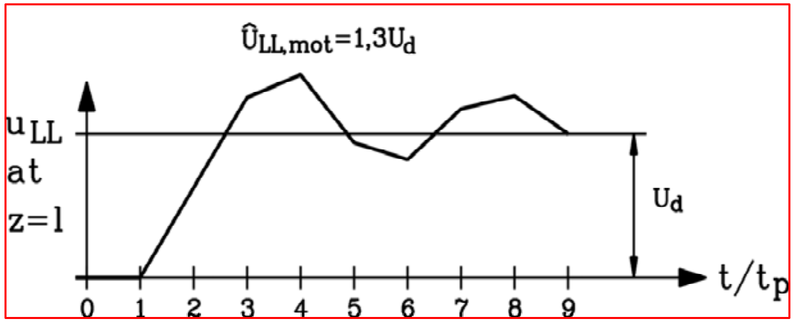


Voltage reflection at short cable length l < $l_{c,crit}$

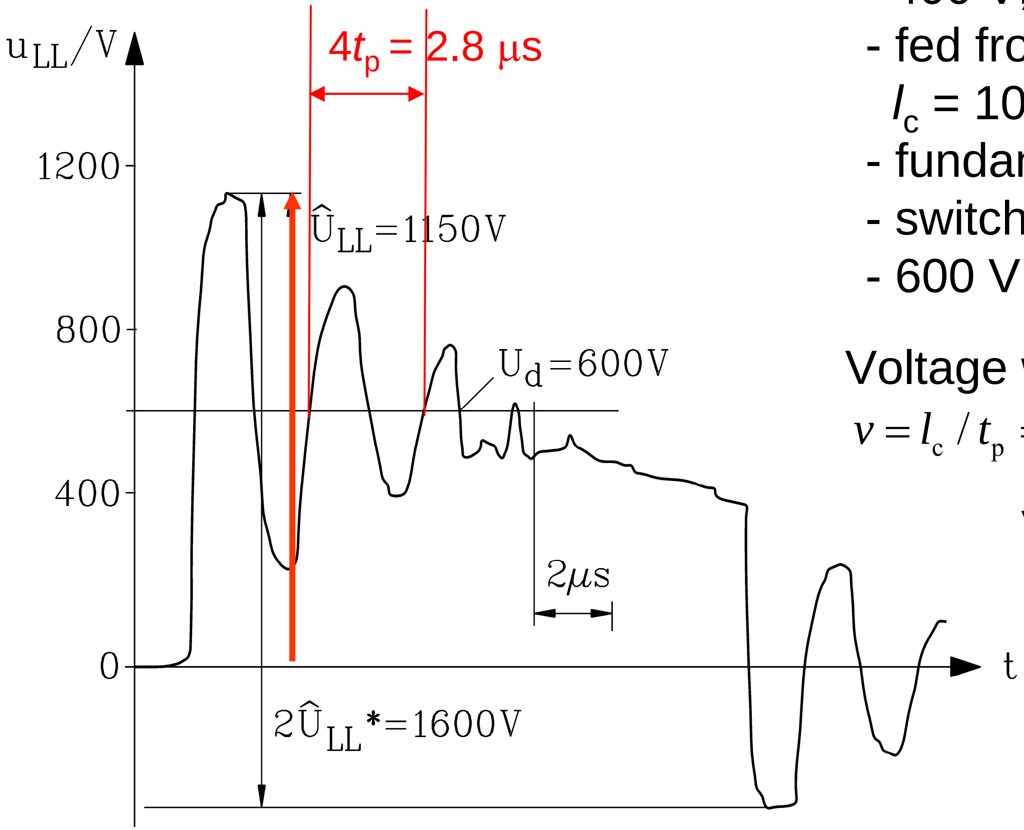
- Oscillating voltage overshoot at motor side due to wave reflection
- Does not reach its worst-case maximum value $(1+r_{mot})U_d$ = 1.75U_d , but only 1.3U_d , as t_r > 2t_p !

Example:

- Motor reflection coefficient r_{mot} = 0.75
- Inverter reflection coefficient r_{inv} = -1
- Voltage rise time t_r = 3t_p



Measured voltage reflection at long cable $l > l_{c,crit}$



Source: Siemens AG

- 2 pole induction motor, frame size 80 mm, 400 V, Y,
- fed from IGBT-inverter with motor cable l_c = 100 m,
- fundamental frequency f_s = 30 Hz
- switching frequency f_T = 8 kHz
- 600 V DC link voltage

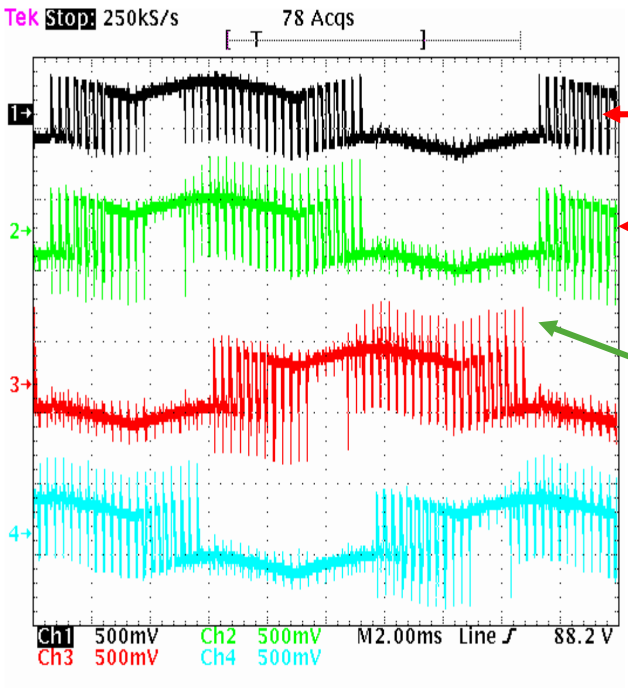
Voltage wave velocity along the cable:

$$v = l_c / t_p = (100 \cdot 4 / 2.8) \cdot 10^6 = 143000\,\text{km/s} = 0.48 c_0$$

Voltage reflection coefficient:

$$r_{mot} = (1150 - 600) / 600 = 0.92$$

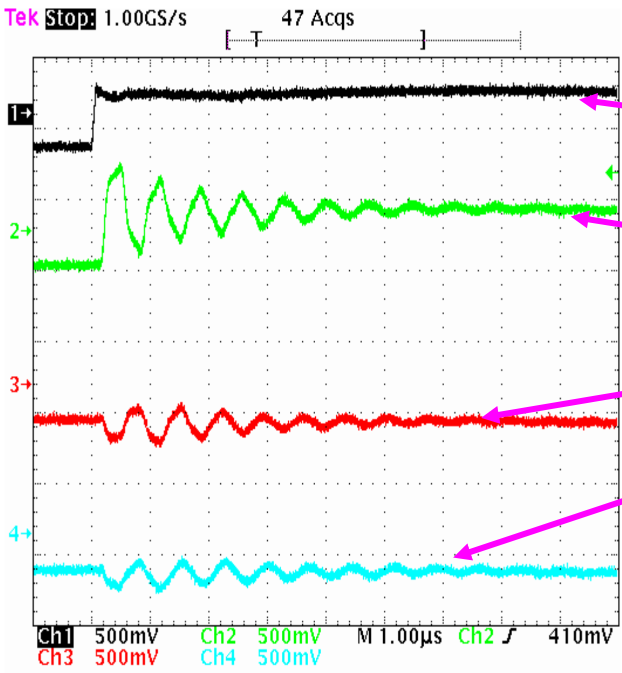
Measured voltage reflection at long cable $l > l_{c,crit}$



Inverter output voltage

Motor terminal voltage

Reflection



Inverter output voltage U-V

Motor terminal voltage U-V

V-W

W-U

Source: Siemens AG

Summary:
Voltage wave reflections at motor terminals

- Fast IGBT switching yields high d*u*/d*t*

- Large motor impedance vs. small cable impedance yields voltage reflections

- Fast switching leads to low critical cable length, where big reflections occur

- Fast switching causes increased voltage insulation stress of winding

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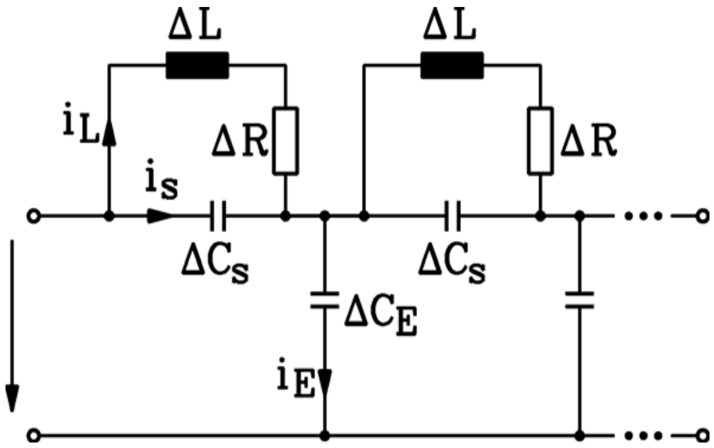
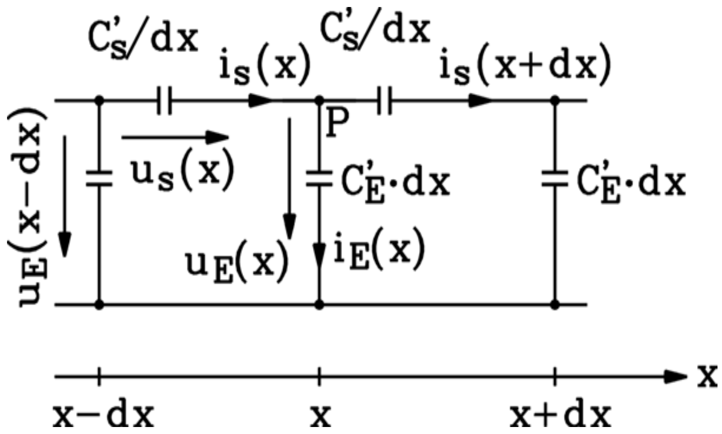
HF voltage distribution in armature winding

- HF equivalent circuit for armature winding per phase
- *Kirchhoff´*s laws applied to one element of equivalent circuit



Source: Heller-Veverka, VEB-Verlag Technik, Berlin, 1957



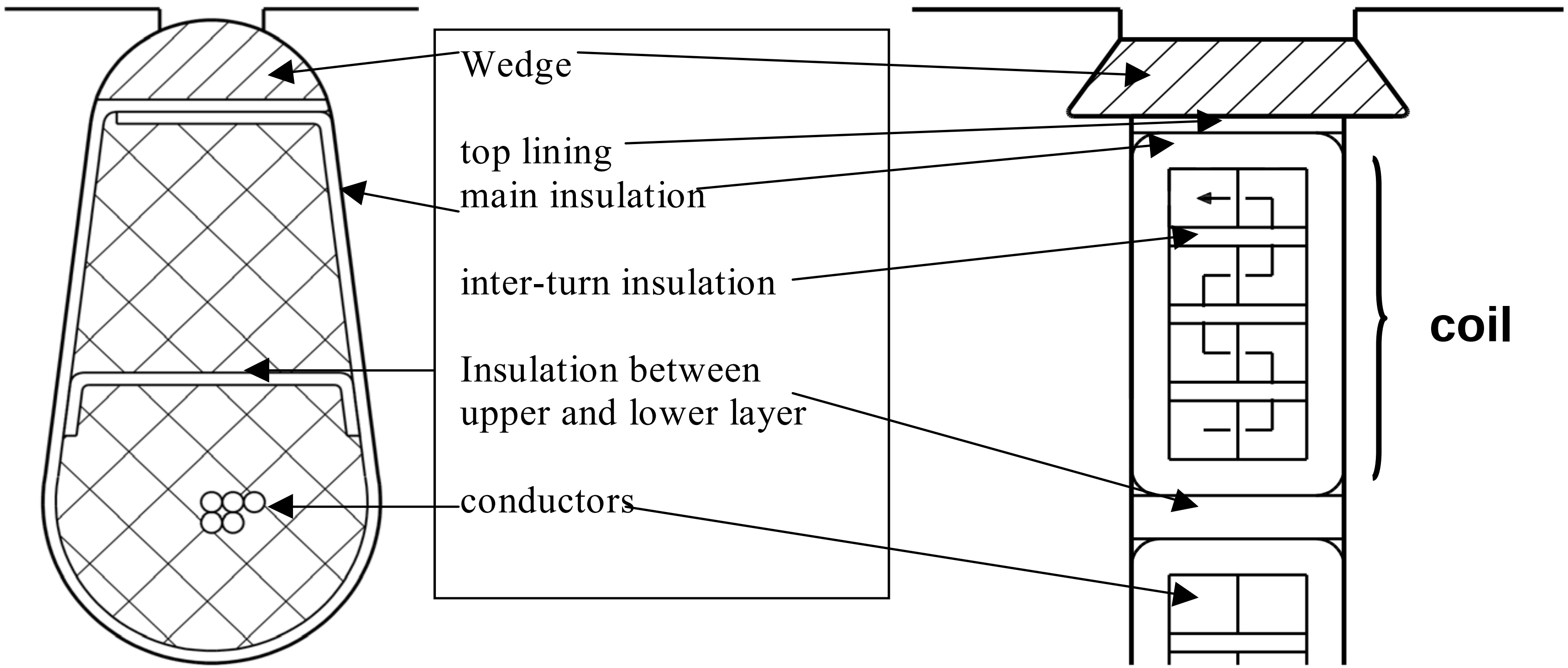
Motor winding equivalent circuit per turn consists of

- inductance per turn ΔL,
- line-to-earth capacitance ΔC_E between conductor and stator iron,
- series capacitance ΔC_s between conductors of adjacent turns in slot.

Ground current: $\int i_E(x) \cdot dx / l = i_g$

For HF the inductance gives an “infinite” impedance!

Example: Two-layer motor winding: Slot and coil insulation



Oval semi-closed slot for round wire low voltage

Rectangular slot for form wound high voltage coil arrangement with $N_c = 8$ turns per coil

Capacities in the stator winding

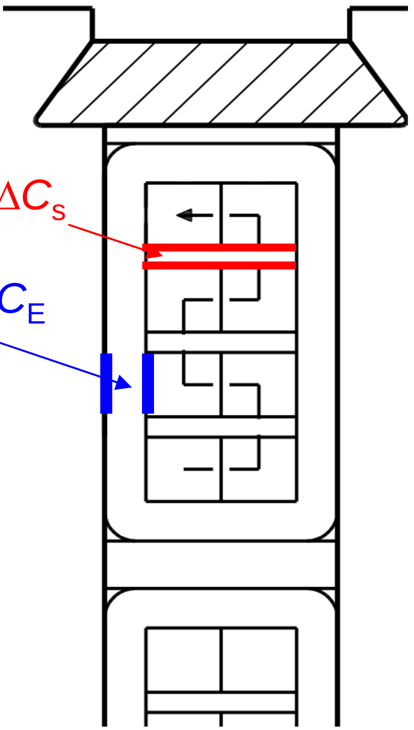
- N_s turns per winding
- Length of winding per turn: Δx,
- winding length $l = \Delta x \cdot N_s$
- Total line-to-earth capacitance

$$C_E = N_s \cdot \Delta C_E$$

- Total series capacitance per phase

$$C_s = \Delta C_s / N_s$$

for Fig.: $\Delta C_E < \Delta C_s$



$$\Delta C_E = C_E / N_s = (C_E / l) \cdot \Delta x = C_E' \cdot \Delta x$$
$$\Delta C_s = C_s \cdot N_s = C_s \cdot l / \Delta x = C_s' / \Delta x$$

$$\Delta C_E = C_E' \cdot \Delta x$$
$$\Delta C_s = C_s' / \Delta x$$

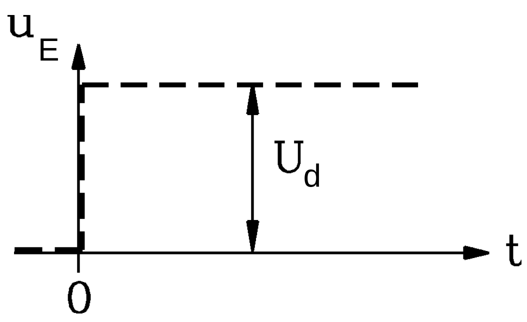
$$\gamma l = \sqrt{\frac{C_E'}{C_s'}} \cdot l = \sqrt{\frac{\Delta C_E}{\Delta C_s}} \cdot \frac{l}{\Delta x} = \sqrt{\frac{\Delta C_E}{\Delta C_s}} \cdot N_s$$

Although $\Delta C_E < \Delta C_s$, the parameter γl is big due to N_s !

Non-linear voltage distribution at "voltage step" ($\mathrm{d}u/\mathrm{d}t \to \infty$)

Differential equation for line-to-earth voltage u_E :

$$\frac{\mathrm{d}^2 u_E(x)}{\mathrm{d}x^2} - \frac{C_E'}{C_s'} u_E(x) = 0$$



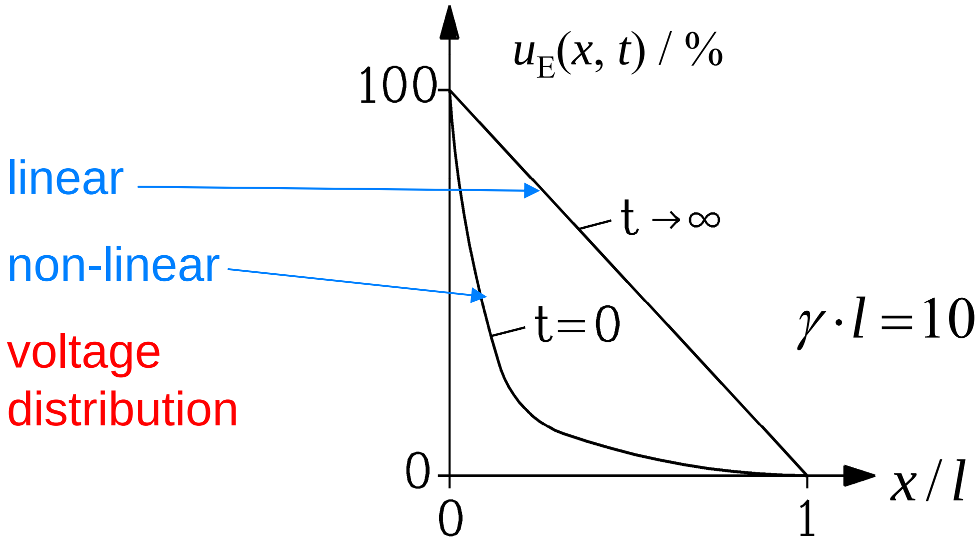
Boundary conditions: $u_E(x=0) = U_d,\ u_E(x=l) = 0$

Solution:

$$u_E(x) = U_d \cdot \frac{\sinh(\gamma \cdot (l - x))}{\sinh(\gamma \cdot l)},\quad t = 0$$

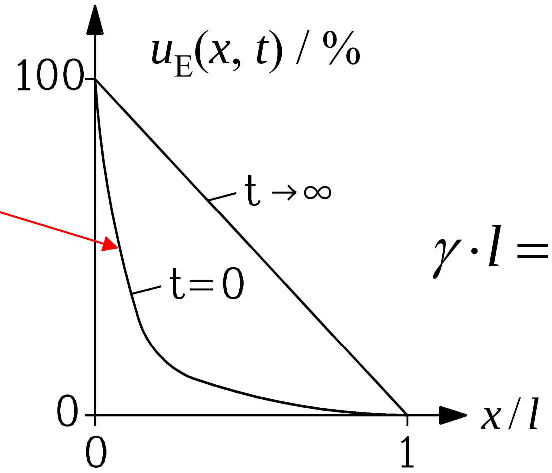
$$\gamma = \sqrt{C_E' / C_s'}$$

unit $[\gamma] = 1/\mathrm{m}$



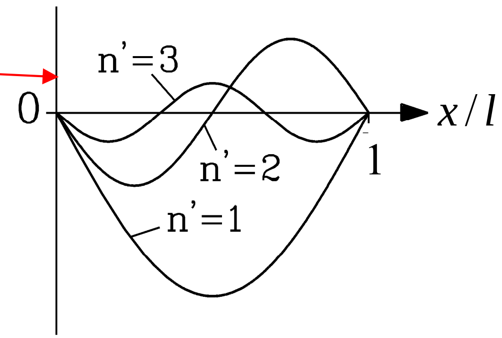
Oscillation of non-linear voltage distribution between *t* = 0 and *t* → ∞

- Voltage distribution shortly after applying the voltage step is only determined by winding capacities



$\gamma \cdot l = 10$

- Winding inductance, capacitance, resistance cause a voltage oscillation, which starts at non-linear distribution $u_E(x, t = 0)$ and ends at linear distribution $u_E(x, t \to \infty)$

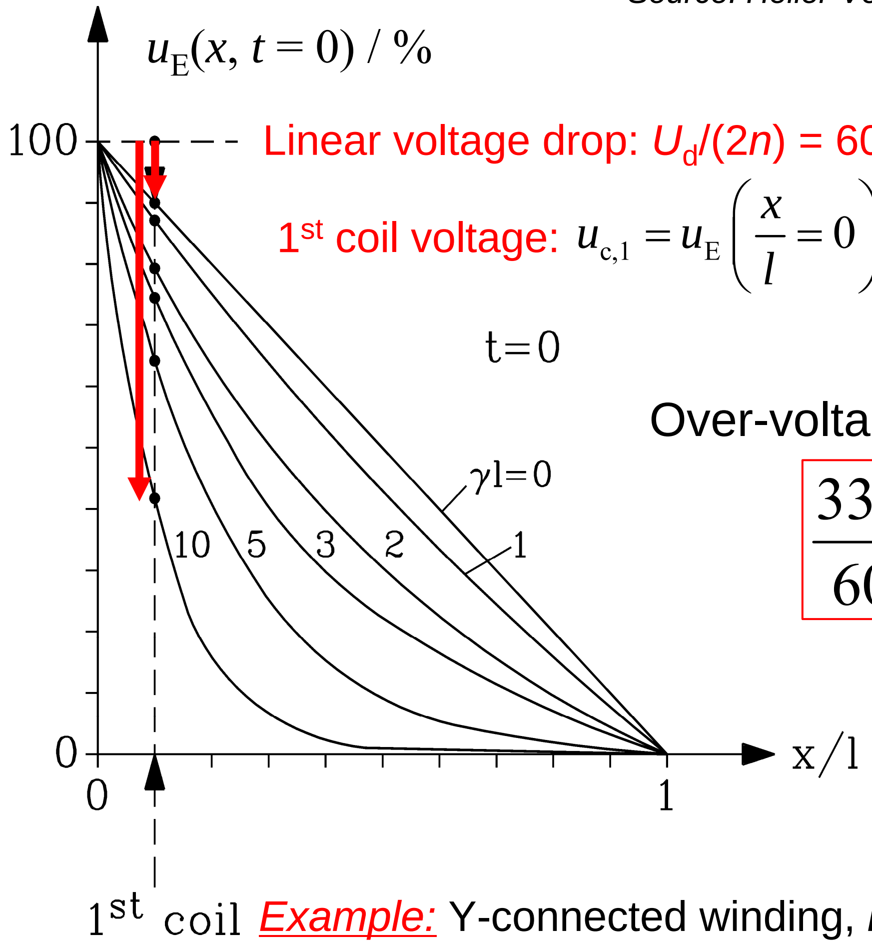


$$u_E(x,t) = \sum_{n'=1,2,\ldots}^{\infty} \hat{U}_{n'} \cdot \cos\left(\frac{n' \cdot \pi \cdot x}{l}\right) \cdot \cos(n' \cdot 2\pi \cdot f \cdot t) \cdot e^{-t/T_{n'}} + $$
$$+ u_E(x, t \to \infty)$$

Source: Heller-Veverka, VEB-Verlag Technik, Berlin, 1957

1st coil receives highest transient voltage

Source: Heller-Veverka, VEB-Verlag Technik, Berlin, 1957

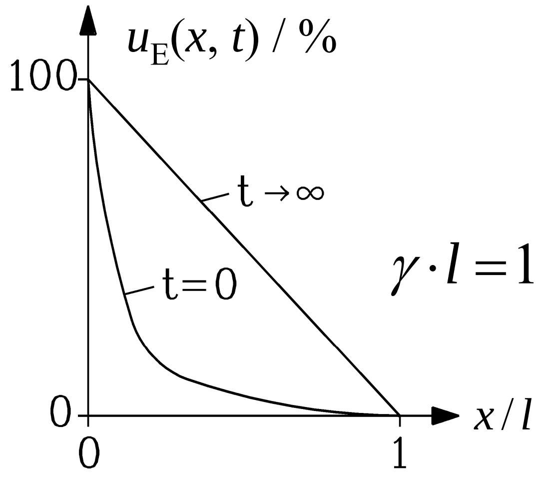


Linear voltage drop: $U_d/(2n)$ = 60 V

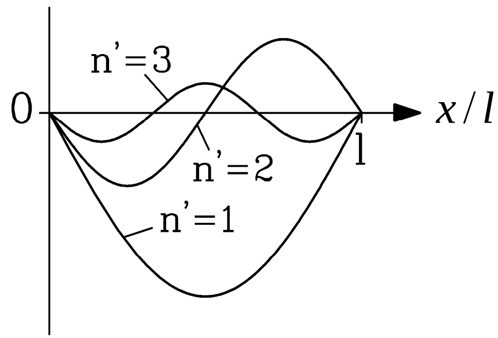
1st coil voltage: $u_{c,1} = u_E\left(\frac{x}{l}=0\right) - u_E\left(\frac{x}{l}=0.1\right)$

Over-voltage factor of 1st coil:

$$\frac{330V}{60V} = 5.5$$



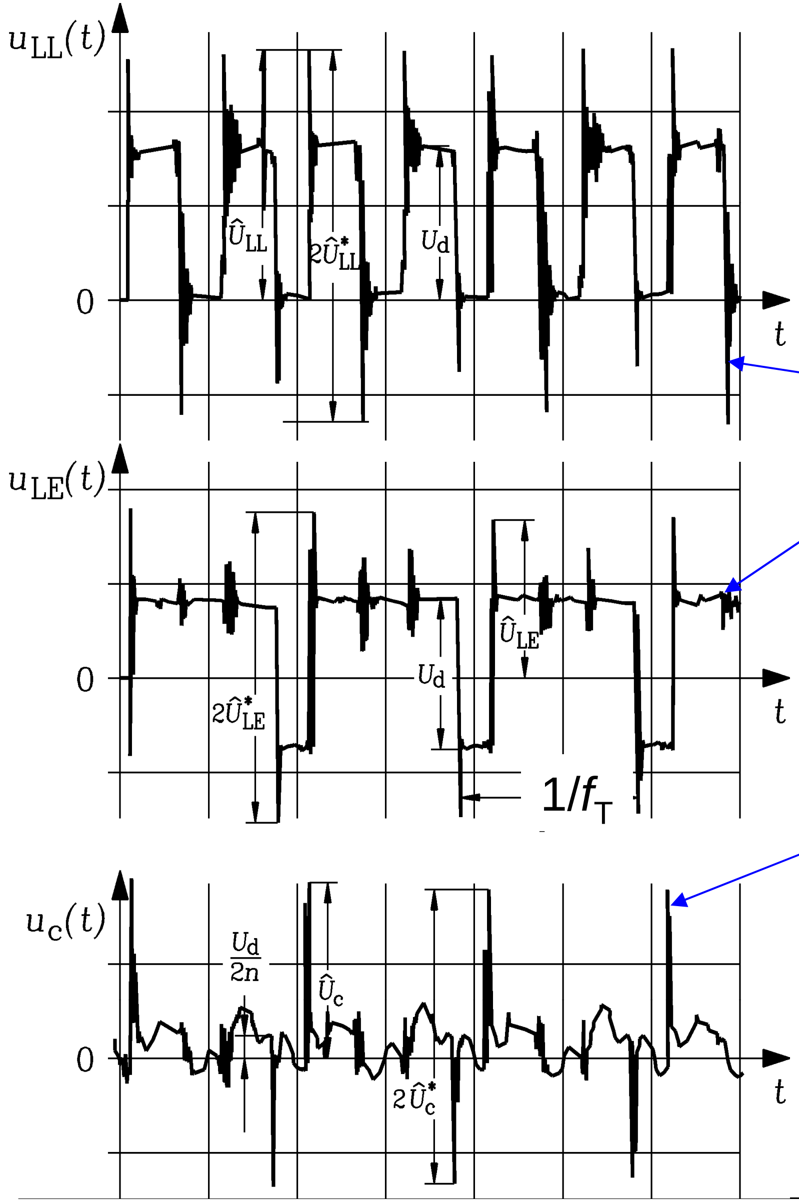
$\gamma \cdot l = 10$



Example: Y-connected winding, n = 5 coils per phase, $2n$ = 10 coils line-to-line, U_d = 600 V. 1st coil voltage: $u_{c,1}/U_d$ = 330/600 = 55% of total voltage!

Measured motor terminal voltages at PWM IGBT-inverter operation

Hentschel E et al (1993): Beanspruchung der Wicklungsisolierung von Drehstrommaschinen. etz Vol. 114 No. 7: 1074-1077



Line-to-line terminal voltage

Line to earth terminal voltage

- 400 V Y-cage induction motor
- DC link voltage U_d = 600 V
- l_c = 30 m cable length between motor and inverter

Voltage drop at first coil per phase (*n* coils per phase)

Measured voltage at 1st coil per phase

Hentschel E et al (1993): Beanspruchung der Wicklungsisolierung von Drehstrommaschinen. etz Vol. 114 No. 7: 1074-1077

- 400 V Y-cage induction motor
- DC link voltage U_d = 600 V
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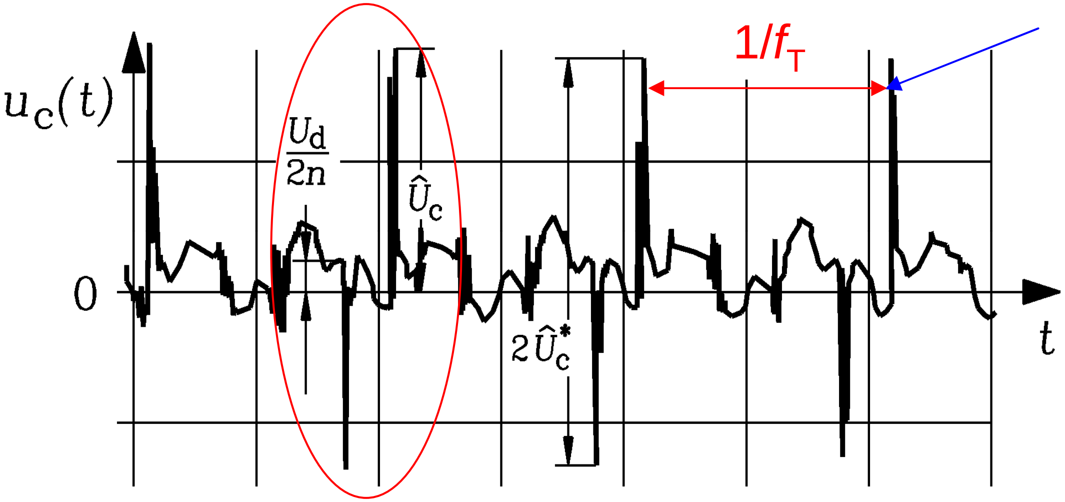

Voltage drop at first coil per phase (*n* coils per phase)

Over-voltage factor of 1st coil:

$$\frac{\hat{U}_c}{U_d/(2n)} \approx 6$$

Summary:
HF voltage distribution in armature winding

- High d*u*/d*t* causes big influence of capacities within winding on voltage

- Non-linear voltage distribution in the winding at high d*u*/d*t*

- Increased insulation stress of the first winding turns at the incoming wave

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Insulation stress due to high d*u* / d*t*

- Steep voltage surges with high repetition rate cause locally high electric field strength usually in voids of the insulation system

⇒ Local high electric fields cause ignition of small sparks ("partial discharges")

⇒ Ignition and extinguishing of local small sparks cause electric erosion of the insulation system with a final collapse of the insulation by direct flash-over

- High frequency electric fields within the healthy insulation cause also increased hysteretic polarisation losses ("dielectric losses"), but the loss density (W/m^3) is much too small to cause a dangerous temperature rise

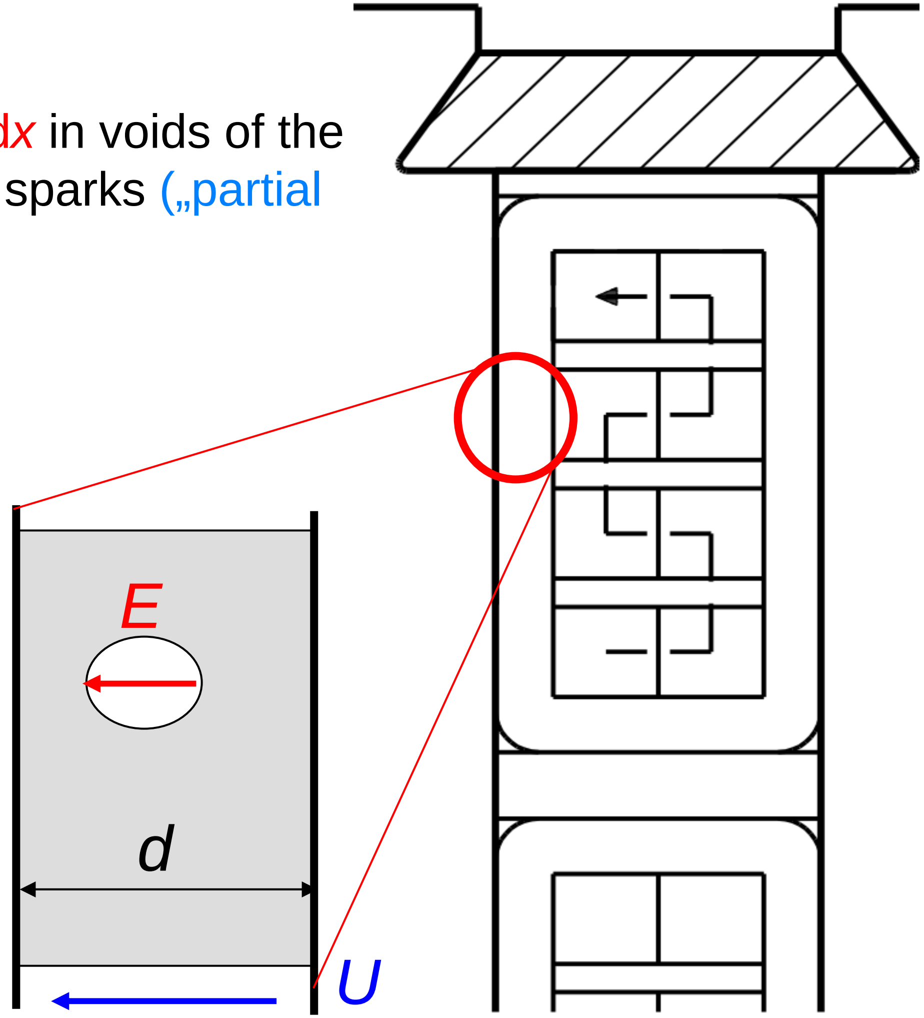
Result:

Insulation stress at high d*u*/d*t* due to partial discharges, not due to increased dielectric losses

Insulation stress due to partial discharges

- Local electrical field strength $E = dU/dx$ in voids of the winding insulation may cause a small sparks („partial discharge“)

- This local arcing, if occurring for long, destroys finally the insulation and causes a short-circuit e.g. between winding and housing



$E_{av} = U/d$: average electrical field strength

$E > E_{av}$: local electrical field strength

Insulation stress of AC winding at inverter supply

Each voltage impulse may cause small spark ignition at weak points (e.g. voids)

a) between the phases,

b) between line and earth.

Small sparks = **"partial discharges (PD)"** are too faint to be visible, but repeated very often they will cause erosion of enamel, leading finally to a big flash over.

Note: Low voltage windings (U_N < 1 kV) with round wire (randomly distributed in the slots) and resin impregnation may not resist for long partial discharges.

Hence they must be kept FREE of partial discharges!

Partial discharge inception voltage U_{pd}

- At the partial discharge inception voltage U_{pd} the sparks start to ignite
- For low voltage resin-insulated round enamel coated wire windings:
  PD inception voltage decreases with increasing winding temperature by ca. 4 V/K
- Thermal Class F motor: Winding temperature ca. 150 °C :
  U_{pd} (50 Hz, r.m.s) at 20 °C: 1200 V → 1180 V at 150 °C

$$20\,°C : U_{\mathrm{pd}} = 1200\mathrm{V},\ \hat{U}_{\mathrm{pd}} = U_{\mathrm{pd}} \cdot \sqrt{2} = 1700\mathrm{V} \Rightarrow$$

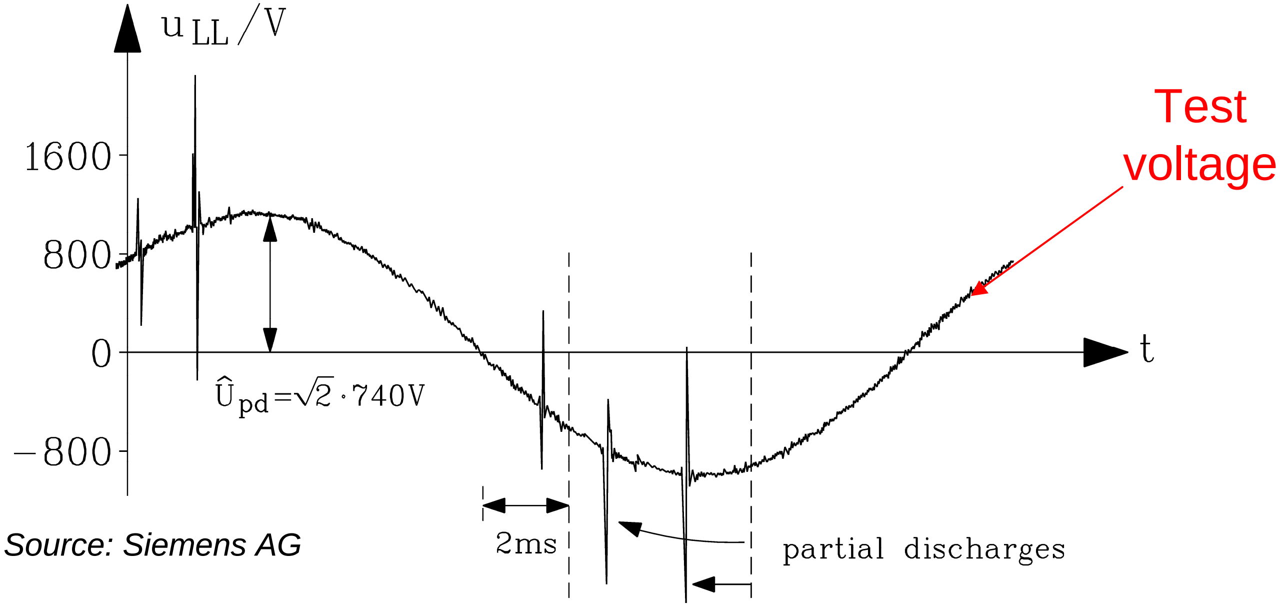
$$150\,°C : \hat{U}_{\mathrm{pd}} = 1700 - 4 \cdot (150 - 20) = 1180\mathrm{V}$$

- Peak motor line-to-line voltage with full wave reflection r_{mot} = 1:

$$\frac{\hat{U}_{\mathrm{LL,mot}}}{\hat{U}_{\mathrm{N}}} \cong \frac{(1 + r_{\mathrm{mot}}) \cdot U_{\mathrm{d}}}{U_{\mathrm{d}}} = 2.0 \qquad \hat{U}_{\mathrm{LL,mot}} = 2 \cdot U_{\mathrm{d}} = 2 \cdot 560\mathrm{V} = 1120\mathrm{V} < \hat{U}_{\mathrm{pd}} = 1180\mathrm{V}$$

Result: The motor winding is safe against d*u*/d*t*-voltage stress !

Partial discharge test of stator winding



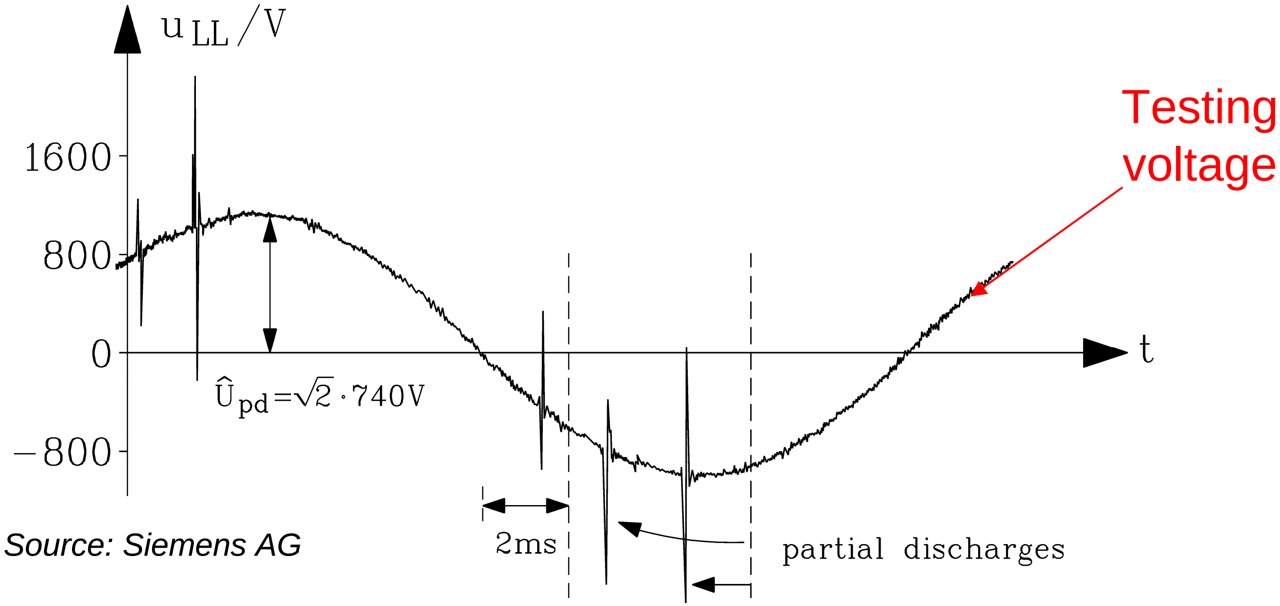
Source: Siemens AG

Test object: 2-pole 400V Y, 50 Hz, synchronous reluctance motor at 20 °C:

Test voltage: Sine wave, 50 Hz, line-to-line, variable amplitude, between the isolated phases U, V, W

- Spark discharge currents flow as HF spikes from one phase to the other.
- Via a HF capacitor this current flow is detected, being visible as additional HF voltage, superimposed on the test voltage

Partial discharge test result of 3-phase stator winding

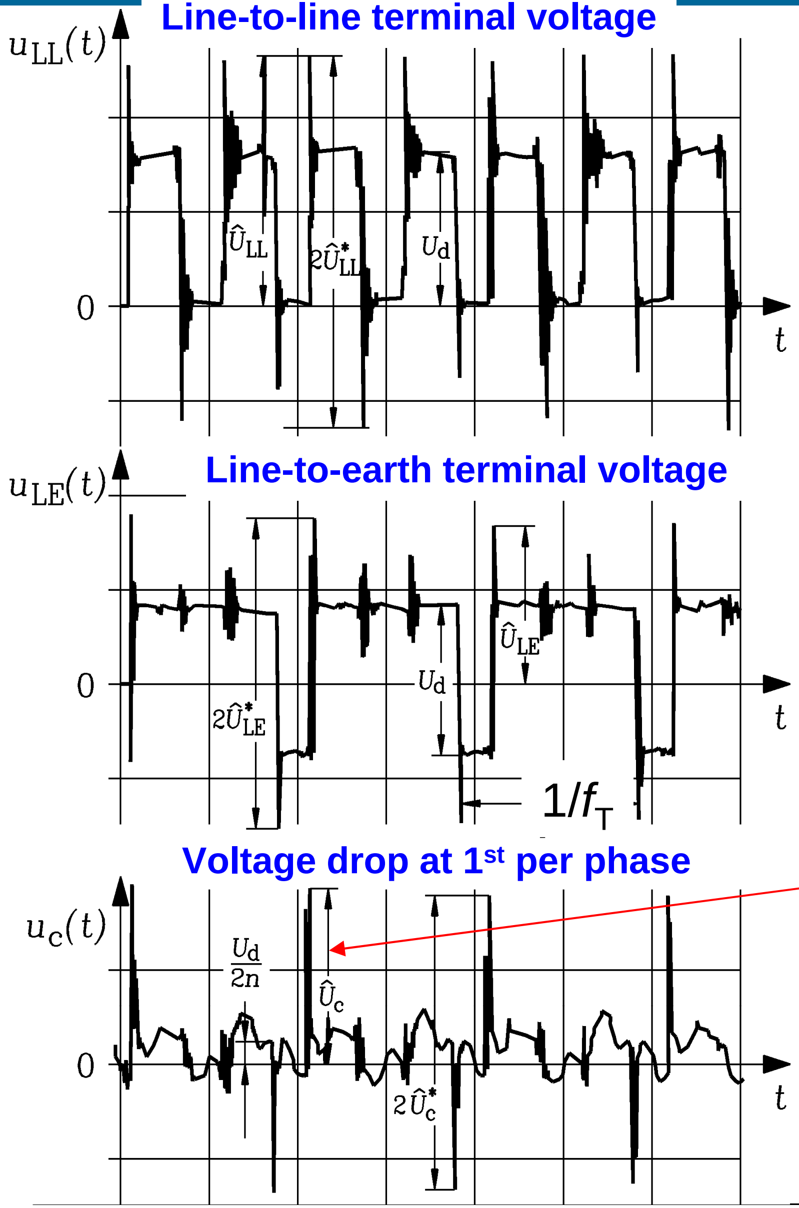


Source: Siemens AG

- Displaced inter-phase lining between phases U and V cause wire contact
- At line-to-line test voltage 740 V (r.m.s) partial discharges ignite at 20 °C
- **Partial inception (PD) voltage U_{pd} = 740 V!**

Result: U_{pd} too low for safe operation at U_d = 600 V with reflections!

PWM motor terminal voltage parameters



DC link voltage: U_d

Motor line-to-line voltage amplitude:

$$\hat{U}_{LL} = (1 + r_{mot}) \cdot U_d$$

Pulse frequent AC line-to-line voltage amplitude: $2 \cdot f_T$

$$\hat{U}^*_{LL} = (0.5 + r_{mot}) \cdot U_d$$

Hentschel E et al (1993): Beanspruchung der Wicklungsisolierung von Drehstrommaschinen. etz Vol. 114 No. 7: 1074-1077

Amplitude of pulse frequent AC voltage of 1st coil per phase: $\hat{U}_c$

Motor winding voltage stress at PWM IGBT-inverter operation

Inverter input voltage	$U_{LL,grid}$	400 V	500 V
DC link voltage	$U_d \approx \sqrt{2} \cdot U_{LL,grid}$	565 V	710 V
Motor rated voltage	U_N	400 V	500 V
Motor line-to-line voltage amplitude	$\hat{U}_{LL} = (1 + r_{mot}) \cdot U_d$	1130 V	1420 V
Motor line-to-earth voltage amplitude	$\hat{U}_{LE} = (0.5 + r_{mot}) \cdot U_d$	850 V	1060 V
Pulse frequent AC line-to-line voltage amplitude ($2 \cdot f_T$)	$\hat{U}^*_{LL} = (0.5 + r_{mot}) \cdot U_d$	850 V	1060 V
Pulse frequent AC line-to-earth voltage amplitude ($2 \cdot f_T$)	$\hat{U}^*_{LE} = (0.5 + r_{mot}) \cdot U_d$	850 V	1060 V
Amplitude of pulse frequent AC voltage of 1st coil per phase *Hentschel E et al.: (1993) Elektrotechn. Zeitschrift etz Vol. 114 No. 7: 1074-1077*	e.g. a) $n = 6$, $k = 0.3$ b) $n = 6$, $k = 0.6$ $\hat{U}_c = \left[k \cdot (1 + r_{mot}) - \frac{1}{2n} \right] \cdot U_d$	290 V 630 V $(r_{mot} = 1)$	365 V 790 V $(r_{mot} = 1)$

Summary:
Insulation stress of AC winding at inverter supply

- Low voltage round wire windings suffer from partial discharges

- Partial discharges must be avoided in low voltage windings

- PD measurement necessary to asses admissible voltage limits

High frequency effects in inverter-fed AC electric machinery

1 Voltage wave reflections at motor terminals

2 HF voltage distribution in armature winding

3 Insulation stress of AC winding at inverter supply

4 Parasitic HF currents

5 System design of inverter drives coping with big du/dt

Parasitic HF currents

HF capacitive currents of cable and motor capacitances:

a) Capacitive cable current

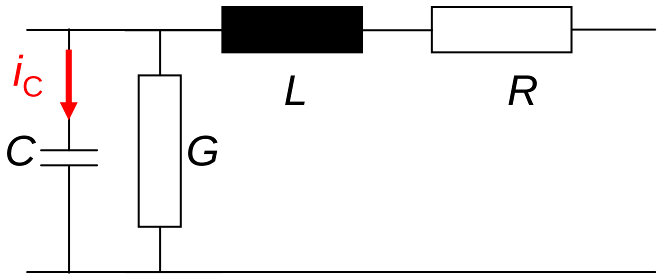
b) Capacitive stator-to-ground current via main insulation and earthed stator housing

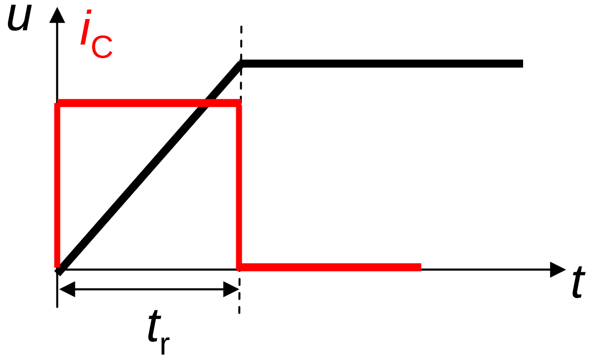
c) In case of rotor grounding: Capacitive rotor-to-ground current via bearings

d) Capacitive currents within the motor e.g. via the bearings

Capacitive motor cable currents i_C

Simplified equivalent circuit of a cable with concentrated elements





$$i_C = C_{cable} \cdot \frac{du}{dt} \approx C_{cable} \cdot \frac{U_d}{t_r}$$

$$C_{cable} = C_c' \cdot l_c$$

Cable parameters:

L: inductance

R: ohmic resistance

C: capacitance

G: lossy insulation conductance

- Cable capacitance C_{cable}
  - increases with cable length l_c
  - depends on cable type (shielded / unshielded etc.)

- Long cables above 30 ... 50 m: HF reactive cable current i_C is big.

- **Inverter output chokes** limit i_C

HF capacitive parasitic currents within the motor

- Motor stray capacitances:
  - bearing lubricant film,
  - winding insulation
  - air gap between stator and rotor

Capacity of winding-to-ground: $C_E \approx C_{wh}$,

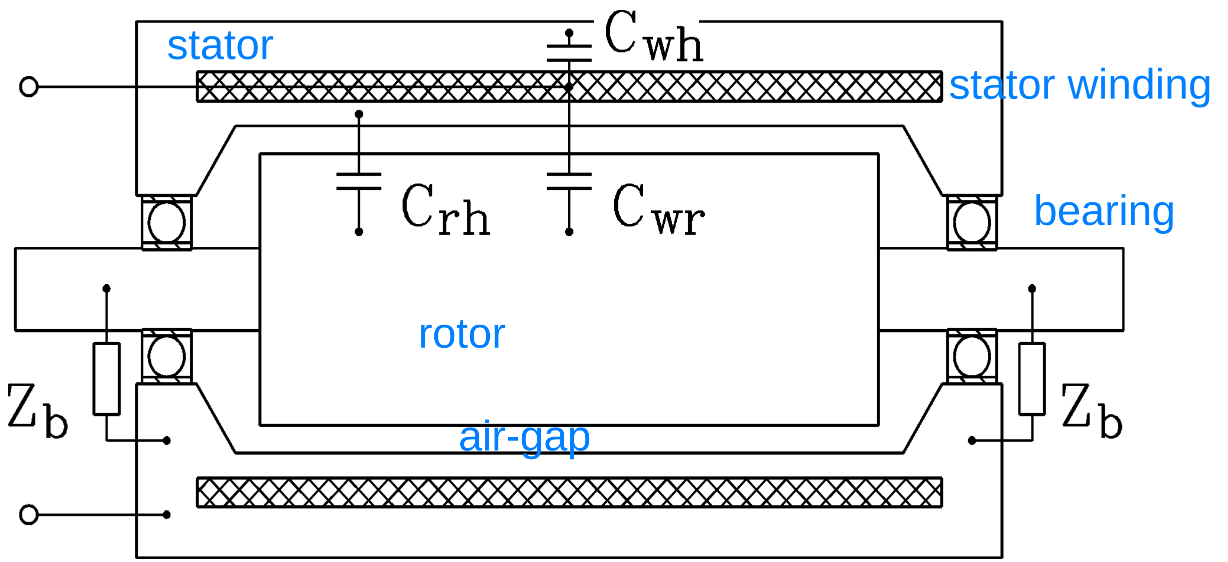
Winding-to-rotor C_{wr}, rotor-to-housing C_{rh}, bearing C_b are ca. 100 times smaller!

w: winding

r: rotor

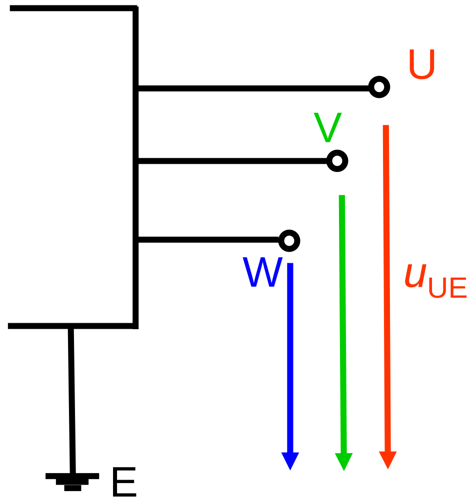
h: housing

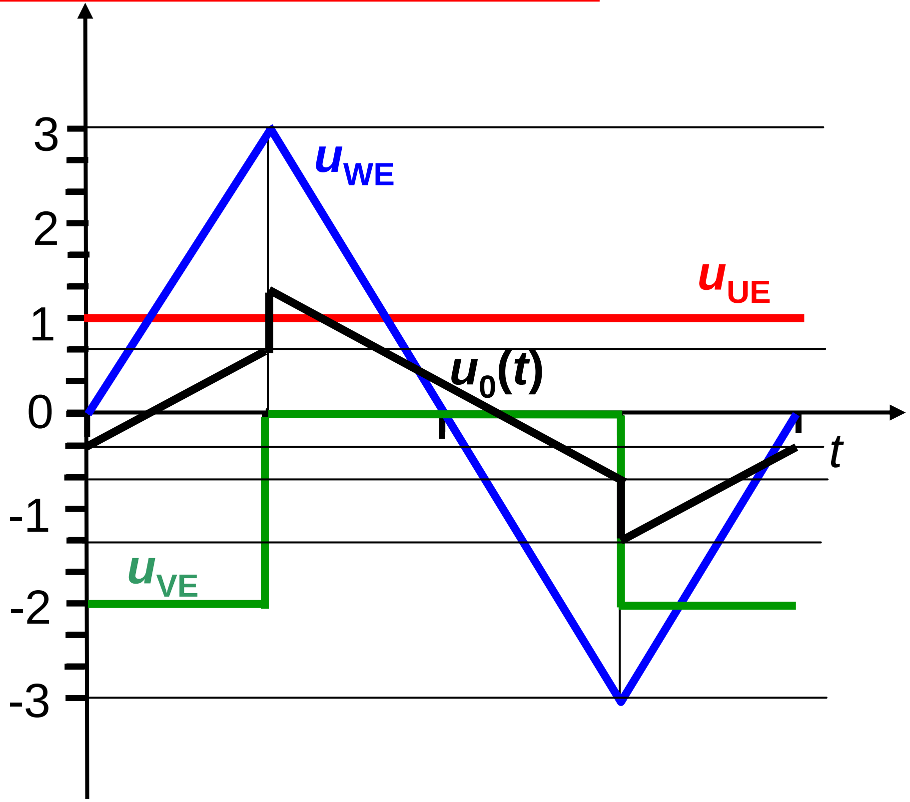
b: bearing



Definition of common mode voltage u_0

$$u_0(t) = \frac{u_{\mathrm{UE}}(t) + u_{\mathrm{VE}}(t) + u_{\mathrm{WE}}(t)}{3}$$





Arbitrary line-to-ground voltages u_{UE}, u_{VE}, u_{WE} lead to the time-dependent common mode voltage u_0

Common mode inverter output voltage u_0

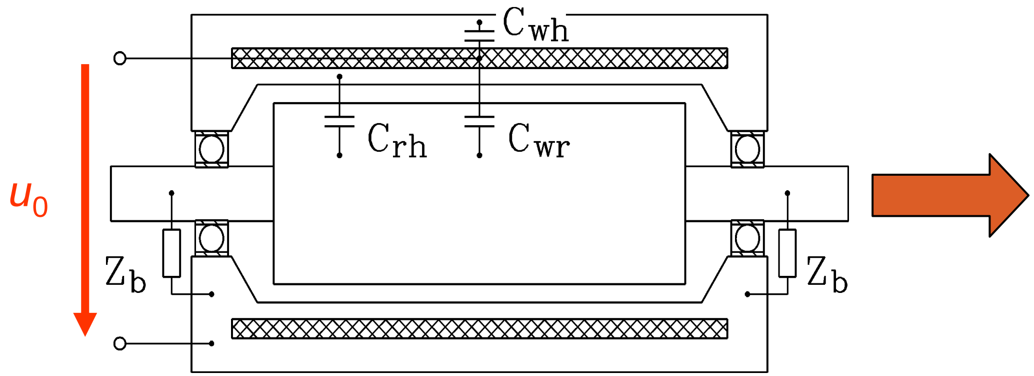
$$u_0(t) = \frac{u_{UE}(t) + u_{VE}(t) + u_{WE}(t)}{3}$$

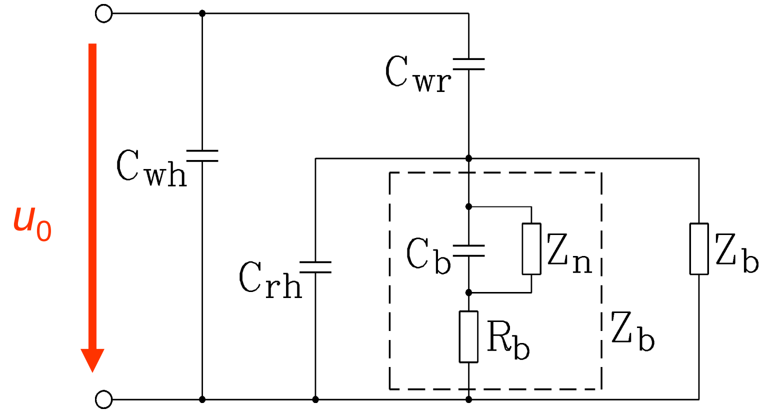
Two-level PWM inverter: Output potential is either $+U_d/2$ or $-U_d/2$

Common mode voltage u_0: - is either $U_d/6$, $-U_d/6$, $U_d/2$, $-U_d/2$

- values change with switching frequency f_T

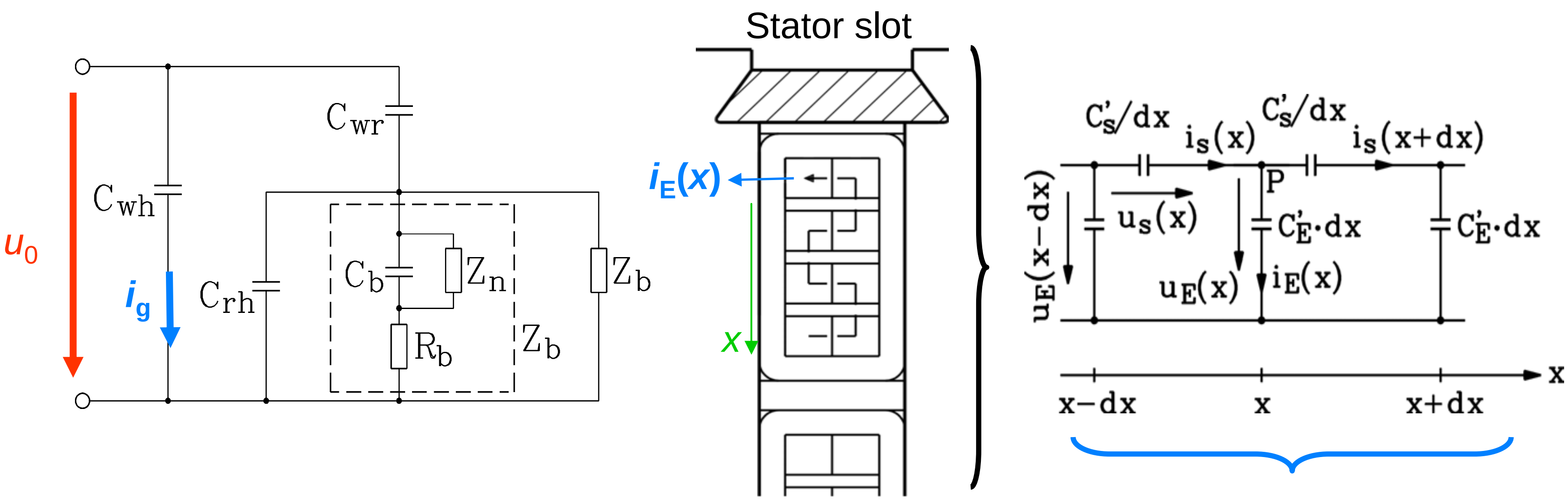
d*u*/d*t* of common mode voltage causes HF parasitic motor currents:





Motor capacitive equivalent circuit

HF stator-to-ground current i_g



Stator-to-ground current: $$\int i_E(x)\cdot dx / l = i_g$$

Via series and ground capacities C_s, C_E of series turns per coil

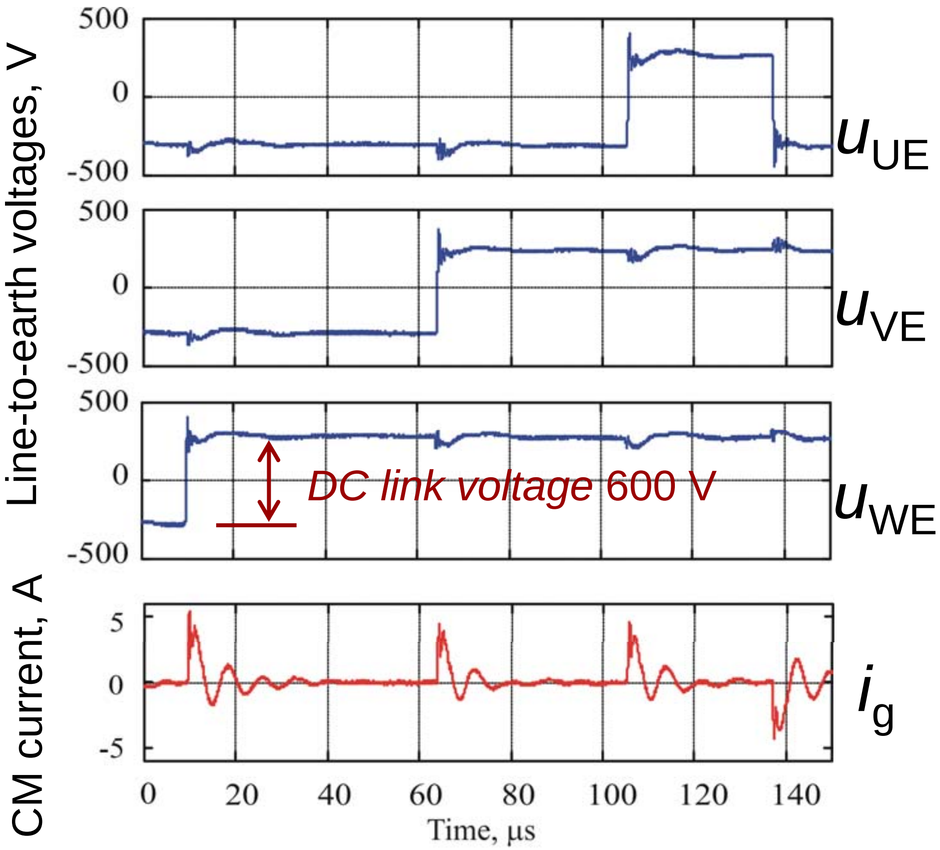
the earth current distribution $i_E(x)$ is integrated along the length l of the winding,

yielding the stator-to-ground current i_g

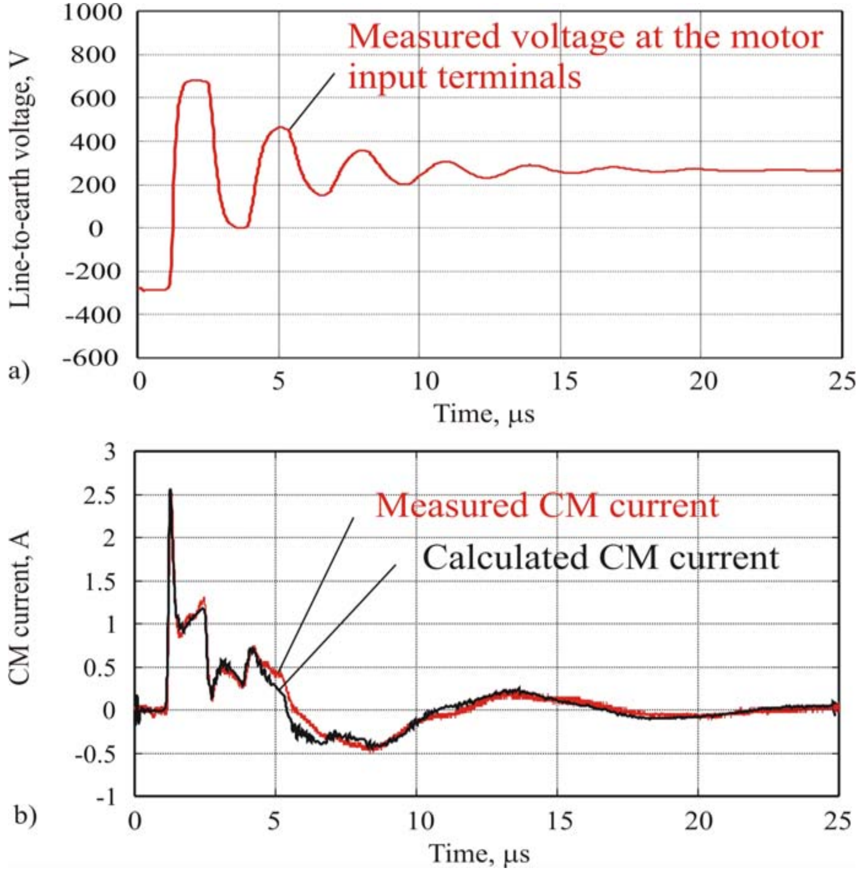
Measured common mode stator-to-ground current i_g

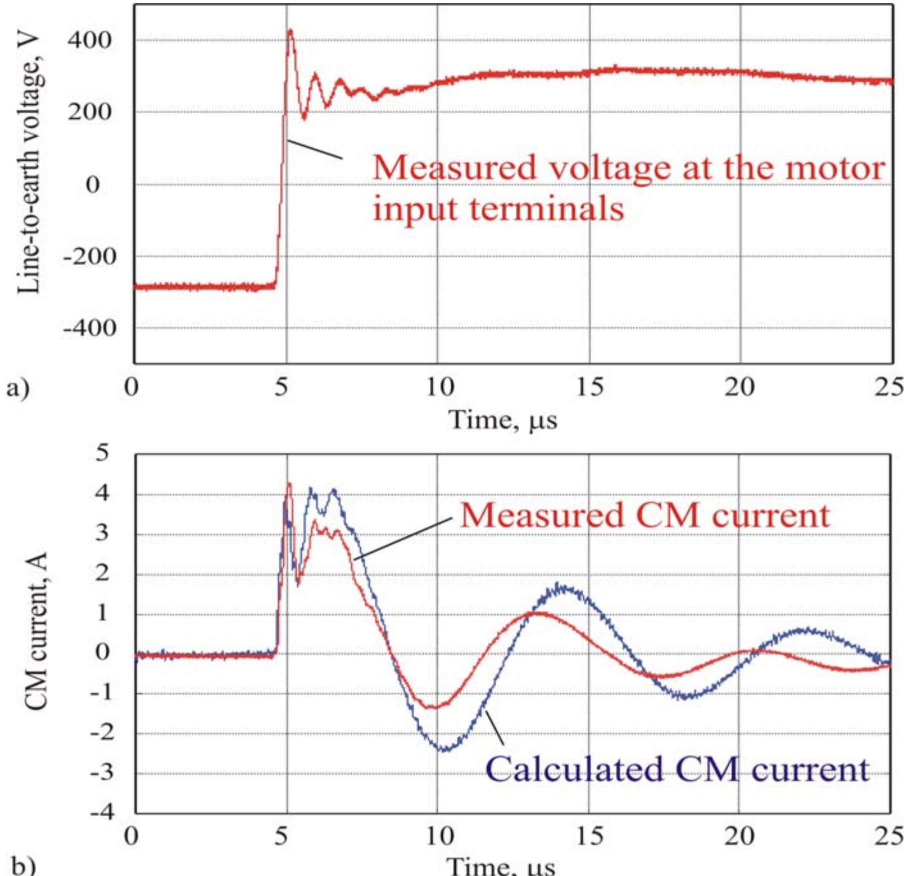
Test bench for measurements of CM currents at a 240 kW induction motor

240 kW, 4 pole cage induction motor



Measured HF stator-to-ground currents i_g





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

Source: O. Magdun,
PhD Thesis,
TU Darmstadt

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

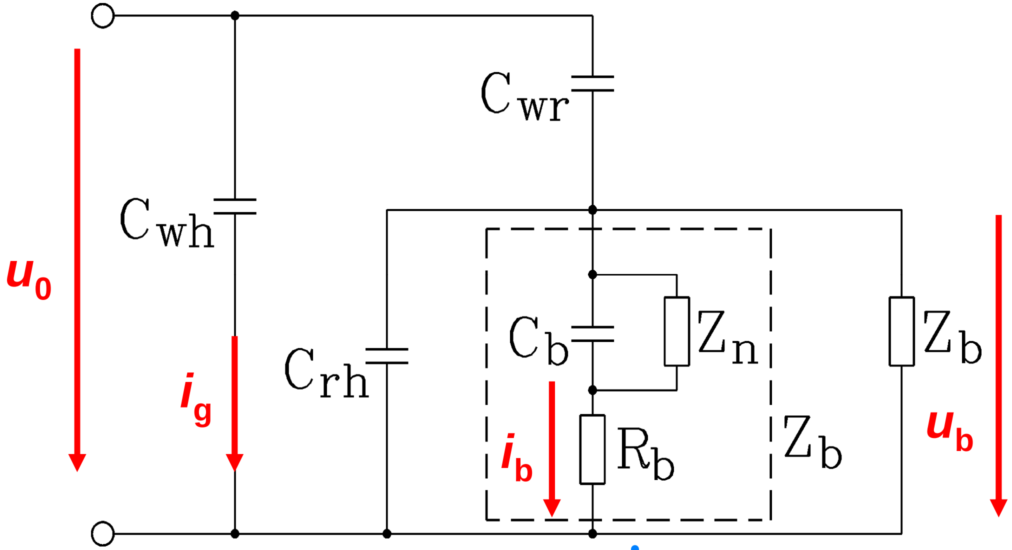
Parasitic HF bearing common mode voltage u_b

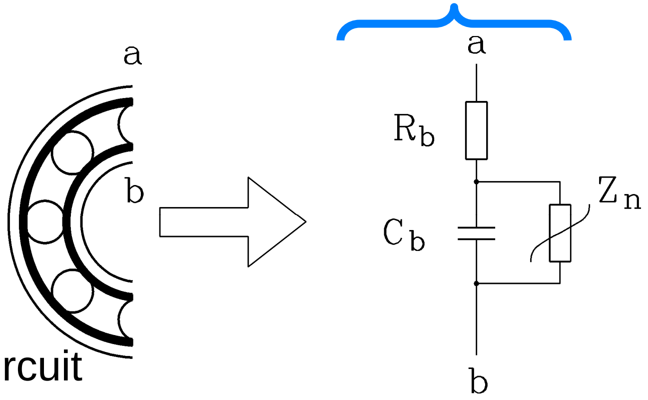
Intact insulating bearing lubrication film: $Z_n \to \infty$
Common mode voltage u_0 is causing
a common mode bearing voltage u_b
over the bearings by a capacitive voltage divider!
(Bearing resistance R_b small!)

$$BVR = \frac{u_b}{u_0} \cong \frac{C_{wr}}{C_{wr} + C_{rh} + 2 \cdot C_b}$$

BVR: bearing voltage ratio
BVR ≈ 0.03 … 0.1

Motor: Equivalent capacitive HF circuit





Ball bearing:
Equivalent electric circuit

Electric field strength E_b in intact lubrication film

$$BVR = \frac{u_b}{u_0} \cong \frac{C_{wr}}{C_{wr} + C_{rh} + 2 \cdot C_b} \approx 0.03 \ldots 0.1$$

$$u_b = u_0 \cdot BVR = \left(\frac{U_d}{6} \ldots \frac{U_d}{2} \right) \cdot (0.03 \ldots 0.1)$$

$$U_d = 600\,\mathrm{V}: \quad u_b \approx (100 \ldots 300) \cdot (0.03 \ldots 0.1) = 3 \ldots 30\,\mathrm{V}$$

Intact insulating bearing lubrication film thickness $h_0 \approx 0.5 \ldots 3.0$ µm (depending on speed, temperature, load, lubricant, …)

$$E_b = u_b / h_0 \approx (3 \ldots 30\mathrm{V})/(0.5 \ldots 3\,\mu\mathrm{m}) = 1 \ldots 60\,\mathrm{kV/mm}$$

At a typical threshold value of E_D = **15 kV/mm** a short electric arc discharges the lubricant, causing a discharge bearing current $i_{b,EDM}$ ($Z_n \rightarrow 0$)

This discharge bearing current $i_{b,EDM}$ deteriorates the bearing race surface by electric erosion (“Machining”) (EDM: electric discharge machining)

Capacitive parasitic HF bearing currents i_{bC}

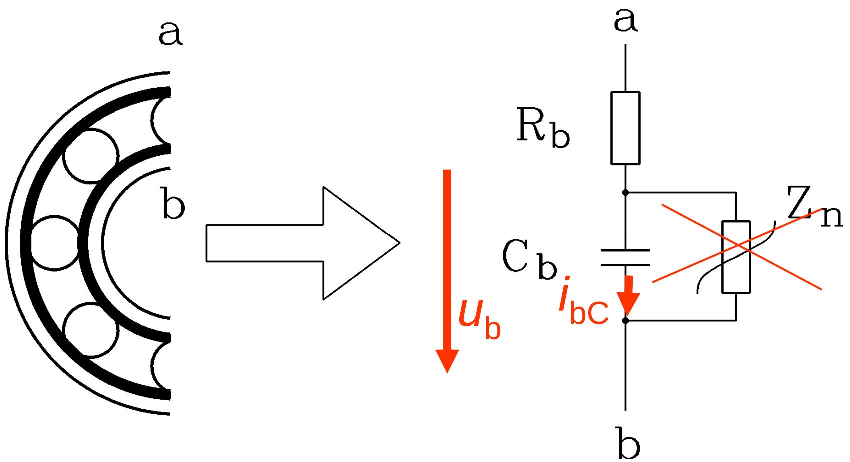
Intact insulating bearing lubrication film: $Z_n \rightarrow \infty$:
bearing behaves as capacitance C_b

$$i_{bC} = C_b \cdot \frac{du_b}{dt} = C_b \cdot BVR \cdot \frac{du_0}{dt}$$

Small values $C_b \approx 50 \ldots 200$ pF, depending on bearing size, type, load, temperature, ….

$$C_b = 200\text{pF}, U_0 = U_d / 2 = 300\text{V}, t_r = 100\text{ns} : i_{bC} = 200\text{pF} \cdot 0.1 \cdot (300\text{V}/100\text{ns}) = 60\text{mA}$$

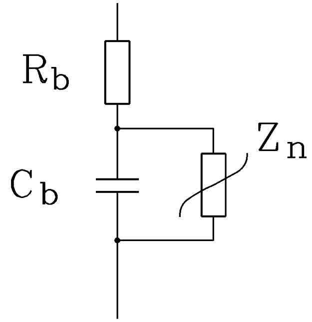
Small & harmless capacitive bearing currents in the mA-range



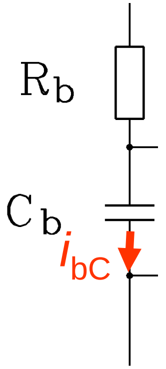
Ball bearing:
Equivalent electric circuit

Electric discharge bearing currents $i_{b,EDM}$

Bearing lubrication film acts as a "switch":



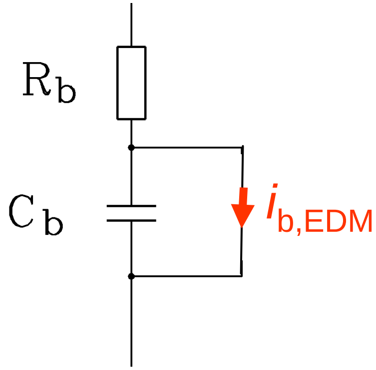
Intact film: $Z_n \to \infty$



E_b < **15 kV/mm**

Capacitive parasitic HF bearing currents i_{bC}

Punched film: $Z_n \to 0$

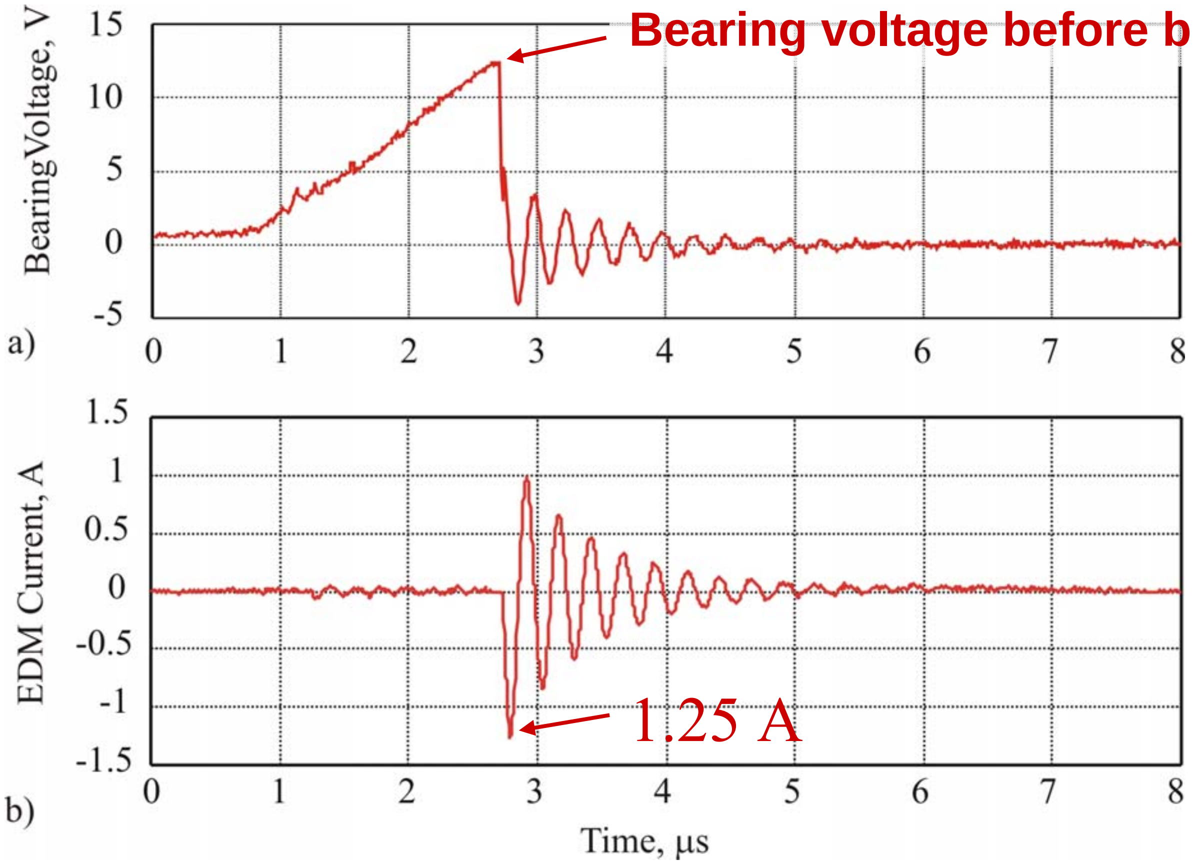


E_b > **15 kV/mm**

Electric discharge parasitic HF bearing currents $i_{b,EDM}$

Measurement of EDM current: Induction motor 240 kW

Bearing voltage (a) and EDM current (b) at a speed of **300 rpm** of the **240 kW induction motor, f_T = 4 kHz** switching frequency, DC link 600 V



$$\hat{u}_{\mathrm{b}} = 12.5\,\mathrm{V}$$

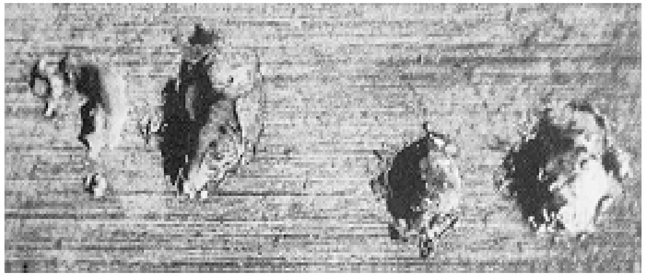
Lubricant thickness:
estimated for a typical threshold value of **15 kV/mm**

$$h_{\mathrm{c}} \cong 0.8\ \mu\mathrm{m}$$

$$\hat{i}_{\mathrm{b,EDM}} = 1.25\mathrm{A}$$

Effects of discharge bearing currents $i_{b,EDM}$

Discharge of lubricant film: Craters at race and ball surface



Crater due to short arcs

Source: SKF bearing catalogue, 1997

$$\hat{i}_b / A_{Hertz} < 0.3\,\text{A/mm}^2$$

Small currents $i_{b,EDM}$ ⇒ Small craters are usually levelled by the rolling elements, yielding a grey and stable race track

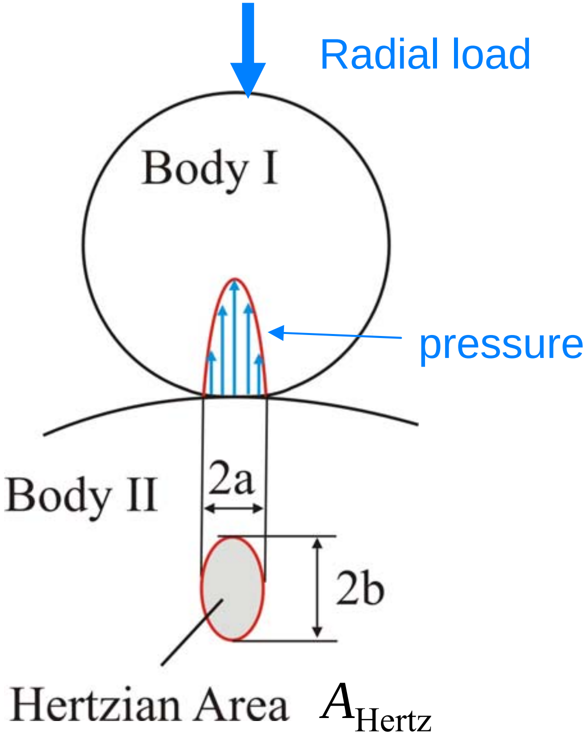
The lubricant is <u>not destroyed</u>

$$\hat{i}_b / A_{Hertz} > 0.6\,\text{A/mm}^2$$

Big currents $i_{b,EDM}$ ⇒ Bigger craters (Ø 1... 5 μm) may cause the rolling elements to "jump" over the crater rim, causing a "hitting pattern" (fluting) behind the craters.

Fluting of the race track in the loading zone of the bearing causes increased friction heat = over-heating of the lubricant, which <u>is destroyed</u>, leading to a bearing failure.

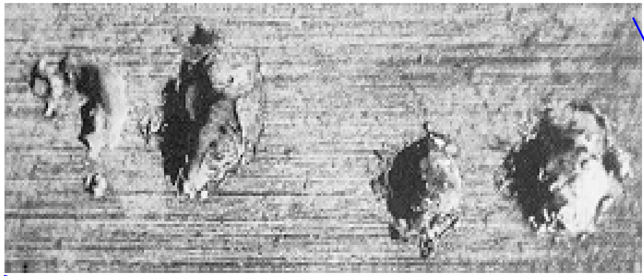
HERTZian area of elastic deformed roller element under radial load

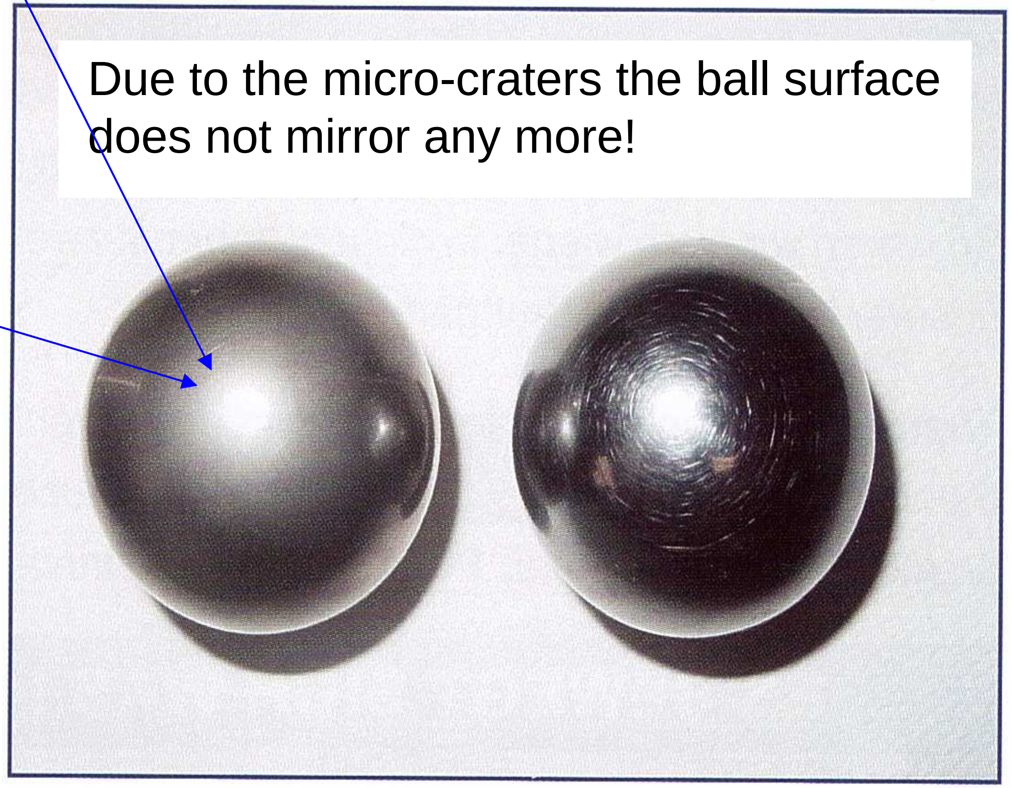


Apparent bearing current J_b:

$$J_b = \frac{\hat{i}_b}{A_{\mathrm{Hertz}}}$$

Micro-craters on the ball surface due to small arcs



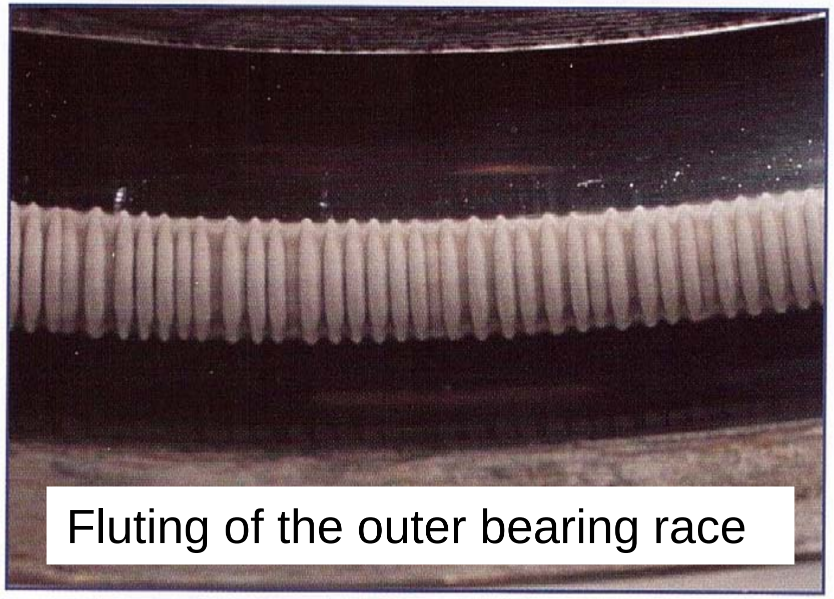


Ball with craters

Ball without craters

Source: Brenner, Bürstadt, Germany

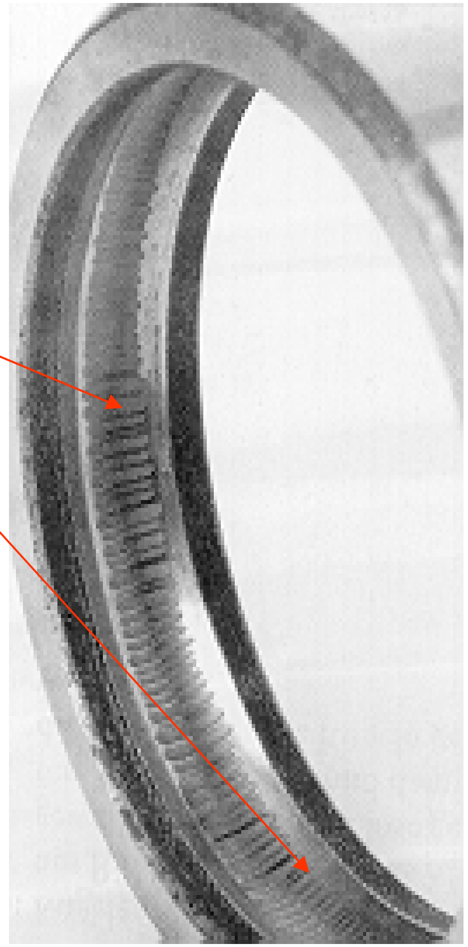
Fluting due to bearing current



Fluting of the outer bearing race

Source: Brenner, Bürstadt, Germany

Fluting
in the bearing
load zone



Source: SKF bearing catalogue, 1997

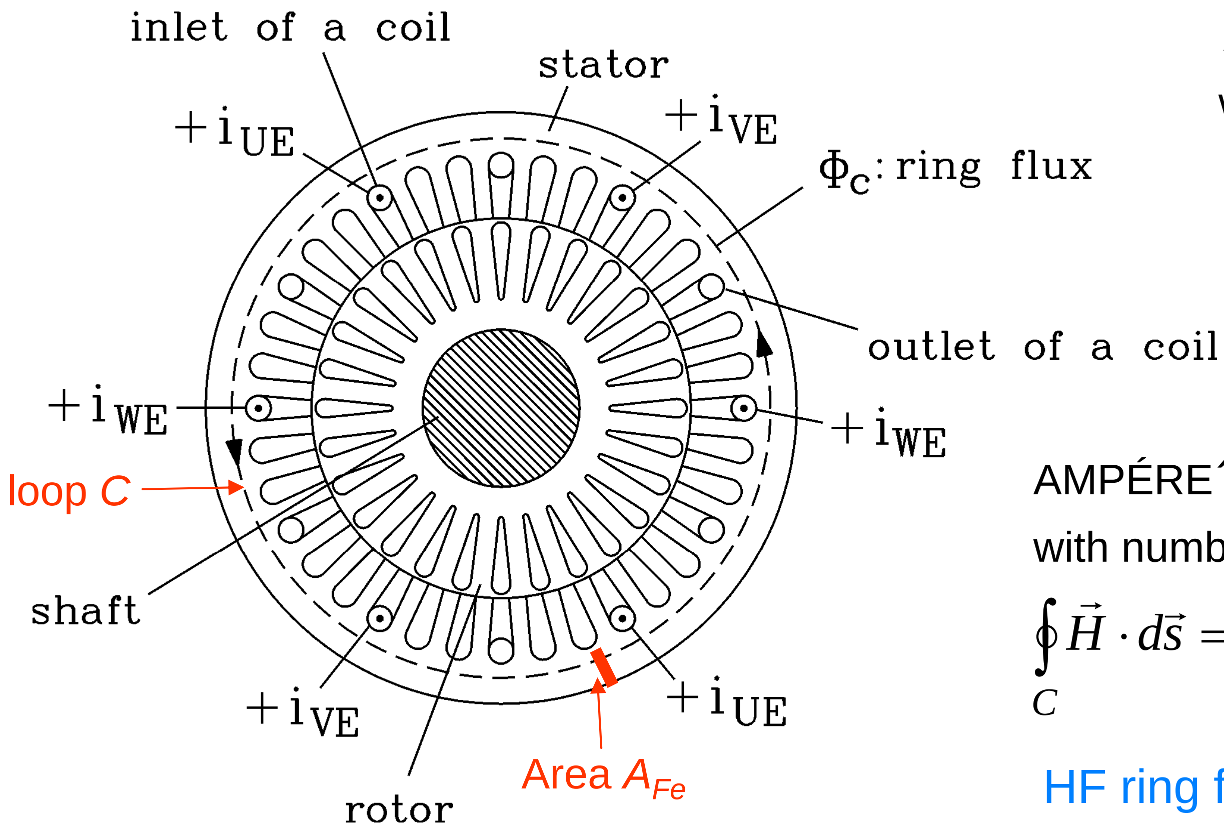
Darkened grease lubricant due to bearing current

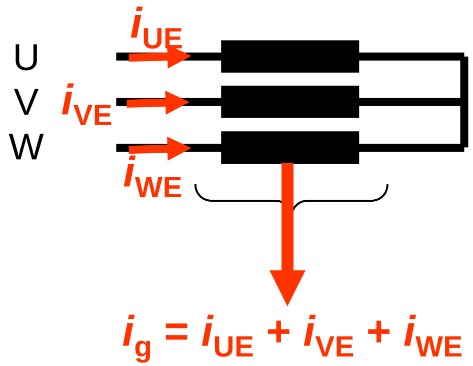
Blackened grease due to current flow

Source: Brenner, Bürstadt, Germany

HF common mode ring flux Φ_c

The rather big stator-to-ground current i_g as per phase i_{UE}, i_{VE}, i_{WE} excites a HF "ring flux" Φ_c around the shaft





AMPÉRE´s law along loop C:

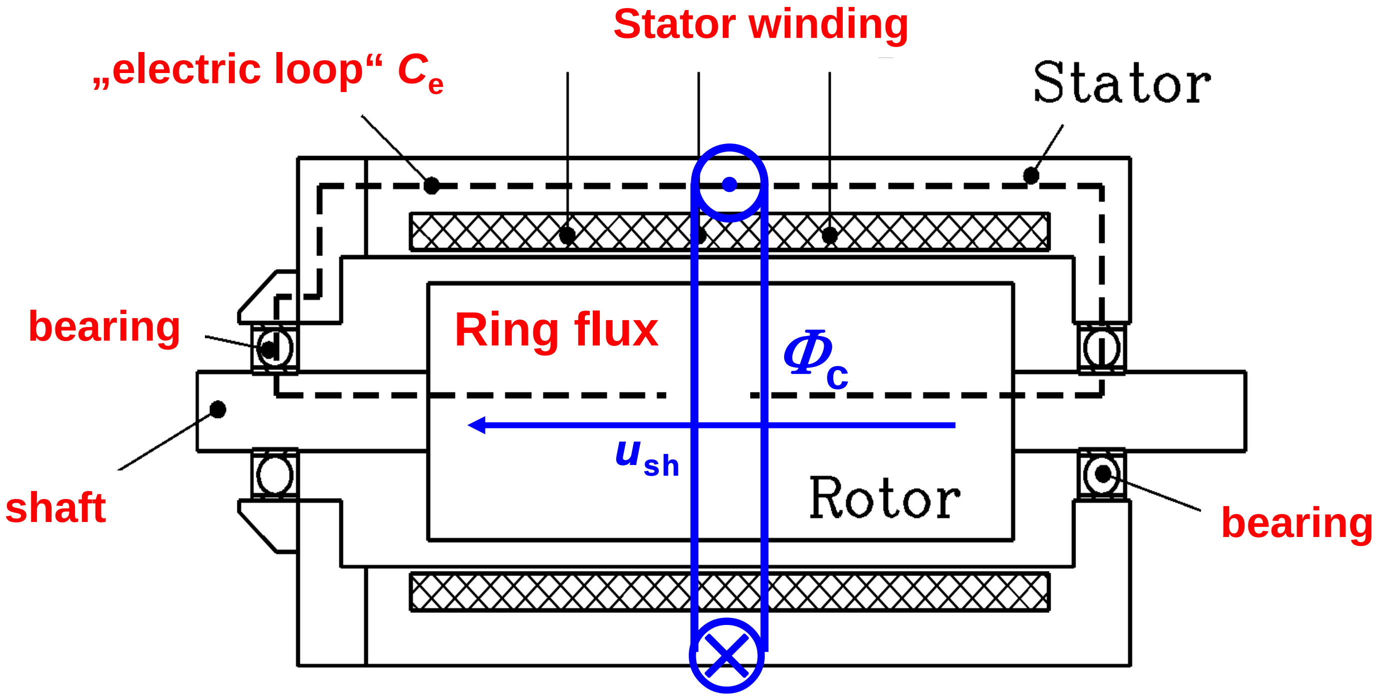
with number of turns N_s

$$\oint_C \vec{H} \cdot d\vec{s} = N_s \cdot (i_{UE} + i_{VE} + i_{WE})$$

HF ring flux: $\Phi_c(t) = \mu_{Fe} \cdot H(t) \cdot A_{Fe}$

e.g.: 4 poles, 3 phases, q = 3 slots per pole & phase

HF common mode ring flux Φ_c induces shaft voltage u_{sh}



FARADAY´s law along loop C_e: $u_{sh} = \oint_{C_e} \vec{E}_{sh} \cdot d\vec{s} = -d\Phi_c / dt$

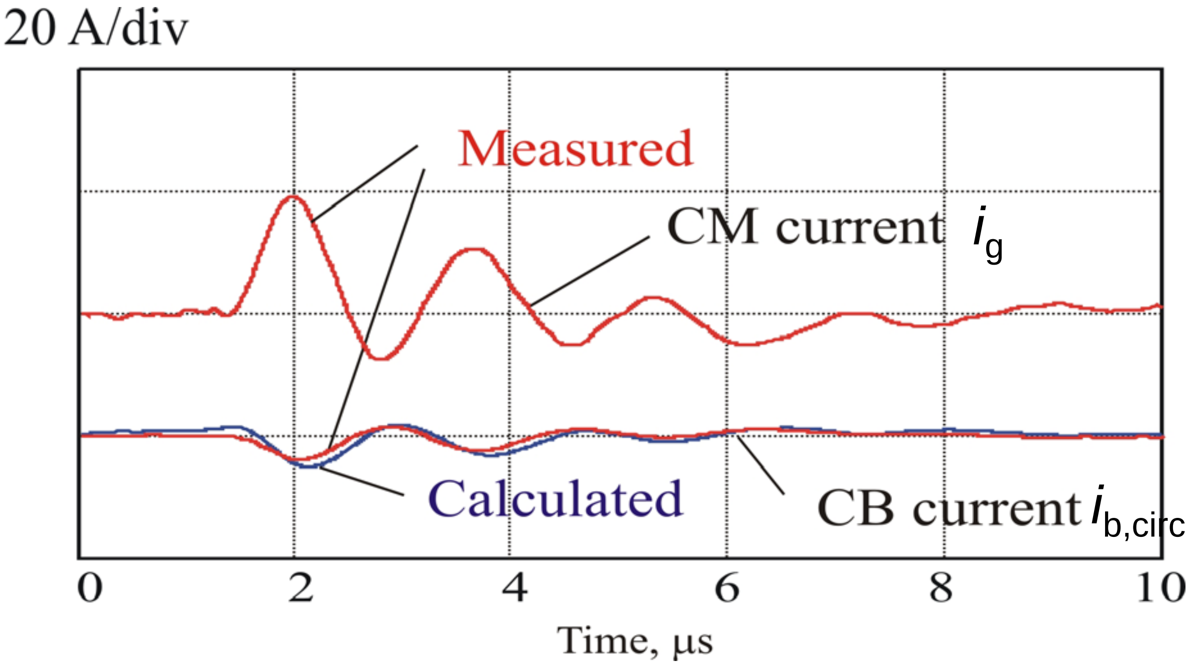
HF "ring flux" $\Phi_c(t)$ induces shaft voltage $u_{sh}(t)$ in the "loop" C_e of stator housing, bearings and rotor shaft

A circulating HF parasitic current $i_{b,circ}$ is driven by u_{sh} via the bearings!

Measured circulating HF bearing current $i_{b,circ}$

560 kW, 2 poles induction motor (s: stator, r: rotor, e: outer, i: inner)

$d_{se} = 680$ 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 series of the CM current waveform i_g is required to calculate $i_{b,circ}$

Sources:

A. Mütze & O. Magdun, PhD Theses, TU Darmstadt

The stator-to-ground current i_g and the circulating bearing current $i_{b,circ}$ have due to *Ampére´*s and *Faraday´*s law the same wave form!

Summary:
Parasitic HF currents

- Capacitive common mode cable current due to PWM inverter
- Common mode voltage and current may cause bearing current flow
- Capacitive, discharge and circulating bearing currents

High frequency effects in inverter-fed AC electric machinery

1 Voltage wave reflections at motor terminals

2 HF voltage distribution in armature winding

3 Insulation stress of AC winding at inverter supply

4 Parasitic HF currents

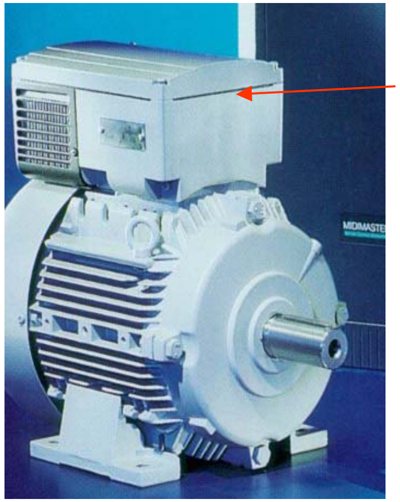
5 System design of inverter drives coping with big du/dt

Short motor cable length to avoid voltage reflection

Combined inverter-induction motors

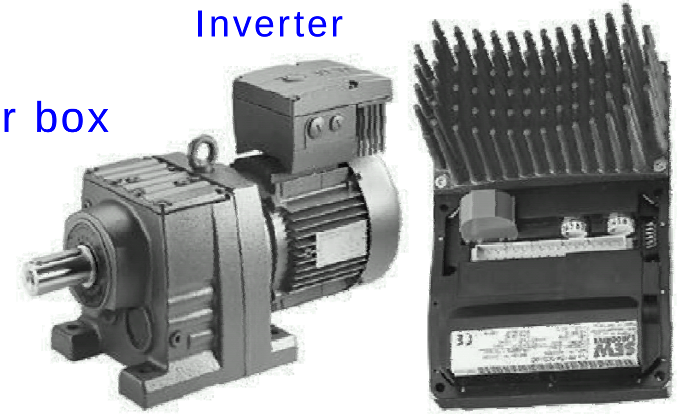
- Inverter on top of the motor (at the terminal box)
- Possible for small inverter power ratings (typically below 20 kVA)
- Short cable length between inverter and motor
- No extra inverter installation necessary (plug-and-play)

BUT: Increased vibration and heat loading for the inverter



Source: Siemens AG

7.5 kW, 4-pole cage induction motor



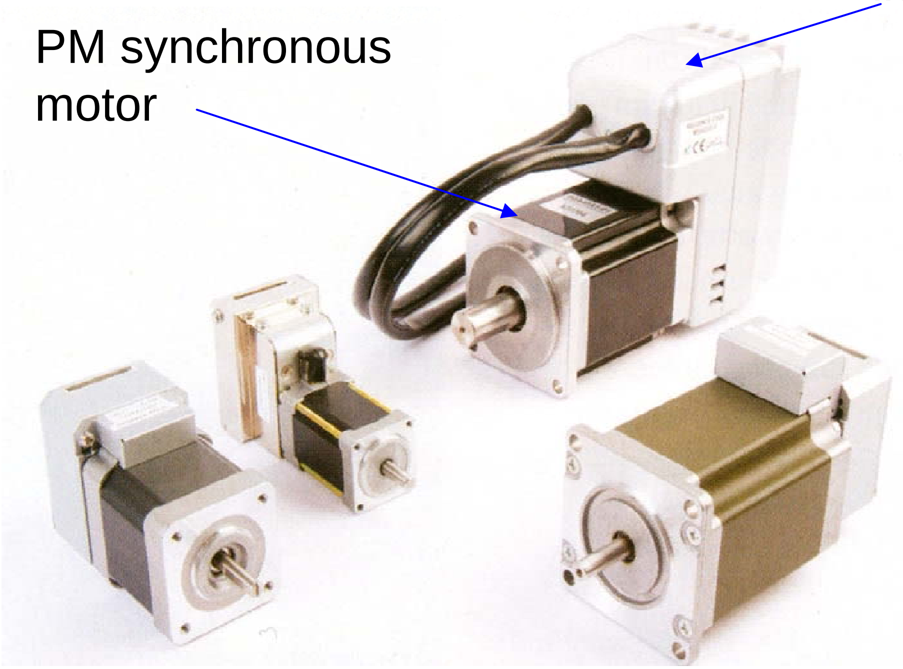
Source: SEW Eurodrive, Bruchsal, Germany

Combination of motor, inverter and gear box

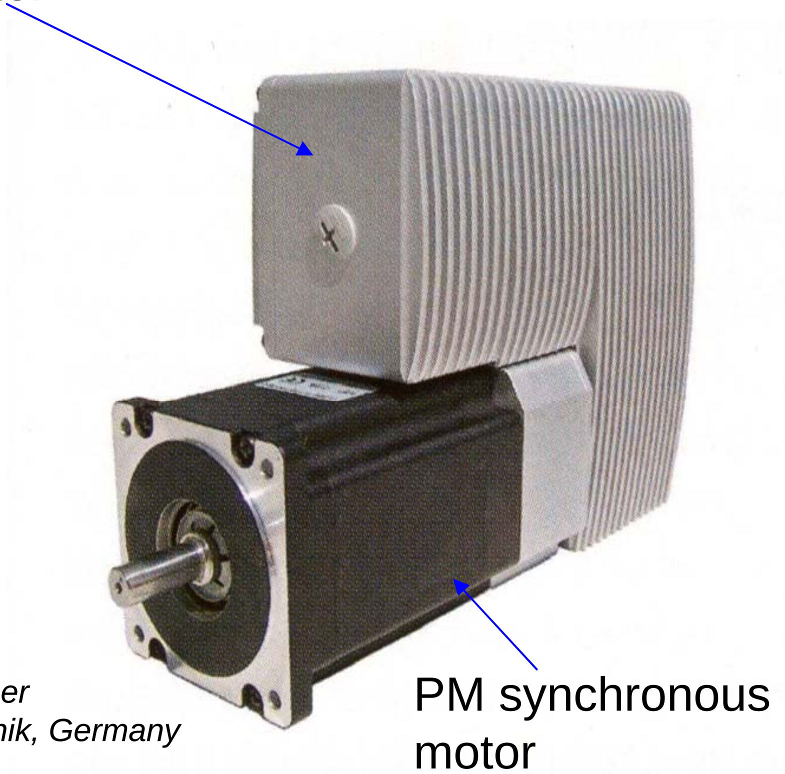
PM synchronous servo motors with integrated inverter

Combined inverter-PM synchronous motors

- Inverter with DC link as input, so DC bus with only two terminals



Source: Reliance Motors, UK



Source: Jenaer Antriebstechnik, Germany

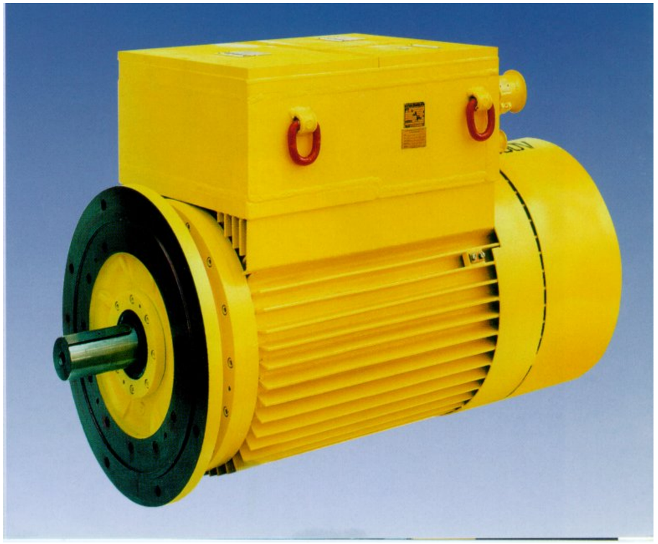
Size limit of combined inverter-motors

Motor size determined by torque

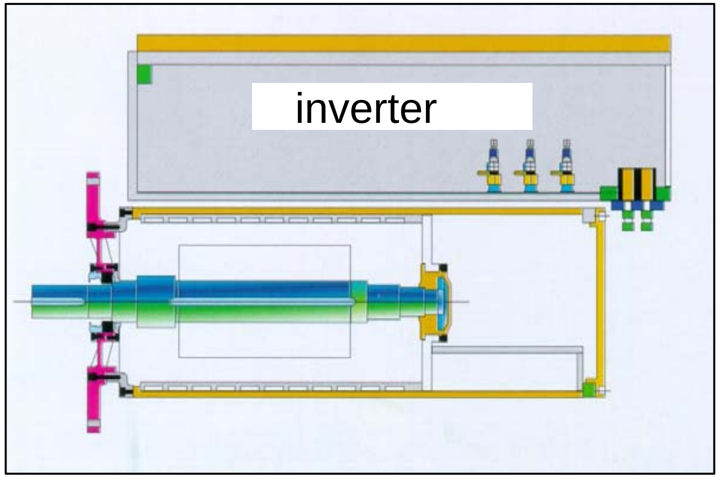
Inverter size determined by power

→ Low speed motors are big at small power, allowing a good integration of the small inverter into the big motor

→ High speed: Small motors at big power rating do not allow a good inverter-motor combination



22 kW integrated inverter motor

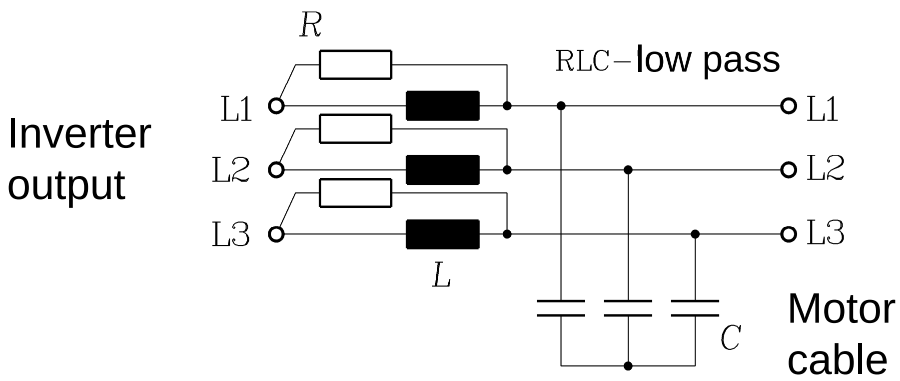


Source: Breuer, Germany

Reducing d*u* / d*t*-effects for motor insulation stress via inverter output filter

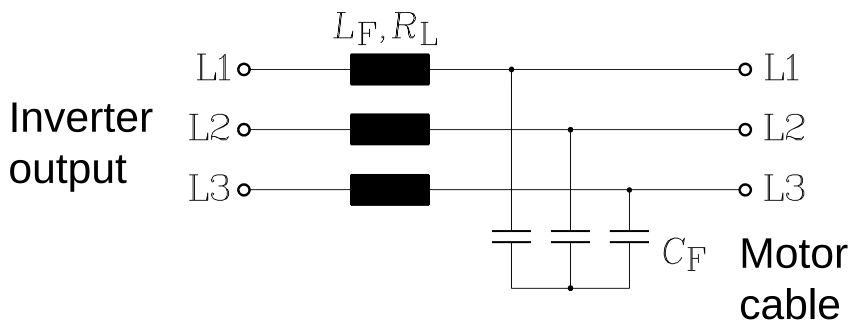
d*u*/d*t*-filter

L-*C*-combination with resonance frequence
ABOVE double switching frequency $f_{res} > 2f_T$
⇒ Steep *du*/*dt*-slopes reduced
⇒ Current switching ripple still active
(magnetic noise, add. losses, …)



sine-wave filter

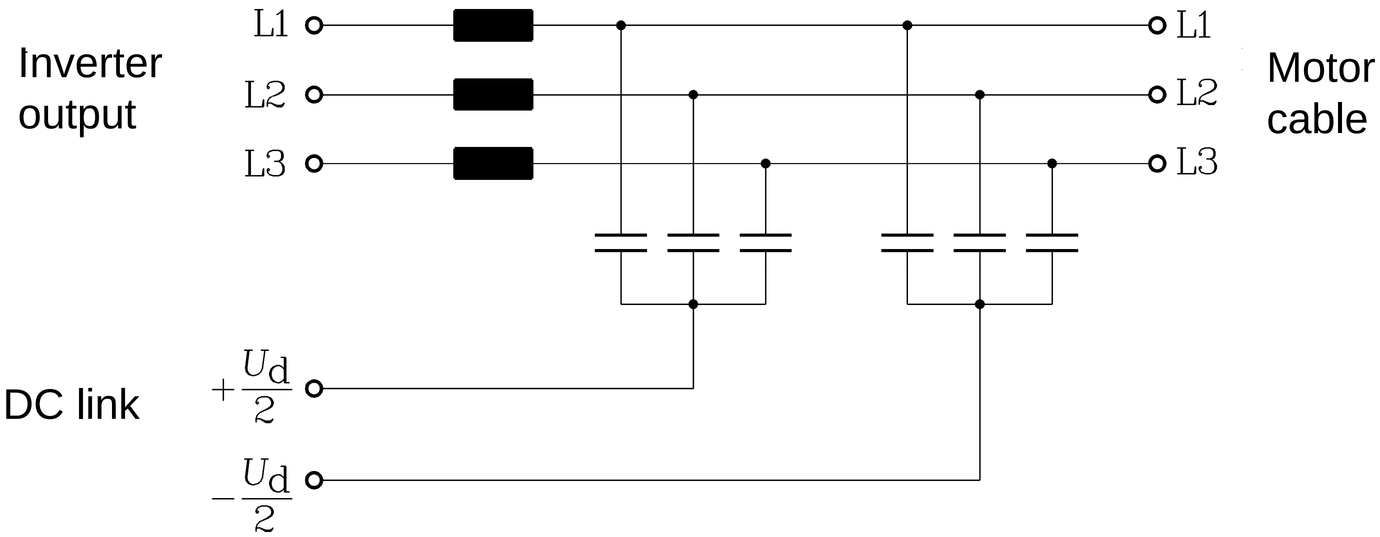
L-*C*-combination with resonance frequence
above fundamental frequency $f_{res} > f_s$
⇒ Nearly sinusoidal line-to-line voltage
⇒ Current switching ripple removed
BUT: Much bigger size than d*u*/d*t*-filter,
more expensive



These filters do not suppress the common mode voltage u_0!

Reducing the inverter common mode voltage u_0 via inverter output filter

- *L*-*C*-combination low pass filter with direct connection to the DC link to suppress the common mode harmonics
- Usually only for small power ratings available



This filter reduces all parasitic HF current effects in the motor, as the common mode voltage u_0 is reduced!

Measures to cope with HF parasitic motor currents

Bearing current type	*EDM current*	*Circulating current*	*Rotor-to-ground current*
dominantes at	**Small motors: Frame size ≤ (132...160) mm**	**Bigger motors: Frame size ≥ (200...280) mm**	**Caused by low-impedance rotor grounding**
Motor cable: shielded or unshielded?	**No influence**	**Shielded: Increases circulating currents slightly**	**Shielded (= stator ground path): strong rotor ground current reduction**
CM voltage rejection filter	**Complete annihilation**	**Complete annihilation**	
du/dt-Filter, sine wave filter, CM HF current chokes	**No influence**	**Current reduction by (30 ... 90) %**	
Electrostatic shielding of stator winding	**Strong reduction**	**No influence**	
Low-impedance grease	**Strong reduction**	**Increase of bearing current**	
One insulated bearing	**Reduction there by (40...60) %**	**Reduction by 60 % … 80 %**	
Hybrid bearings	**Complete annihilation**	**Complete annihilation**	
Shaft grounding brush	**Strong reduction**	**By-pass for bearing current; check overload of brush**	

High frequency effects in inverter-fed AC electric machinery

Summary:
System design of inverter drives coping with big d*u* / d*t*

- Many system parameters influence the HF performance
  - Grounding system (low impedance?)
  - Stator vs. rotor grounding (e.g. roller mill)
  - Cable shielding (grounding, EMI, …)
- Filter technologies for Differential Mode and Common Mode voltages and currents available (limit for power ratings, additional costs)
- Motor design for low d*u*/d*t*-voltage stress = high partial discharge inception voltage
- Motor design for low bearing currents (small motors: no circulating currents!)
- Low impedance grease and one insulated bearing as a good combination for reducing EDM and circulating currents

That´s all, folks !

Thank you for your attention!