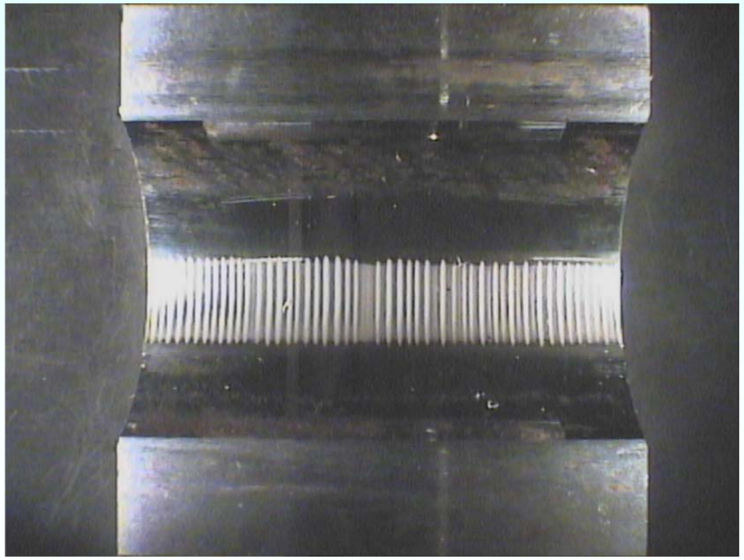
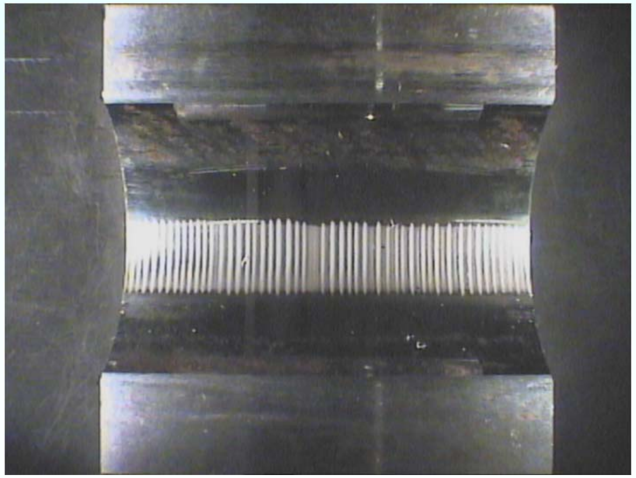
6. d*u*/d*t*-effects in inverter-fed machines



Source:
A. Mütze, PhD Thesis,
TU Darmstadt

6. d*u*/d*t*-effects in inverter-fed machines

6.1 Voltage wave reflections at motor terminals



Source:
A. Mütze, PhD Thesis,
TU Darmstadt

Fast voltage change rates *du/dt*

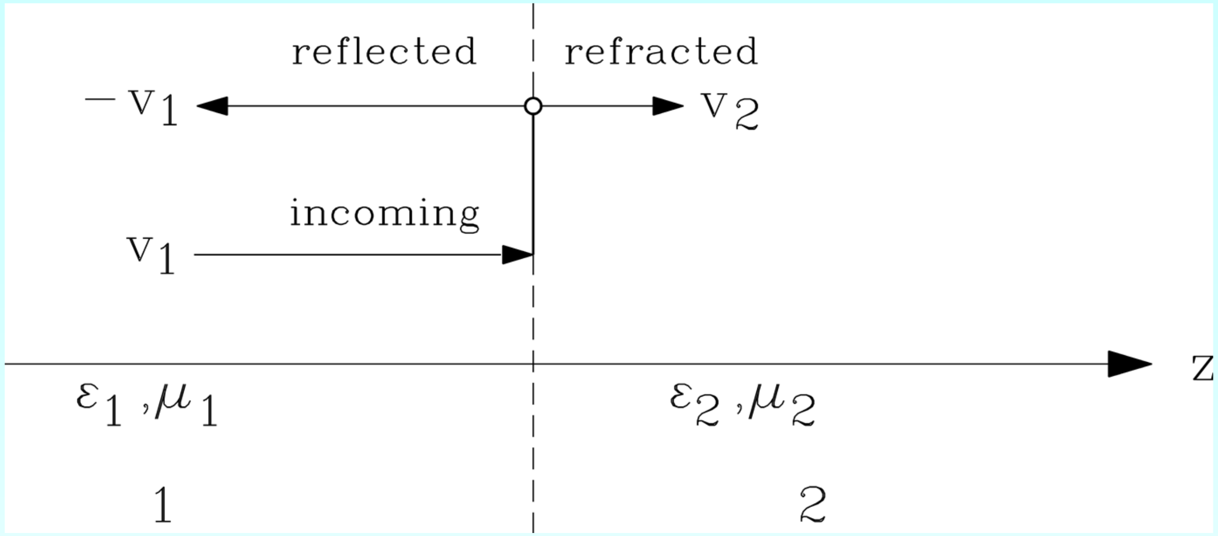
- Fast switching IGBT inverters: short **voltage rise time** t_r between zero and dc link voltage 100 ns: $du/dt \cong U_d/t_r$

Line supply	*dc link voltage*	$du/dt \cong U_d/t_r$
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 !**

Voltage wave reflection at motor terminals



Motor cable: low wave impedance Z_{cable} Motor winding: high wave impedance Z_{mot}

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

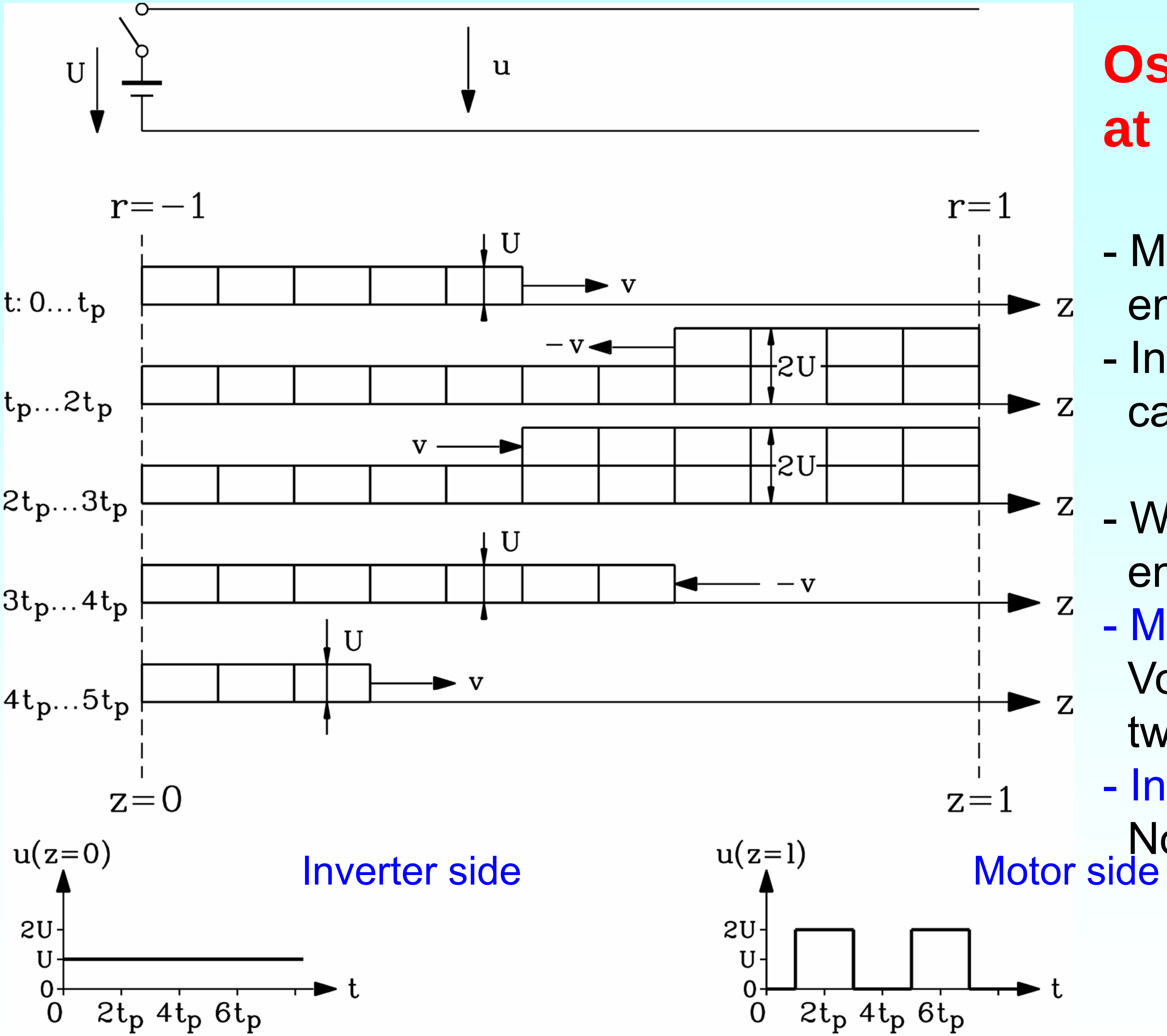
Positive voltage wave reflection at motor terminals: voltage increase

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

Inverse voltage wave reflection at inverter, because dc link capacitor is HF short circuit

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

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
- Motor side:
  Voltage oscillation with twice dc link voltage
- Inverter side:
  No oscillation

Motor cable parameter

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: $\varepsilon_r = 4$

Phase inductance per unit length: $L'_{cable} = \frac{\mu_0}{2\pi} \cdot \left(\ln(2a/d) + 0.25\right) = 0.4\mu\,\mathrm{H/m}$

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

Cable wave impedance: $Z_{cable} = \sqrt{\frac{L'_{cable}}{C'_{cable}}} = \underline{\underline{56.6}}\,\Omega$ (measured: 83 Ω)

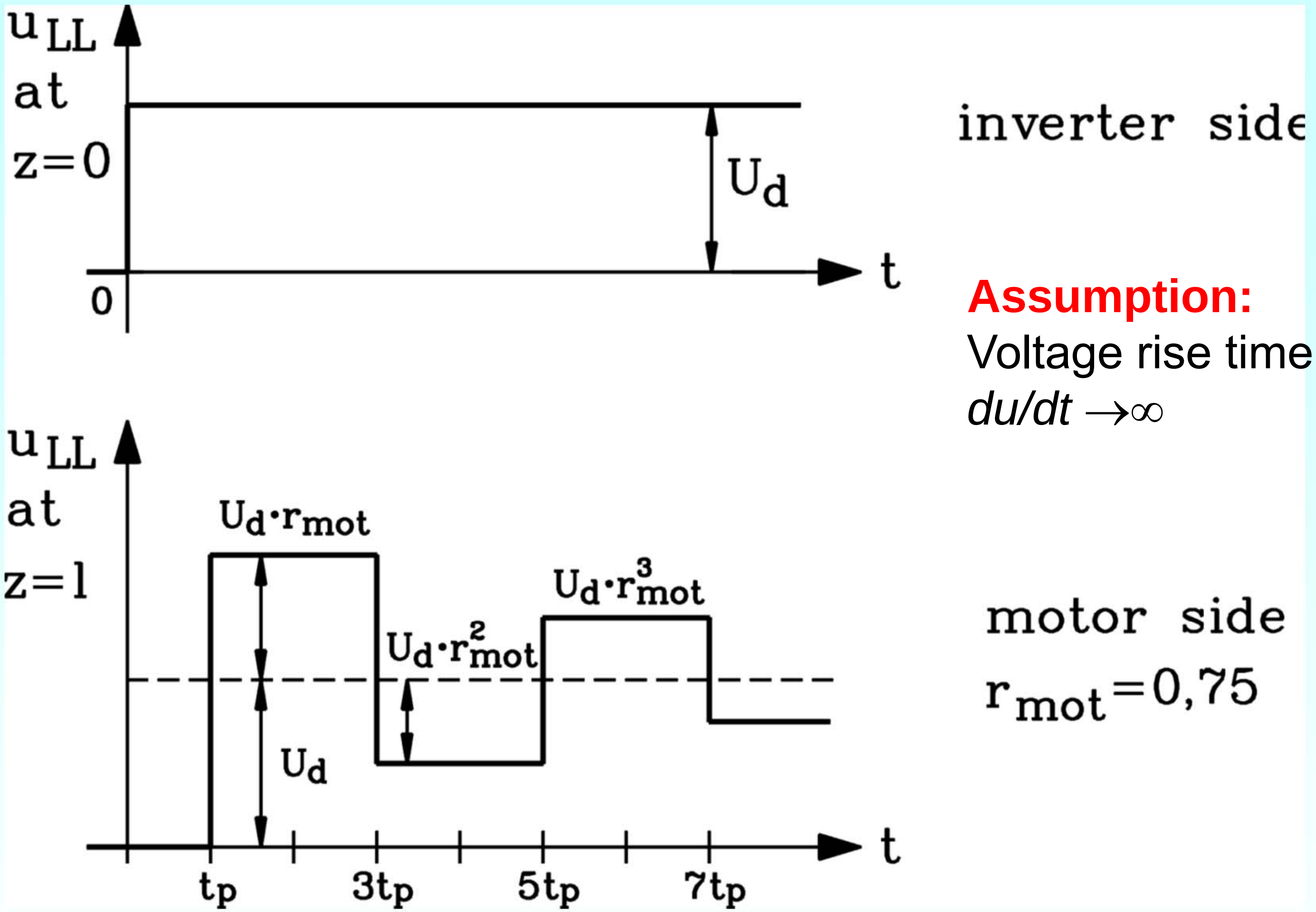
Wave velocity : $v = \frac{1}{\sqrt{L'_{cable} C'_{cable}}} = \underline{\underline{141 \cdot 10^6}}$ m/s ≈ 150 000 km/s

dc link voltage 560 V, motor reflection coefficient $r_{mot} = 1$.

Line to line over-voltage at motor terminals: $\hat{U}_{LL,mot} = (1 + r_{mot})U_d = 2 \cdot 560 = \underline{\underline{1120}}\,\mathrm{V}$

Wave propagation time: $t_p = l_c / v = 100/(150 \cdot 10^6) = 0.67\,\mu\mathrm{s}$, $1/(4t_p)$= **375 kHz**

Motor reflection r < 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 cable (loss-free cable) with reflection coefficient r_{mot} = 0.75 on motor side and r_{inv} = –1 at inverter side.

Voltage rise time neglected.

Influence of motor size on reflection coefficient

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

Motor impedance is determined by $Z_{mot} = \omega\sigma L_s$. With $L_s \sim N_s^2$ motor impedance decreases with increased motor size. Motor size: ↑, N_s ↓ for the same rated voltage.

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 5000 Ohm.
- Motor cable 4 x 1.5 mm², Type H05VVF4G1.5: current density: $J = 2.1/1.5 = 1.4$ A/mm², wave impedance 83 Ohm.

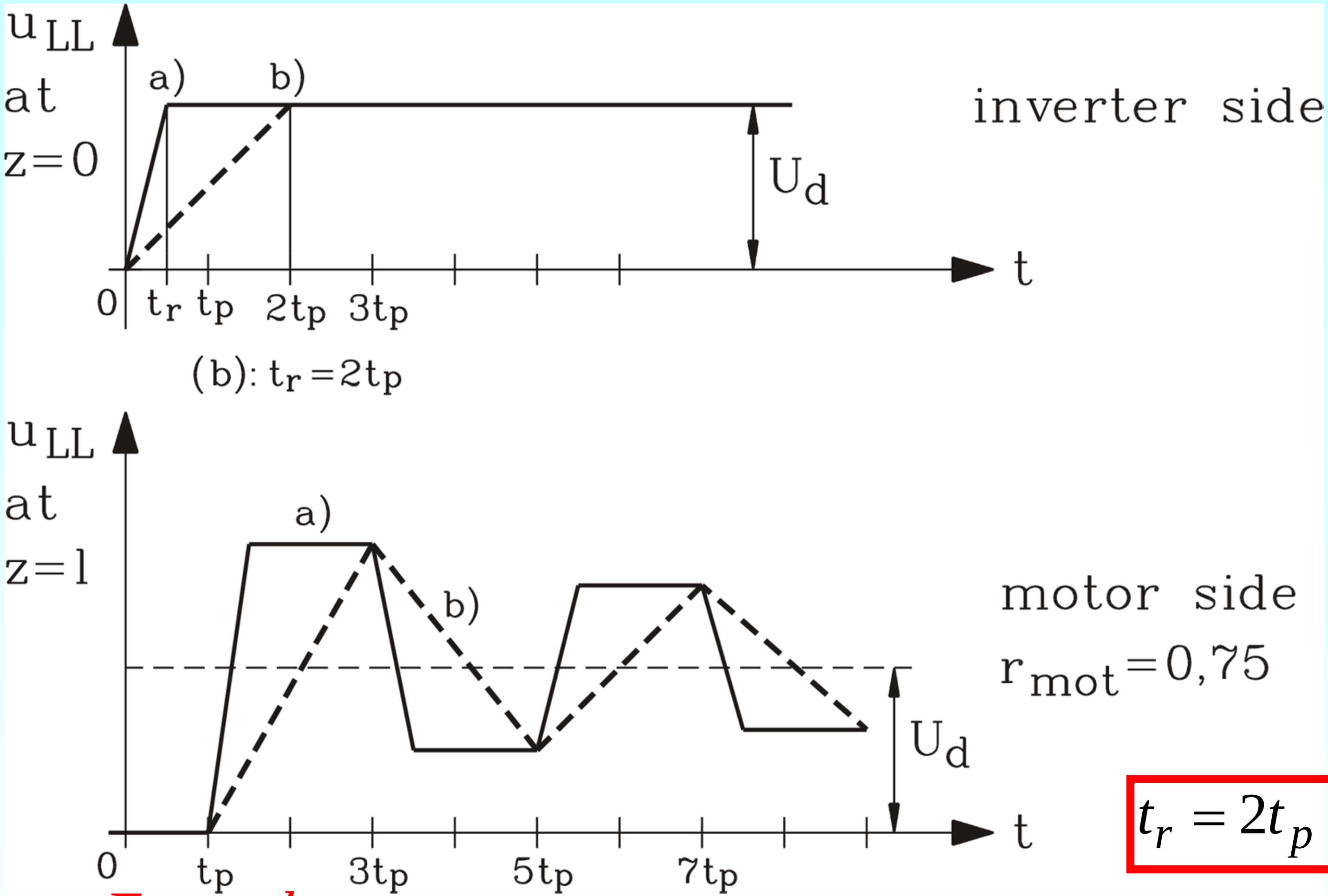
Motor reflection coefficient: $r_{mot} = \frac{5000-83}{5000+83} = \underline{\underline{0.967}}$

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 ($du/dt \cong U_d/t_r$)



- 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 $t_r < 2t_p$: Wave propagation "visible" !
- Shorter cables lead to reduced voltage overshoot: as $t_r > 2t_p$.

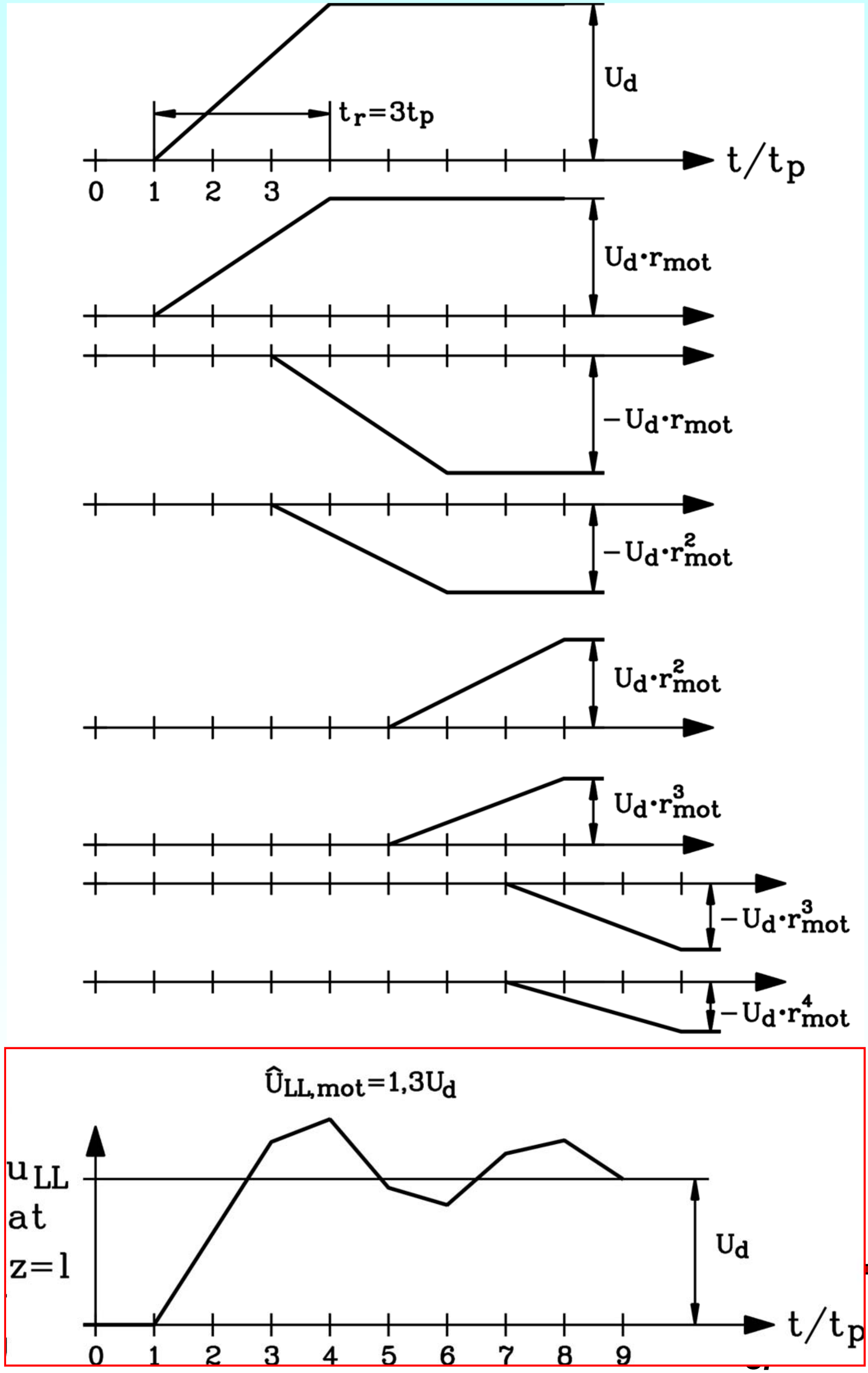
$$t_r = 2t_p = 2 \cdot l_c / v \quad \Rightarrow \quad l_{c,crit} = v \cdot t_r / 2$$

Example:

Wave velocity in cable $v = 150 \cdot 10^6$ m/s, IGBT-inverter rise time: $t_r = 200$ ns:

Critical cable length $l_{c,crit} = v \cdot t_r / 2 = 150 \cdot 10^6 \cdot 200 \cdot 10^{-9} / 2 = \underline{\underline{15}}$ m

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

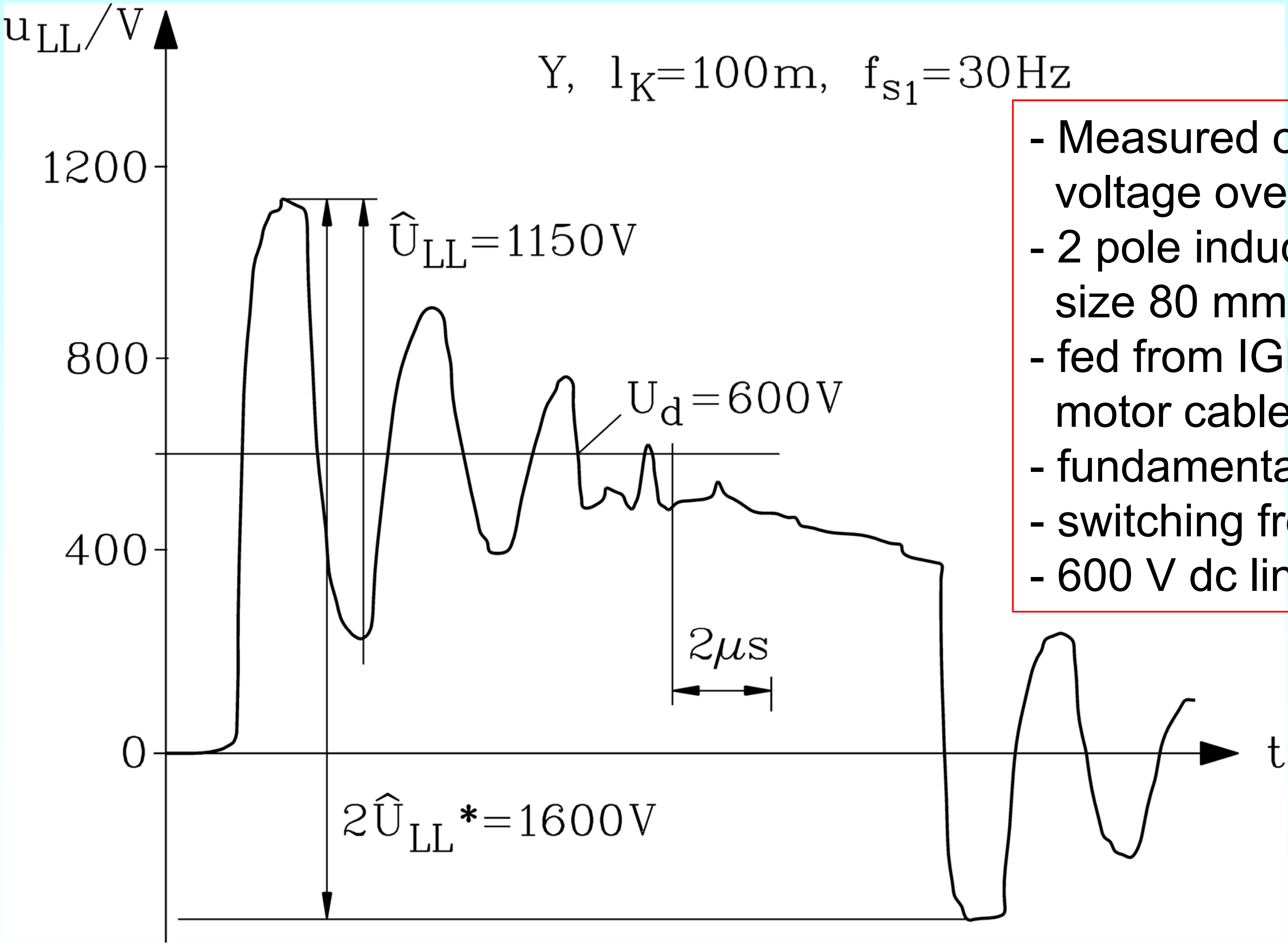


- Oscillating voltage overshoot at motor side due to wave reflection
- Does not reach its worst-case maximum value $(1+r_{mot})U_d = 1.75U_d$, but only $1.3U_d$, as $t_r > 2t_p$!

Example:

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

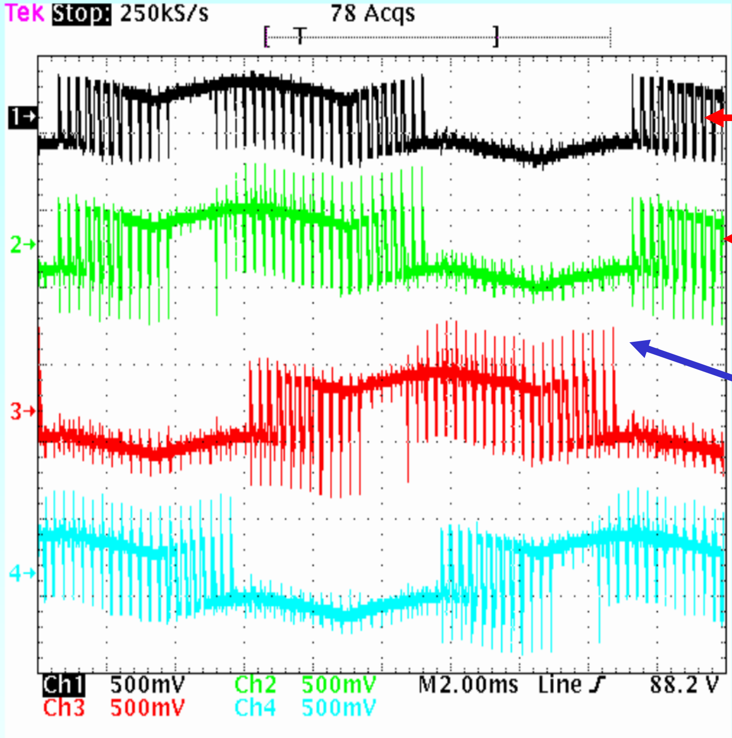
Measured voltage reflection at long cable $l > l_{c,crit}$



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

Source: Siemens AG

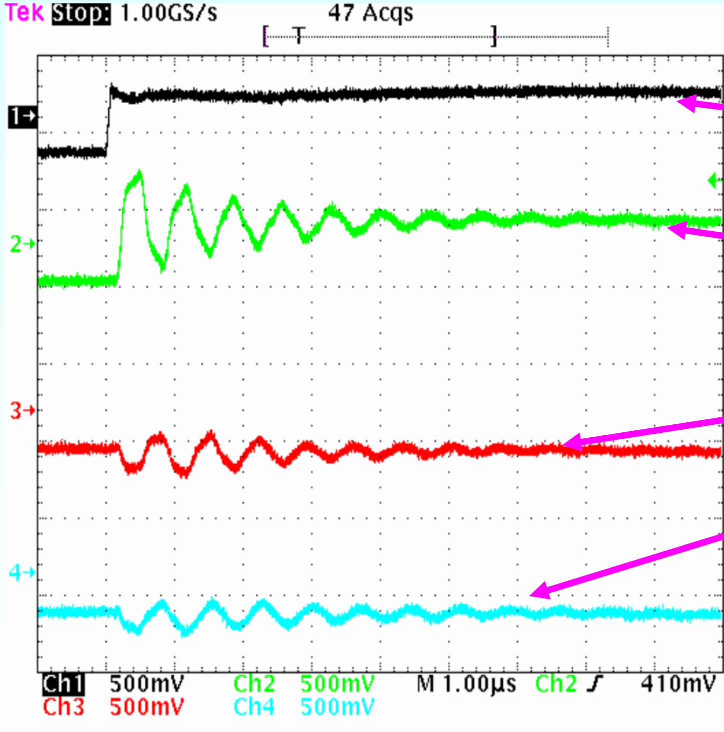
Measured voltage reflection at long cable $l > l_{c,crit}$



Inverter output voltage

Motor terminal voltage

Reflection



Inverter output voltage U-V

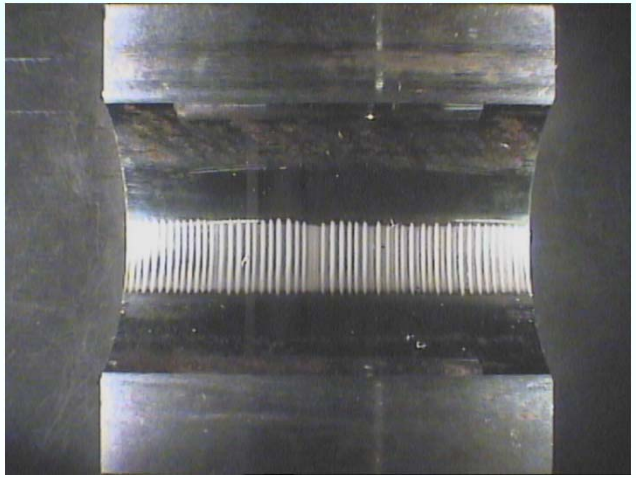
Motor terminal voltage U-V

V-W

W-U

Source: Siemens AG

6.2 HF voltage distribution in armature winding

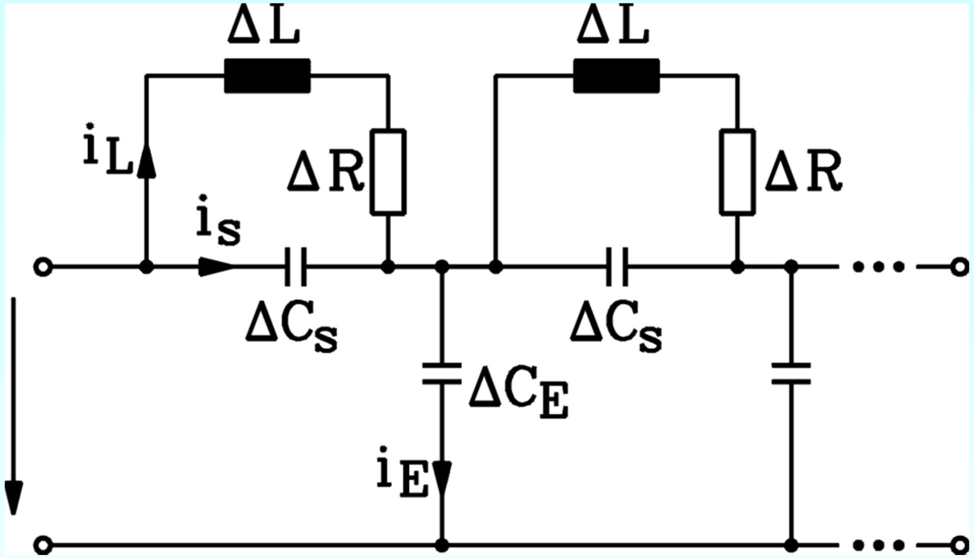


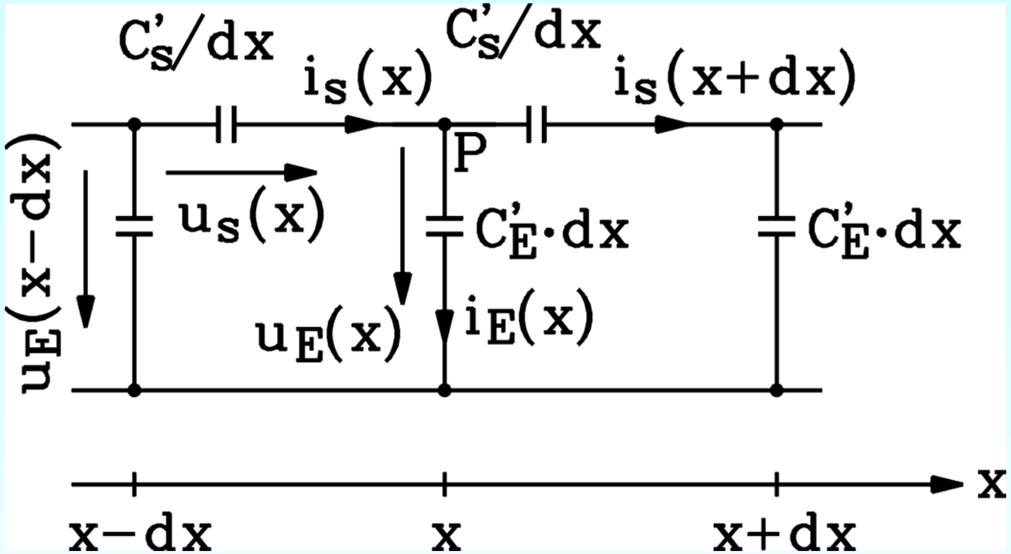
Source:
A. Mütze, PhD Thesis,
TU Darmstadt

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





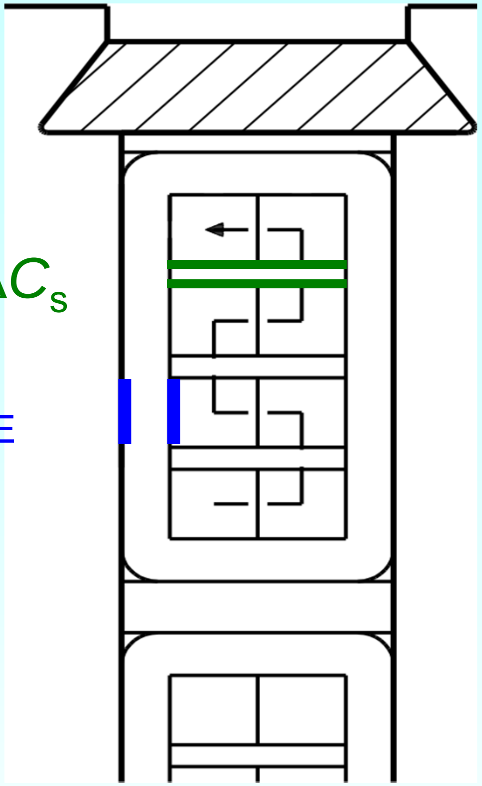
Ground current: $\int i_E(x) \cdot dx / l = i_g$

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.

Usually $\Delta C_E < \Delta C_s$. For HF the inductance gives an “infinite” impedance !

Capacities in the stator winding

Usually $\Delta C_E < \Delta C_s$



Per turn: - series capacitance ΔC_s

Per turn: - line-to-earth capacitance ΔC_E

- 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** $C_s = \Delta C_s / N_s$

$$\Delta C_E = C'_E \cdot \Delta x$$
$$\Delta C_s = C'_s / \Delta x$$

$$\frac{C'_E}{C'_s} = \frac{\Delta C_E}{\Delta C_s} \cdot \frac{1}{\Delta x^2} > 1$$

$$\gamma = \sqrt{\frac{C'_E}{C'_s}} = \sqrt{\frac{\Delta C_E}{\Delta C_s} \cdot \frac{1}{\Delta x}}$$

Although $\Delta C_E < \Delta C_s$, the parameter γ is due to $1/\Delta x$ a big value!

Non-linear voltage distribution at “voltage impulse”

Differential equation for line-to-earth voltage u_E :

$$\frac{d^2 u_E(x)}{dx^2} - \frac{C'_E}{C'_s} u_E(x) = 0$$

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

Solution:

$$u_E(x) = U_d \cdot \frac{\sinh(\gamma \cdot (l-x))}{\sinh(\gamma \cdot l)} \qquad \gamma = \sqrt{C'_E / C'_s} \qquad \text{unit } [\gamma] = 1/m$$

Example:

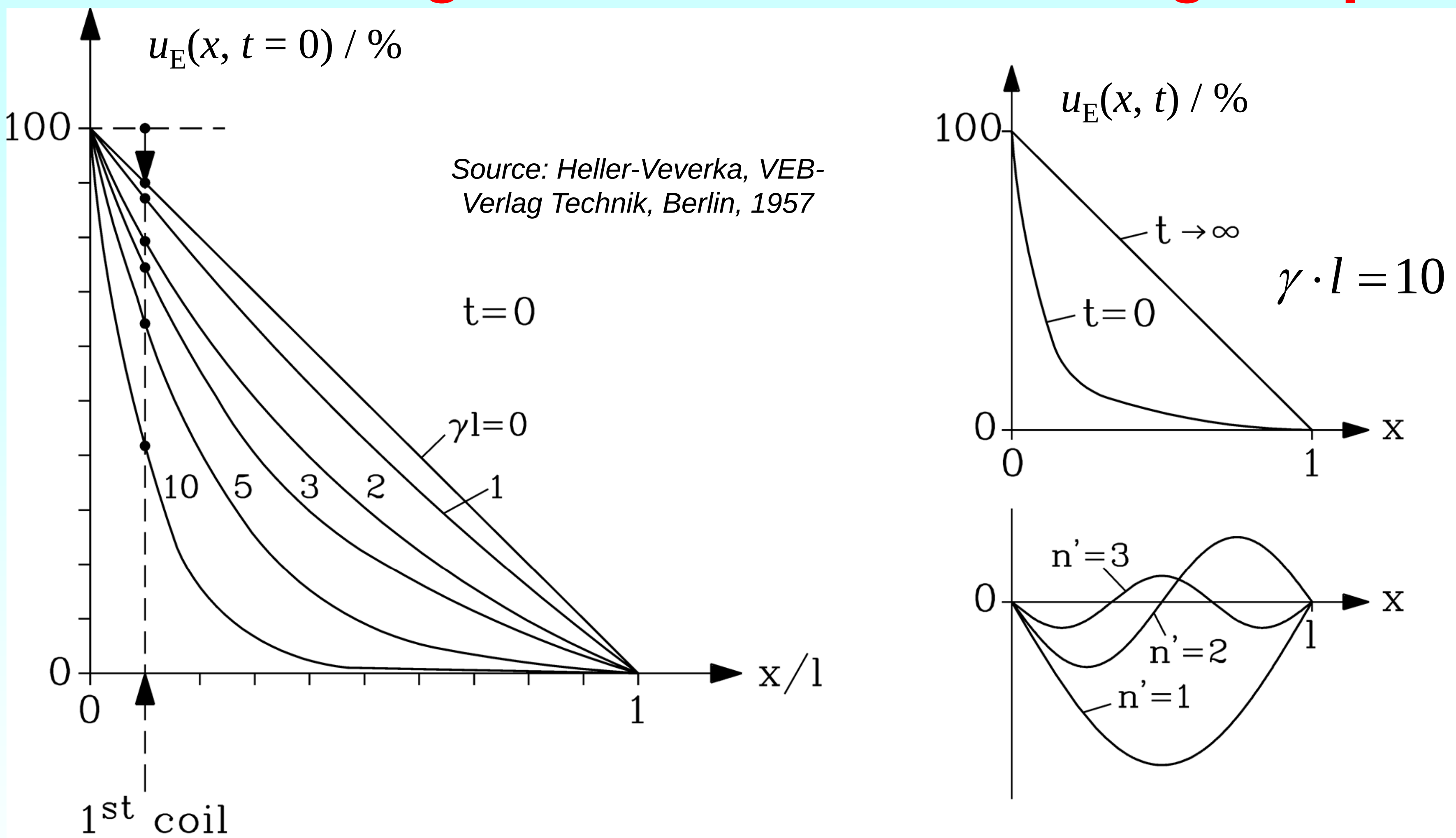
Star connected winding, n = 5 coils per phase, 2n = 10 coils line-to-line, $\gamma \cdot l = 8$.

U_d = 600 V, Coil voltage $u_{s,12} = u_{E(1)} - u_{E(2)}$

First coil stress: 330/600 = 55% of total voltage !

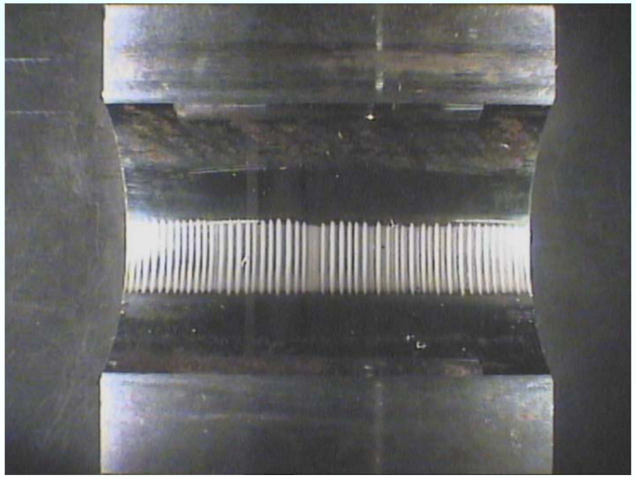
x/l	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
u_E / V	600	270	121	54	24	11	5	2.2	1	0.4	0
u_s / V	-	330	149	67	30	13	6	2.8	1.2	0.6	0.4
Number of coil		1.	2.	3.	4.	5.	6.	7.	8.	9.	10.

Non-linear voltage distribution at "voltage impulse"



- Voltage distribution shortly after applying the voltage step is only determined by winding capacities
- Winding inductance, capacitance, resistance cause a voltage oscillation, which starts at non-linear distribution $u_E(x, t = 0)$ and ends at linear distribution $u_E(x, t \to \infty)$

6.3 Insulation stress of AC winding at inverter supply



Source:
A. Mütze, PhD Thesis,
TU Darmstadt

Insulation stress of AC winding at inverter supply

Each voltage impulse may cause small spark ignition at weak points
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.

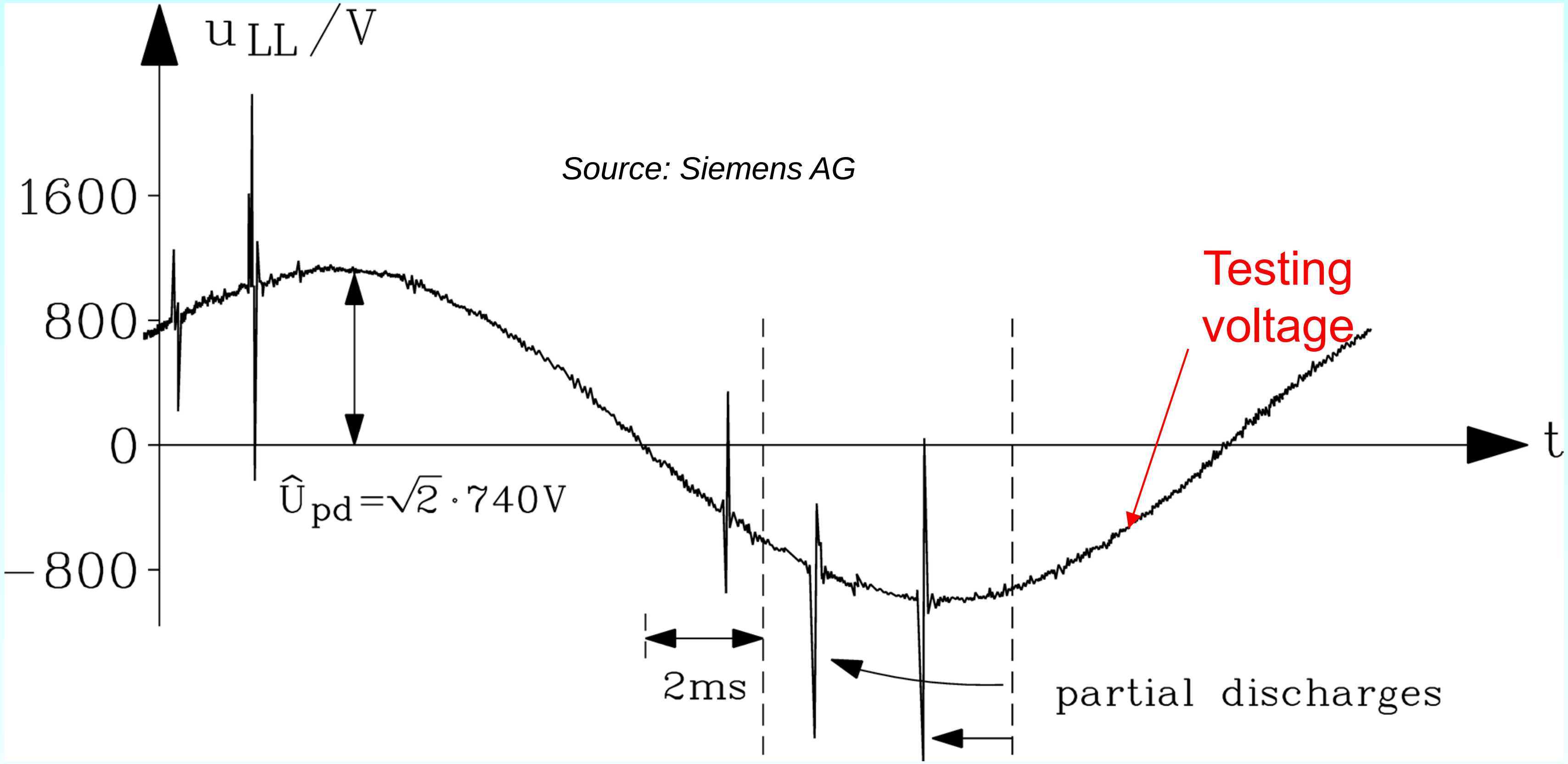
$$\frac{\hat{U}_{LL,mot}}{\hat{U}_N} \cong \frac{2U_d}{U_d} = 2.0 \qquad 2U_d = 2 \cdot 560 = \underline{1120\ \text{V}}$$

PD inception voltage decreases with increasing winding temperature by about 4 V/K.
Thermal Class F motor = 150°C winding temperature: **needs at 20°C a PD inception voltage (r.m.s.) of about** $U_{pd} = 1200$ **V to be safe at 150°C.**

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

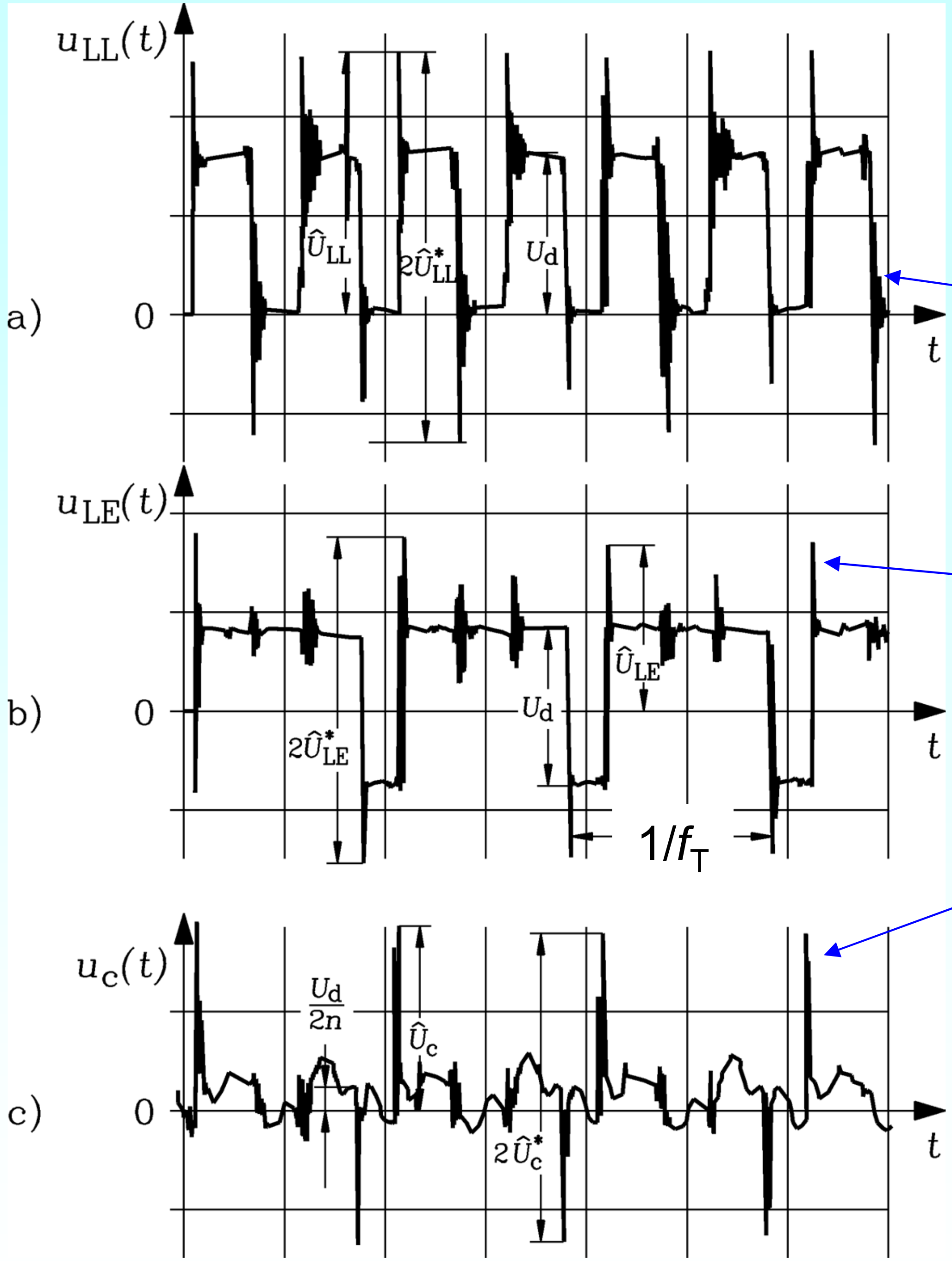
$$150°C : U_{pd} = 1700 - 4 \cdot (150 - 20) = 1180V \geq \hat{U}_{LL,mot} = 1120V$$

Partial discharge test of stator winding



- 2-pole 400V Y, 50 Hz, synchronous reluctance motor at 20°C:
- A sinus 50 Hz line-to-line voltage with variable amplitude between the non-connected phases U, V, W is applied.
- Spark discharge currents flow as HF spikes from one phase to the other.
- Via a HF capacitor this current flow may be detected and is made visible as additional HF voltage, superimposed on the testing voltage.

Measured motor voltages at PWM IGBT-inverter operation



Line-to-line voltage

Hentschel E, Niedermeier K, Schäfer K (1993) Beanspruchung der Wicklungsisolierung von Drehstrommaschinen. Elektrotechn. Zeitschrift etz Vol. 114 No. 7: 1074-1077

Line to earth voltage

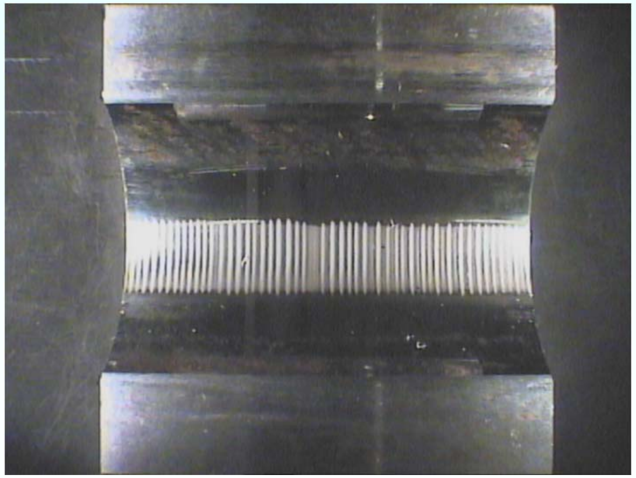
Voltage drop at first coil per phase (*n* coils per phase).

- 400 V Y-motor at dc link voltage 600 V
- 30 m cable length between motor and inverter

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
Amplitude motor line-to-line voltage	$\hat{U}_{LL} = (1 + r_{mot}) \cdot U_d$	1130 V	1420 V
Amplitude of line-to-earth voltage	$\hat{U}_{LE} = (0.5 + r_{mot}) \cdot U_d$	850 V	1060 V
Amplitude of pulse frequent AC line-to-line voltage	$\hat{U}^*_{LL} = (0.5 + r_{mot}) \cdot U_d$	850 V	1060 V
Amplitude of pulse frequent AC line-to-earth voltage	$\hat{U}^*_{LE} = (0.5 + r_{mot}) \cdot U_d$	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	365 V 790 V

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



Source:
A. Mütze, PhD Thesis,
TU Darmstadt

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

a) Increased voltage stress of motor winding:

- Improving motor insulation
- Filter combination at inverter output: **d*u*/d*t*-filters**, **sine wave filters**
- Add-on benefit: **Electromagnetic interference (EMI)** is reduced !
- BUT: Filters are expensive.

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

b) Capacitive motor cable currents i_C:

Especially with long cables above 30 ... 50 m the cable capacity and the reactive cable current spikes are big. **Inverter output chokes** reduce these current spikes.

c) Motor bearing currents:

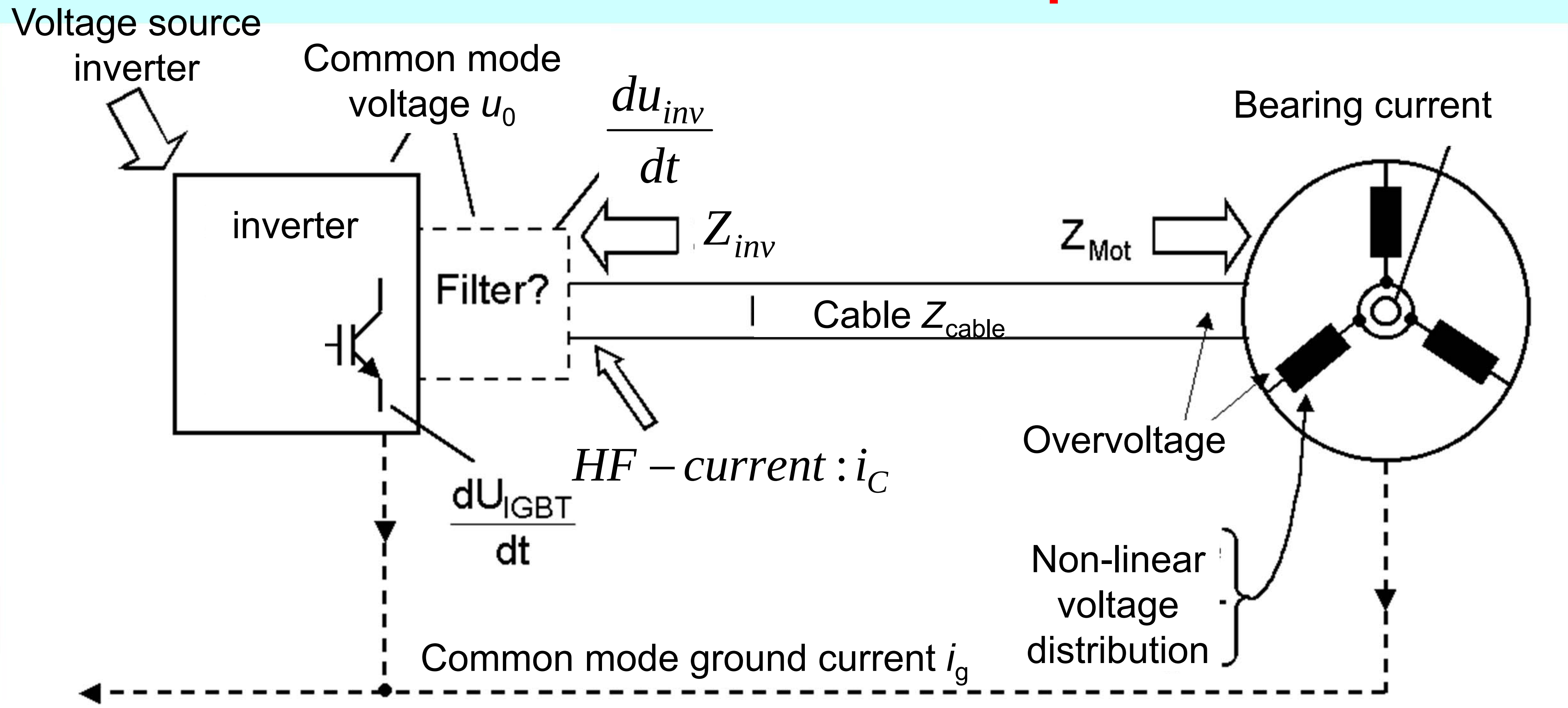
Stray capacitance of bearing lubricant film, of winding line-to-earth capacitance and of air gap between stator and rotor act as a capacitive voltage divider for **HF "common mode voltage" u_0.**

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

Bearing voltage u_b of up to 30 V is possible, causing discharge current, leading to ruin of bearing races = bearing failure.

Help: **Common mode filters**, insulated or **ceramic bearings**.

HF inverter effects in variable speed drives



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

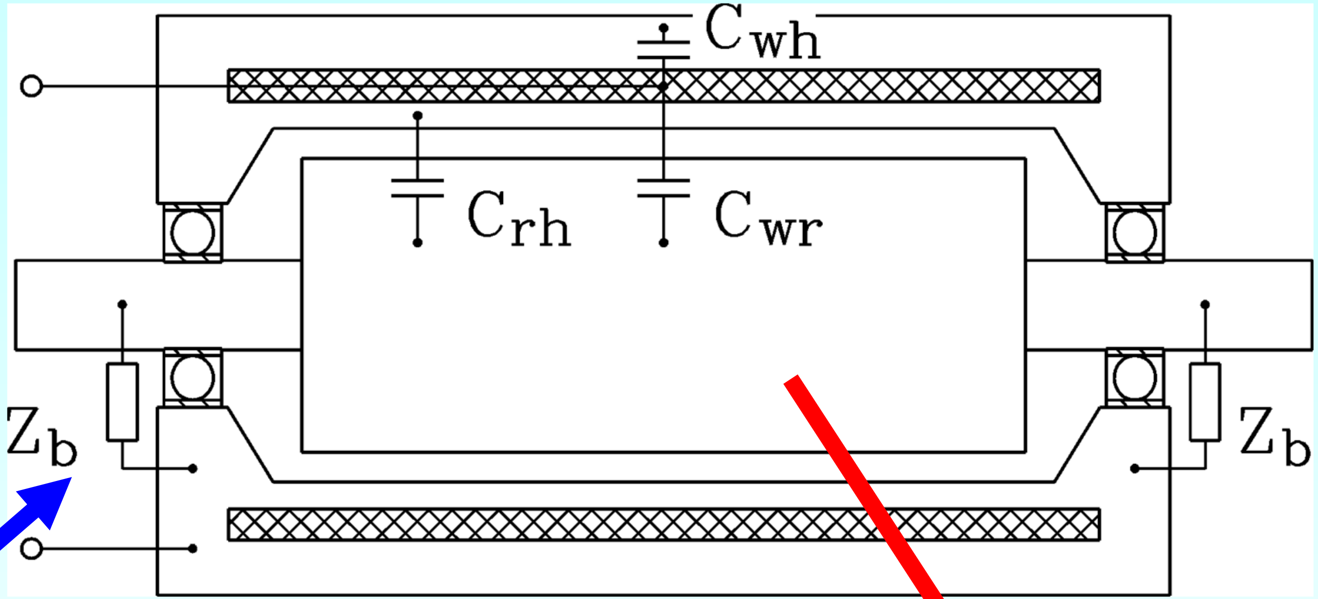
Parasitic capacitances in AC machines

w: winding

r: rotor

h: housing

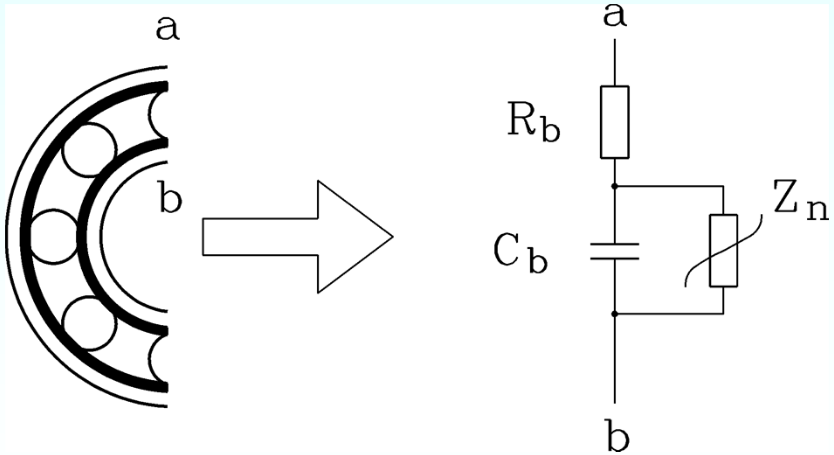
b: bearing



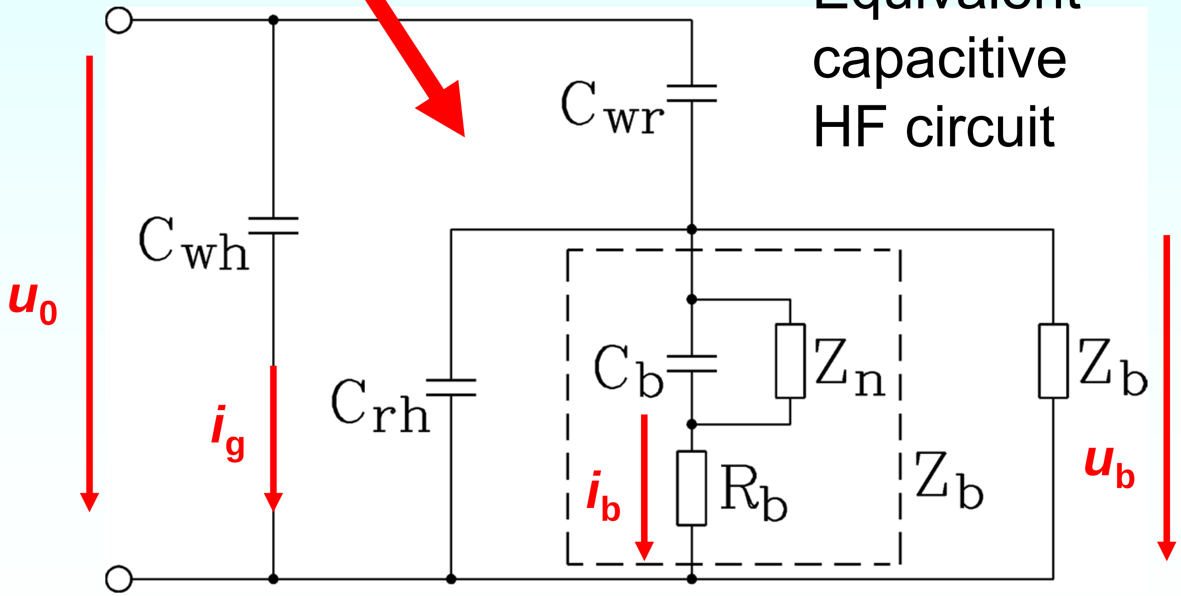
Capacity of winding to ground:

$C_E \approx C_{wh}$, as C_{wr}, C_{rh}, C_b are about 100 times smaller !

Motor bearings: Equivalent circuit



Motor: Equivalent capacitive HF circuit

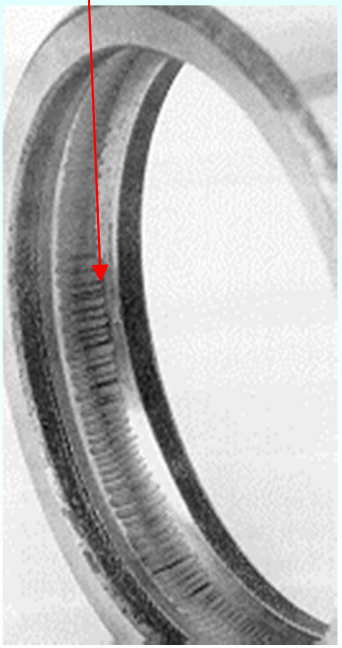


Bearing damage due to discharge currents

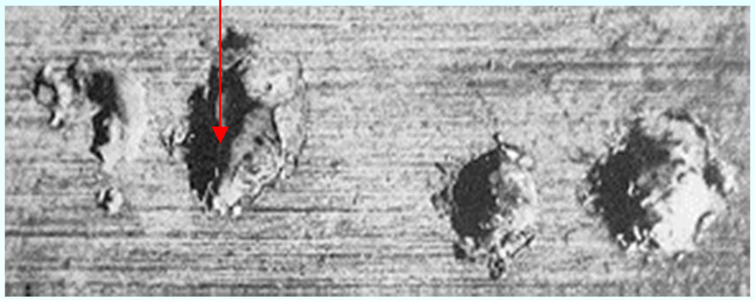
Discharge of lubricant film:

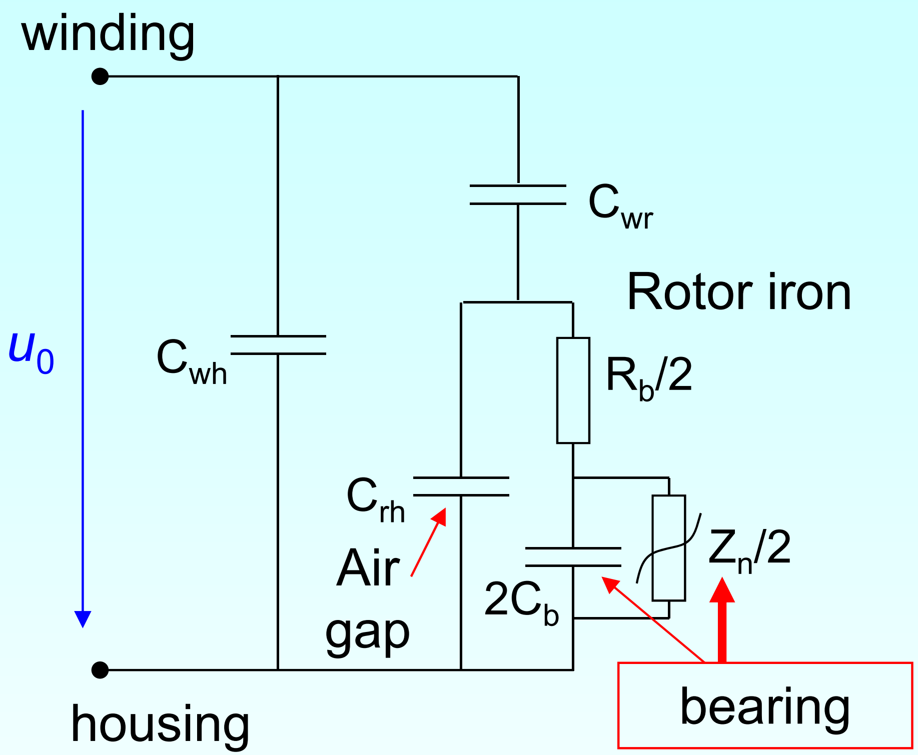
- → **bearing discharge current i_b**
- → **Craters at race surface, lead to fluting**

Fluting



Craters (1... 5 μm) lead to fluting





Source: SKF bearing catalogue, 1997

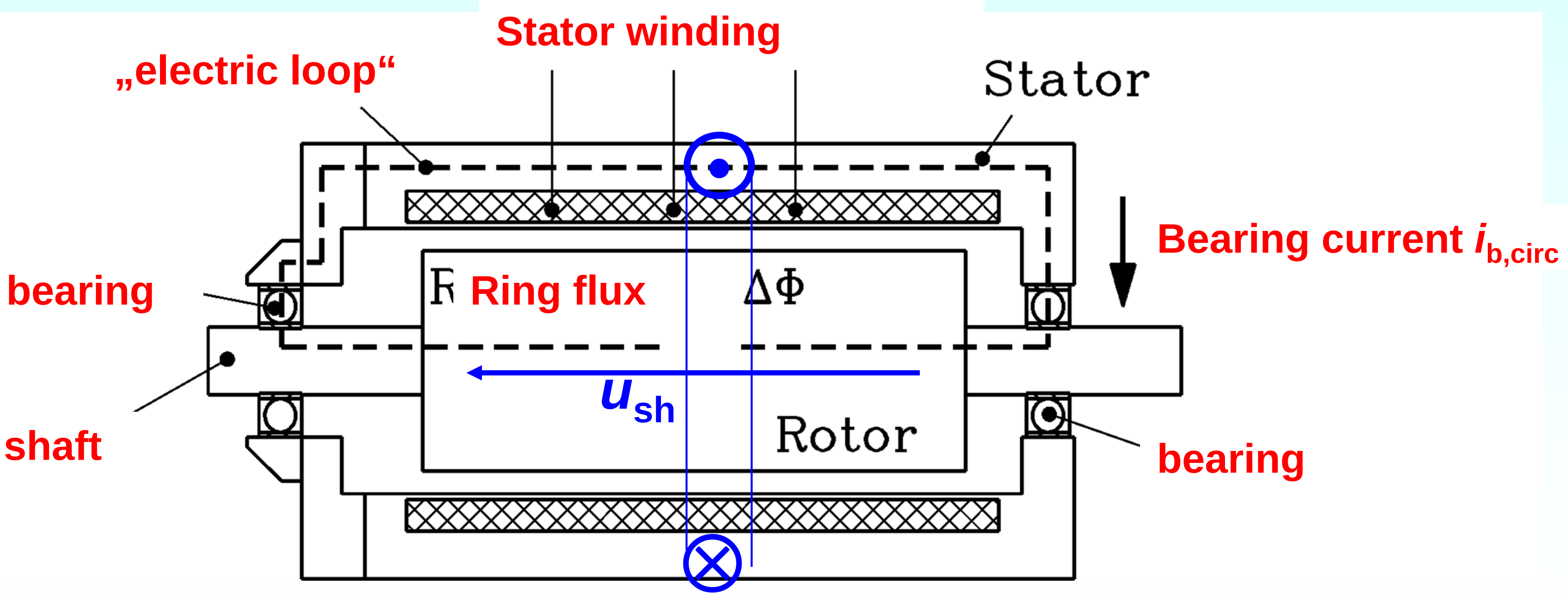
- **Influence of drive parameters:**

  Frame size, speed, bearing temperature, bearing type

- **<u>Counter-measure:</u> Common mode voltage filter**

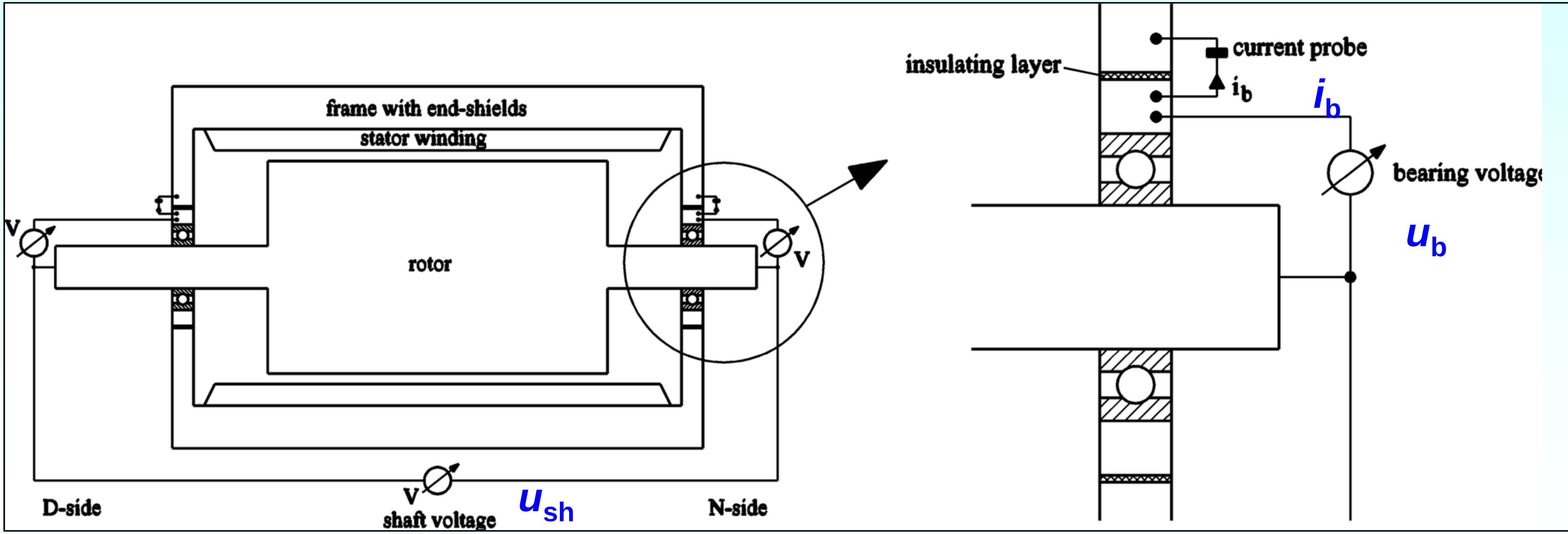
Bearing damage due to HF circulating currents

- Rather big winding-to-earth capacitive current i_g excites a HF "ring flux" $\Delta\Phi$ around the shaft, which induces a shaft voltage u_{sh} in the "loop" of stator housing, bearings and rotor shaft
- Circulating HF bearing currents $i_{b,circ}$ are driven by u_{sh} !
- Counter-measure: Insulation of one bearing

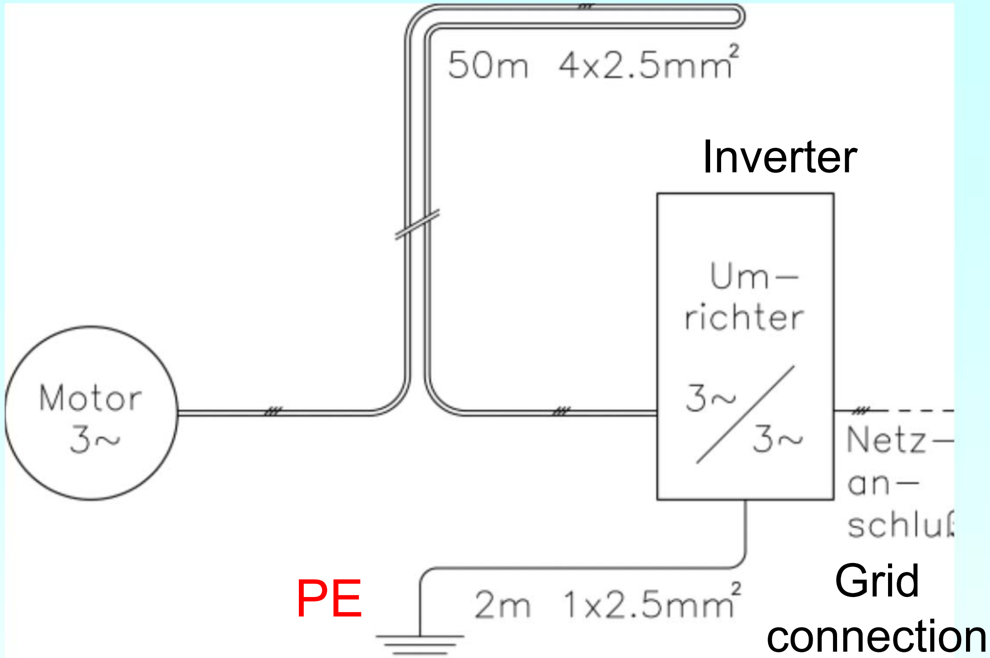


Measurement of bearing currents

- HF bearing voltage u_b between inner and outer bearing race
- HF shaft voltage u_{sh} between both bearings
- Measurement method: Guide the bearing current i_b via an insulation over a bridging loop to get access to the bearing current

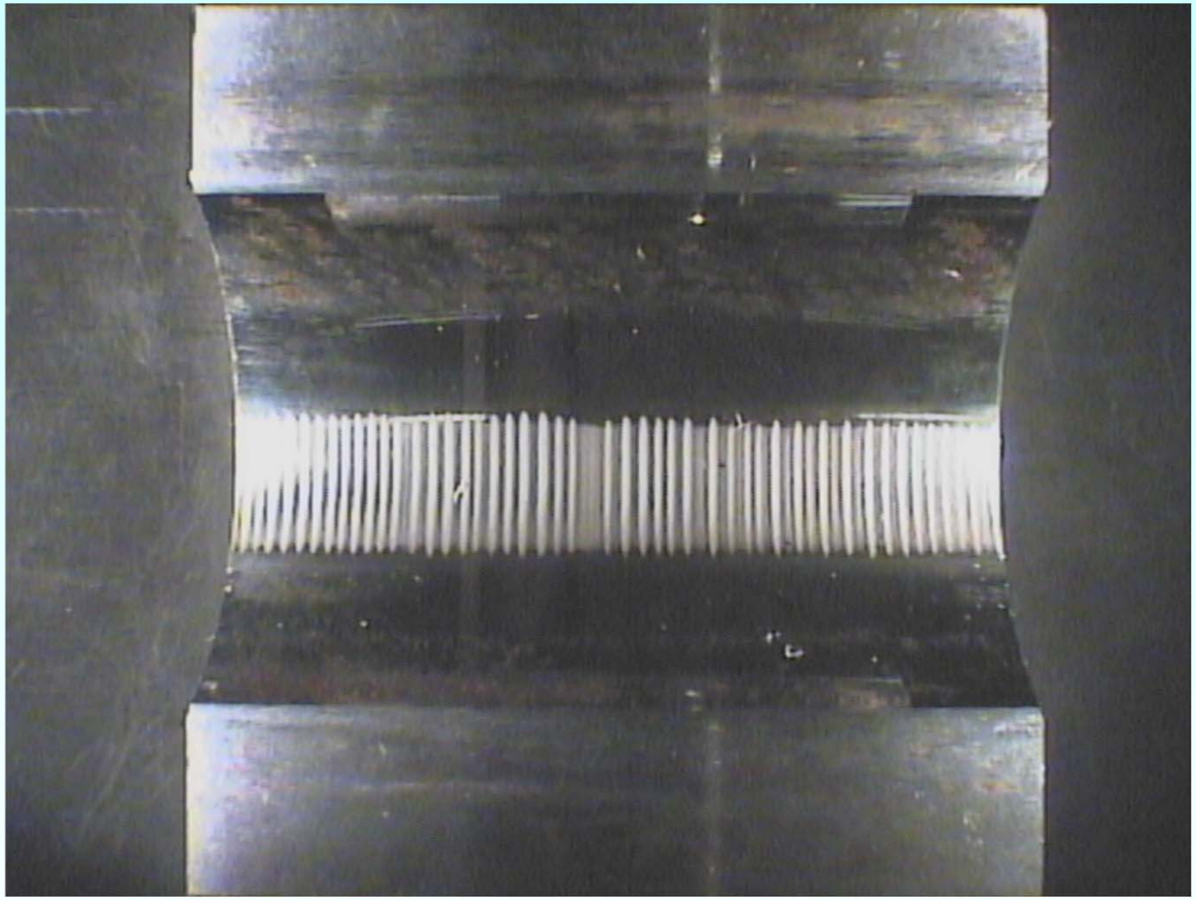


Fluting of inner bearing race



Experimental set-up:

11 kW motor, no-load, 400 V, PE of motor via inverter and motor cable

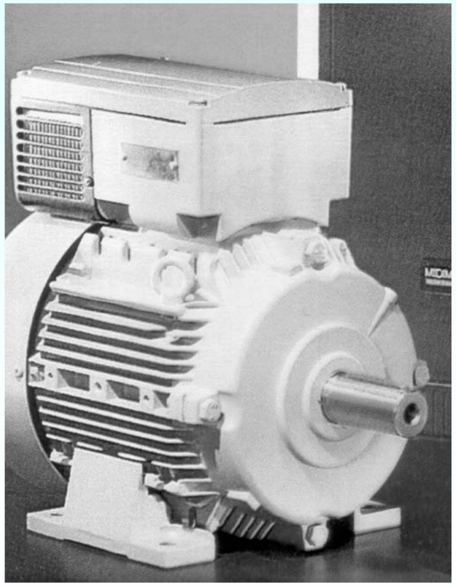


Source: A. Mütze, PhD Thesis, TU Darmstadt

4-pole 11 kW cage induction motor operated for about 2500 hours at no-load with a bearing current density of 2 A/mm^2

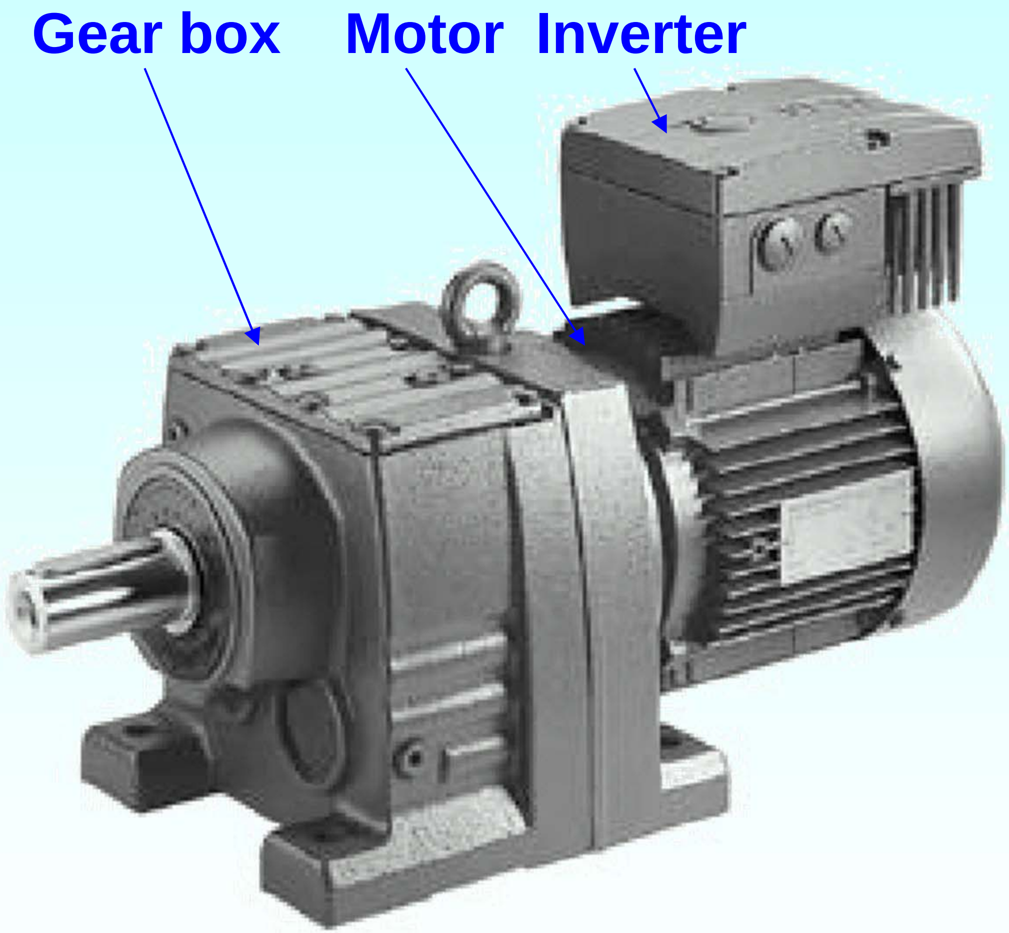
6. d*u*/d*t*-effects in inverter-fed machines

6.5 Combined inverter-motors



Source: Siemens AG

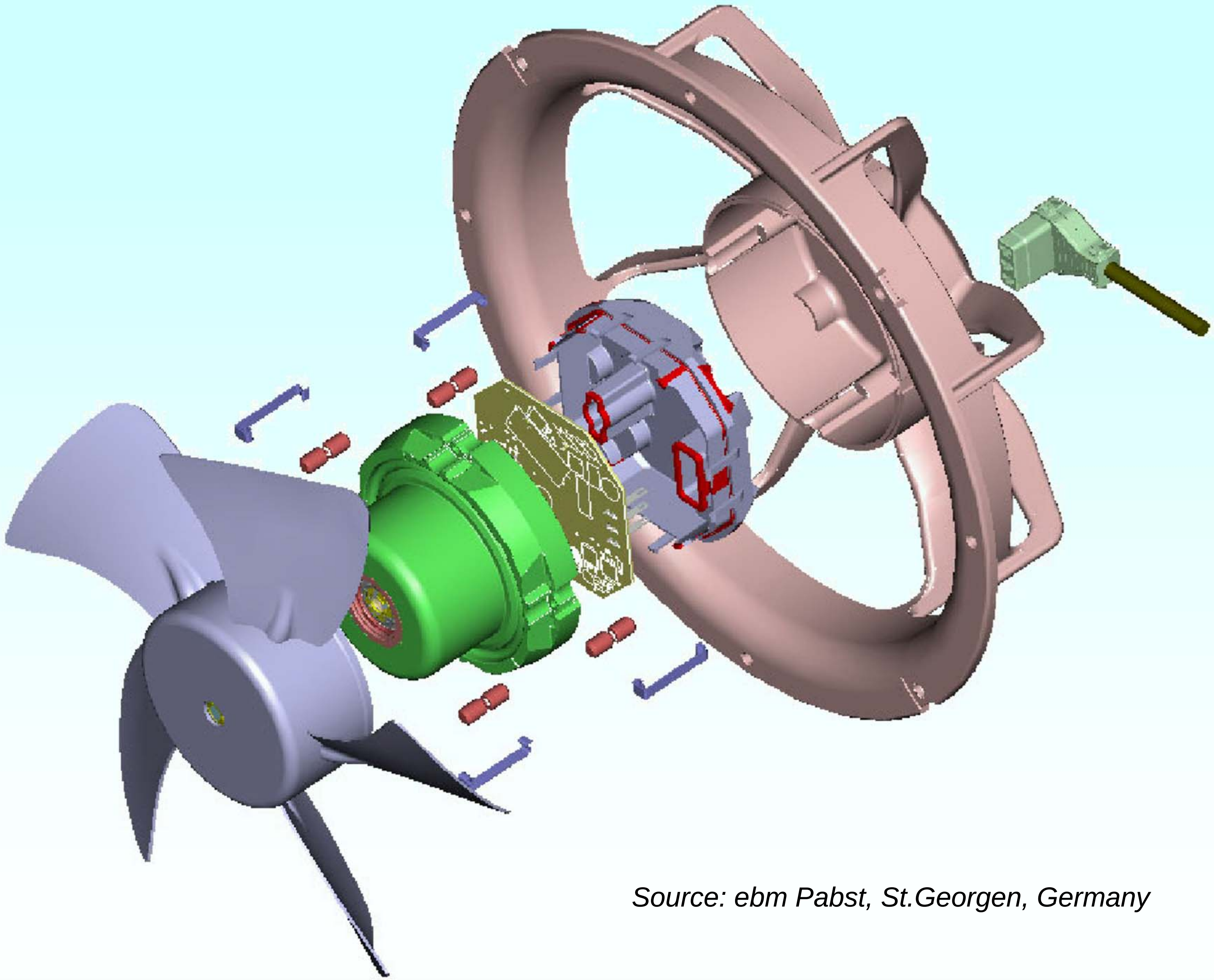
Combination of motor, inverter and gear box



Source: SEW Eurodrive, Bruchsal, Germany

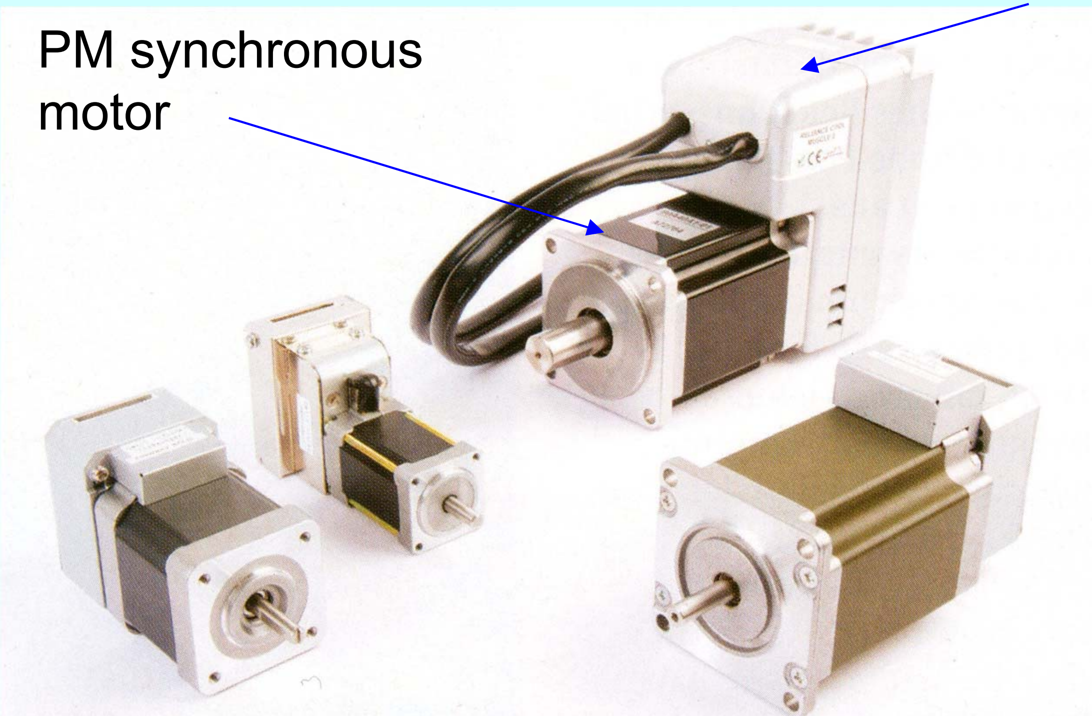
Inverter self-cooling via cooling fins

PM synchronous motor as brushless DC fan drive

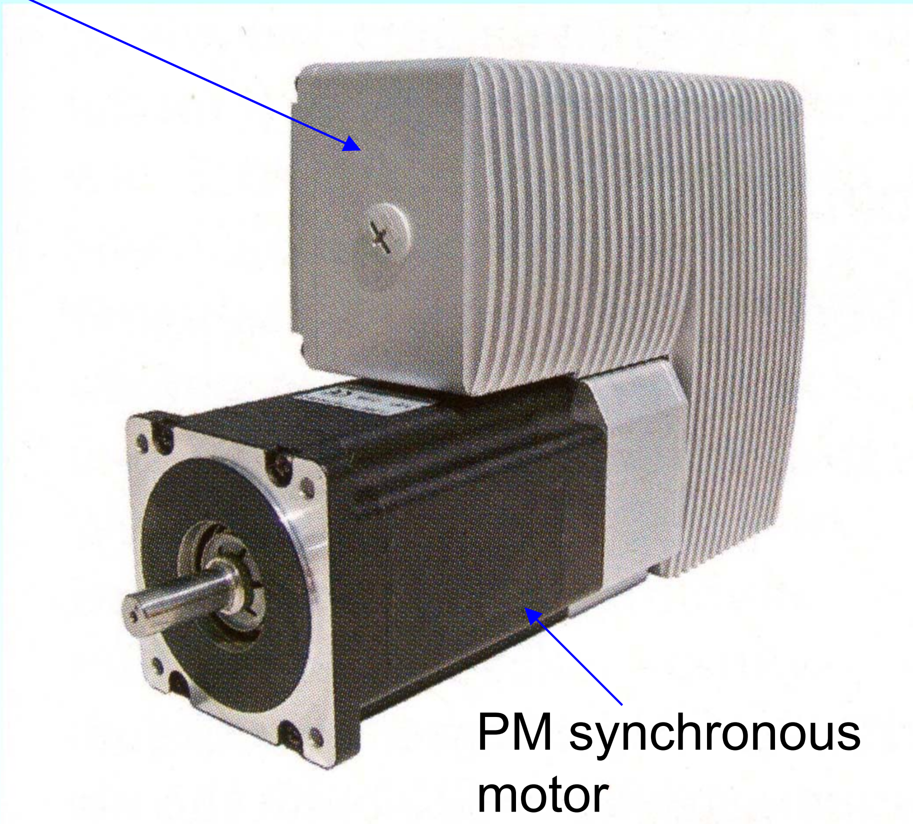


Source: ebm Pabst, St.Georgen, Germany

PM synchronous servo motors with integrated inverter



Source: Reliance Motors, UK



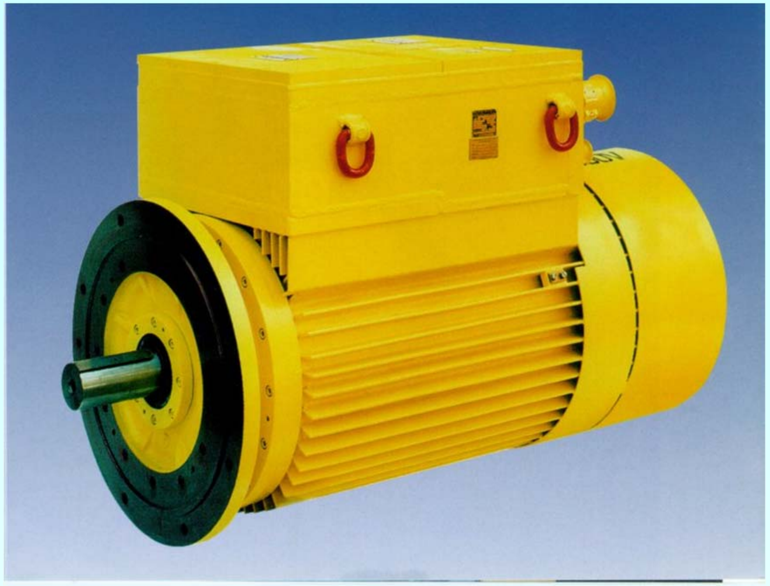
Source: Jenaer Antriebstechnik, Germany

Integrated inverter motors

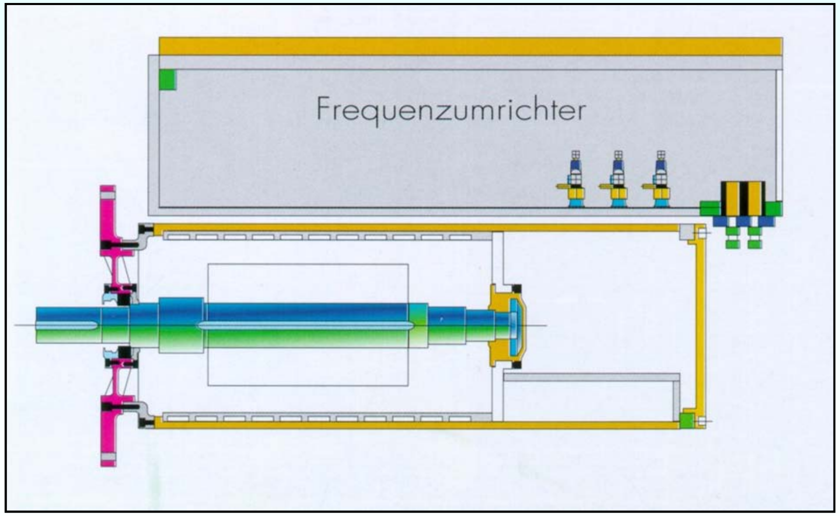
Source: Siemens AG, Germany

7.5 kW integrated inverter motor;

0.75 … 75 kW IGBT-inverters



22 kW integrated inverter motor



Source: Breuer, Germany

That´s all, folks !