High frequency effects in inverter-fed AC electric machinery

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Fast voltage change rates $\frac{du}{dt}$

- Fast switching IGBT inverters: short voltage rise time $t_r$ between zero and DC link voltage 100 ns:
  \[
  \frac{du}{dt} \cong \frac{U_d}{t_r}
  \]

<table>
<thead>
<tr>
<th>Line supply</th>
<th>dc link voltage</th>
<th>$\frac{du}{dt} \cong \frac{U_d}{t_r}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single phase 230 V 50 Hz</td>
<td>310 V</td>
<td>3.1 kV/μs</td>
</tr>
<tr>
<td>Three phase 400 V 50 Hz</td>
<td>560 V</td>
<td>5.6 kV/μs</td>
</tr>
<tr>
<td>Three phase 500 V 50 Hz</td>
<td>700 V</td>
<td>7.0 kV/μs</td>
</tr>
</tbody>
</table>

- “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

Voltage source inverter
Common mode voltage
Poly-phase AC motor
bearing currents

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

HF cable current
Voltage over-shoot
Non-linear voltage distribution

Source: DFG research group FOR575:
Binder/Mutschler, TU Darmstadt
High frequency effects in inverter-fed AC electric machinery

**High \( \frac{du}{dt} \) = 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 $du/dt$
Voltage wave reflection at motor terminals

Wave propagation velocity \( v \)

Permittivity & permeability of medium: \( \varepsilon, \mu \)

Voltage wave amplitude: \( u \)

1: Motor cable:
low wave impedance \( Z_{\text{cable}} \)

2: Motor winding:
high wave impedance \( Z_{\text{mot}} \)

\[
\frac{u_{\text{reflected}}}{u_{\text{incom}}} = r = \frac{Z - Z_{\text{cable}}}{Z + Z_{\text{cable}}}
\]
Voltage wave reflection coefficient \( r \)

\[
\frac{u_{\text{reflected}}}{u_{\text{incom}}} = r = \frac{Z - Z_{\text{cable}}}{Z + Z_{\text{cable}}}
\]

**Positive voltage wave reflection at motor terminals**: voltage increased

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

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

\[
r_{\text{inv}} = \frac{Z_{\text{inv}} - Z_{\text{cable}}}{Z_{\text{inv}} + Z_{\text{cable}}} \quad Z_{\text{inv}} \to 0: \quad r_{\text{inv}} = -1
\]
Inverter side Motor side

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

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 mm$^2$

- Conductor diameter $d = 1.4$ mm, $q = d^2 \pi / 4 = 1.5$ mm$^2$
- Cable length $l_c = 100$ m
- Distance between conductor centres: $a = 4.15$ mm,
- Average relative permittivity: $\varepsilon_r = 4$

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:

\[ C'_{\text{cable}} = \frac{2\pi \cdot \varepsilon_r \cdot \varepsilon_0}{\ln(2a/d)} = 125 \text{ pF/m} \]

Cable wave impedance \((R' \approx 0, \ G' \approx 0)\):

\[ Z_{\text{cable}} = \sqrt{\frac{L'_{\text{cable}}}{C'_{\text{cable}}}} = 53.7 \Omega \quad \text{measured: 83\,\Omega} \]

Wave velocity:

\[ v = \frac{1}{\sqrt{L'_{\text{cable}} \cdot C'_{\text{cable}}}} = 149 \cdot 10^6 \text{ m/s} \approx 150000 \text{ km/s} \]

\[ v \approx \frac{c_0}{2} = 150000 \text{ km/s} \]
Motor cable voltage reflection

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

\[ r_{\text{mot}} = 1 \]

Line to line over-voltage at motor terminals:

\[ \hat{U}_{\text{LL,mot}} = (1 + r_{\text{mot}}) \cdot U_d = 2 \cdot 560 = 1120 \text{ V} \]

Wave propagation time: \[ t_p = \frac{l_c}{v} = 100 / (150 \cdot 10^6) = 0.67 \mu\text{s} \]

\[ \frac{1}{4t_p} = 375 \text{ kHz} \]
Motor reflection coefficient $r_{\text{mot}} = 0.75 < 1$

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

Reflection coefficient:
- $r_{\text{mot}} = 0.75$ on motor side
- $r_{\text{inv}} = -1$ at inverter side.

Assumption:
Voltage rise time $t_r = 0$, $du/dt \to \infty$
Influence of motor size on cable and motor wave impedance

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

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

- Frequency $f$
- Total motor flux leakage coefficient $\sigma$
- 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 $Z_{\text{mot}}$ 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: $r_{mot} = \frac{5000 - 83}{5000 + 83} = 0.967$

b) Bigger 18.5 kW-motor:
frame size 180 mm, wave impedance 570 Ohm.
Motor cable wave impedance 75 Ohm.

Motor reflection coefficient: $r_{mot} = \frac{570 - 75}{570 + 75} = 0.77$
Critical cable length $l_{c,crit}$ at $du/dt \approx U_d/t_r$

- 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 $l_{c,\text{crit}}$

\[ t_r = 2t_p = 2 \cdot \frac{l_c}{v} \quad \Rightarrow \quad l_{c,\text{crit}} = \frac{v \cdot t_r}{2} \]

Voltage rise time $t_r = 100$ ns,
Voltage wave propagation velocity $v = \frac{c_0}{2} = 150\,000$ km/s

\[ l_{c,\text{crit}} = \frac{v \cdot t_r}{2} = 150 \cdot 10^6 \cdot 100 \cdot 10^{-9} \cdot 2 = 7.5 \text{ m} \]

If the cable is longer than 7.5 m between inverter and motor, then full voltage wave reflection occurs at the motor terminals!
Voltage reflection at short cable length $l < l_{c,\text{crit}}$

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

Example:
- Motor reflection coefficient $r_{\text{mot}} = 0.75$
- Inverter reflection coefficient $r_{\text{inv}} = -1$
- Voltage rise time $t_r = 3t_p$
Measured voltage reflection at long cable $l > l_{c,\text{crit}}$

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

Voltage reflection coefficient:
$$r_{\text{mot}} = (1150 - 600) / 600 = 0.92$$

Source: Siemens AG
Inverter output voltage
Motor terminal voltage
Reflection

Measured voltage reflection at long cable

\[ I > I_{c,\text{crit}} \]

Source: Siemens AG
High frequency effects in inverter-fed AC electric machinery

Summary:
Voltage wave reflections at motor terminals

- Fast IGBT switching yields high $du/dt$
- 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
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 $du/dt$
HF voltage distribution in armature winding

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

Motor winding equivalent circuit per turn consists of
- inductance per turn $\Delta L$,
- line-to-earth capacitance $\Delta C_E$ between conductor and stator iron,
- series capacitance $\Delta C_s$ between conductors of adjacent turns in slot.

For HF the inductance gives an “infinite” impedance!

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

Source: Heller-Veverka, VEB-Verlag Technik, Berlin, 1957
**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: $\Delta x$,
- 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 \[ C_s = \Delta C_s / N_s \]

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

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

\[ \gamma l = \sqrt{\frac{C_E'}{C_s}} \cdot l = \sqrt{\frac{\Delta C_E}{\Delta C_s}} \cdot \frac{l}{\Delta x} = \sqrt{\frac{\Delta C_E}{\Delta C_s}} \cdot N_s \]
Non-linear voltage distribution at “voltage step”
\( (du/dt \to \infty) \)

**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:**

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

\[\gamma = \sqrt{\frac{C'_E}{C_s}}\]

unit \( [\gamma] = 1/\text{m} \)
Oscillation of non-linear voltage distribution between \( t = 0 \) and \( t \to \infty \)

- 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 \( u_E(x, t \to \infty) \)

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

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: \( U_d/(2n) = 60 \text{ V} \)

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:

\[
\frac{330\text{V}}{60\text{V}} = 5.5
\]

Example: Y-connected winding, \( n = 5 \) coils per phase, \( 2n = 10 \) coils line-to-line,

\( U_d = 600 \text{ V}. \) 1st coil voltage: \( u_{c,1}/U_d = 330/600 = 55\% \) of total voltage!
Measured motor terminal voltages at PWM IGBT-inverter operation

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


Line-to-line terminal voltage

Line to earth terminal voltage

Voltage drop at first coil per phase ($n$ coils per phase)
Measured voltage at 1st coil per phase


- 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)

Over-voltage factor of 1st coil:

$$\frac{\hat{U}_c}{U_d / (2n)} \approx 6$$
High frequency effects in inverter-fed AC electric machinery

Summary:
HF voltage distribution in armature winding

- High $du/dt$ causes big influence of capacities within winding on voltage
- Non-linear voltage distribution in the winding at high $du/dt$
- Increased insulation stress of the first winding turns at the incoming wave
High frequency effects in inverter-fed AC electric machinery

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Insulation stress due to high $du/dt$

- 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 $du/dt$ due to partial discharges, not due to increased dielectric losses
Insulation stress due to partial discharges

- Local electrical field strength $E = \frac{dU}{dx}$ 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

$E_{av} = \frac{U}{d}$: 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 \((U_N < 1 \text{ kV})\) 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 $\rightarrow$ 1180 V at 150 °C

  \[
  20^\circ C: U_{pd} = 1200V, \quad \hat{U}_{pd} = U_{pd} \cdot \sqrt{2} = 1700V \Rightarrow
  \]

  \[
  150^\circ C: \hat{U}_{pd} = 1700 - 4 \cdot (150 - 20) = 1180V
  \]

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

  \[
  \frac{\hat{U}_{LL,mot}}{\hat{U}_N} \approx \frac{(1 + r_{mot}) \cdot U_d}{U_d} = 2.0
  \]

  \[
  \hat{U}_{LL,mot} = 2 \cdot U_d = 2 \cdot 560V = 1120V < \hat{U}_{pd} = 1180V
  \]

**Result:** The motor winding is safe against du/dt-voltage stress!
Partial discharge test of stator winding

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: $2 \cdot f_T$
$$\hat{U}_{LL}^* = (0.5 + r_{mot}) \cdot U_d$$

# Motor winding voltage stress at PWM IGBT-inverter operation

<table>
<thead>
<tr>
<th>Inverter input voltage</th>
<th>$U_{LL,\text{grid}}$</th>
<th>400 V</th>
<th>500 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC link voltage</td>
<td>$U_d \approx \sqrt{2 \cdot U_{LL,\text{grid}}}$</td>
<td>565 V</td>
<td>710 V</td>
</tr>
<tr>
<td>Motor rated voltage</td>
<td>$U_N$</td>
<td>400 V</td>
<td>500 V</td>
</tr>
<tr>
<td>Motor line-to-line voltage amplitude</td>
<td>$\hat{U}<em>{LL} = (1+r</em>{mot}) \cdot U_d$</td>
<td>1130 V</td>
<td>1420 V</td>
</tr>
<tr>
<td>Motor line-to-earth voltage amplitude</td>
<td>$\hat{U}<em>{LE} = (0.5+r</em>{mot}) \cdot U_d$</td>
<td>850 V</td>
<td>1060 V</td>
</tr>
<tr>
<td>Pulse frequent AC line-to-line voltage amplitude $(2 \cdot f_T)$</td>
<td>$\hat{U}^*<em>{LL} = (0.5+r</em>{mot}) \cdot U_d$</td>
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</table>
| Amplitude of pulse frequent AC voltage of 1st coil per phase | e.g. a) $n = 6$, $k = 0.3$  
   b) $n = 6$, $k = 0.6$ | 290 V | 365 V |
   | $\hat{U}_c = \left[ k \cdot (1+r_{mot}) - \frac{1}{2n} \right] \cdot U_d$ | $(r_{mot} = 1)$ | $(r_{mot} = 1)$ |

High frequency effects in inverter-fed AC electric machinery

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 assess admissible voltage limits
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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 $i_C$

- 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 $i_C$

Cable parameters:
- $L$: inductance
- $R$: ohmic resistance
- $C$: capacitance
- $G$: lossy insulation conductance

Simplified equivalent circuit of a cable with concentrated elements

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

$$C_{cable} = C_c \cdot l_c$$
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** $u_0$

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

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

Graph showing the relationships and calculations.
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 $f_T$

$du/dt$ of common mode voltage causes HF parasitic motor currents:

Motor capacitive equivalent circuit
HF stator-to-ground current $i_g$

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 $i_g$. 

\[
\int i_E(x) \cdot dx / l = i_g
\]
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

Line-to-earth voltages, V

- $U_{UE}$
- $U_{VE}$
- $U_{WE}$

DC link voltage 600 V

CM current, A

- $i_g$

Time, μs

0 20 40 60 80 100 120 140

0 2 4 6

0 -500 -250 0 250 500
Measured HF stator-to-ground currents $i_g$

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

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

*Source: O. Magdun, PhD Thesis, TU Darmstadt*
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!)

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

BVR: bearing voltage ratio

$BVR \approx 0.03 \ldots 0.1$

**Motor**: Equivalent capacitive HF circuit

**Ball bearing**: Equivalent electric circuit
Electric field strength $E_b$ in intact lubrication film

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

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

$$U_d = 600V : \quad u_b \approx (100\ldots300) \cdot (0.03 \ldots 0.1) = 3\ldots30 \text{ V}$$

Intact insulating bearing lubrication film thickness $h_0 \approx 0.5 \ldots 3.0 \mu\text{m}$ (depending on speed, temperature, load, lubricant, ...)

$$E_b = \frac{u_b}{h_0} \approx (3\ldots30\text{V})/(0.5 \ldots 3\mu\text{m}) = 1 \ldots 60 \text{ kV/mm}$$

At a typical threshold value of $E_D = 15 \text{ kV/mm}$ 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 \( C_b \approx 50 \ldots 200 \text{ pF} \), 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

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**Ball bearing:**
Equivalent electric circuit
Electric discharge bearing currents $i_{b,EDM}$

Bearing lubrication film acts as a "switch":

**Intact film:** $Z_n \to \infty$

- $E_b < 15 \text{ kV/mm}$
  - Capacitive parasitic HF bearing currents $i_{bC}$

**Punched film:** $Z_n \to 0$

- $E_b > 15 \text{ kV/mm}$
  - 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**, \( f_T = 4 \text{ kHz} \) switching frequency, DC link 600 V

**Bearing voltage before breakdown:**

\[ \hat{u}_b = 12.5 \text{ V} \]

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

\[ h_c \approx 0.8 \text{ \( \mu \)m} \]

**Measurement of EDM current:** Induction motor 240 kW

\[ \hat{i}_{b, \text{EDM}} = 1.25 \text{A} \]
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

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

The lubricant is not destroyed

Big currents $i_{b,EDM} \Rightarrow$ Bigger craters ($\varnothing$ 1... 5 $\mu$m) 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 is destroyed, leading to a bearing failure.
HERTZian area of elastic deformed roller element under radial load

Apparent bearing current $J_b$:

$$J_b = \frac{\hat{i}_b}{A_{Hertz}}$$
Micro-craters on the ball surface due to small arcs

Due to the micro-craters the ball surface does not mirror any more!

Source: Brenner, Bürstadt, Germany

Ball with craters

Ball without craters
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

Source: Brenner, Bürstadt, Germany
HF common mode ring flux $\Phi_c$

The rather big stator-to-ground current $i_g$ as per phase $i_{UE}$, $i_{VE}$, $i_{WE}$ excites a HF “ring flux” $\Phi_c$ around the shaft.

AMPÈRE’s law along loop $C$:

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

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 $\Phi_c$ 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

20 A/div

The equivalent transformer circuit is a harmonic circuit. Thus, the FOURIER series of the CM current waveform $i_g$ is required to calculate $i_{b,circ}$

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!

Sources:
A. Mütze & O. Magdun, PhD Theses, TU Darmstadt
High frequency effects in inverter-fed AC electric machinery

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 $du/dt$
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

7.5 kW, 4-pole cage induction motor

Source: Siemens AG

Combination of motor, inverter and gear box

Source: SEW Eurodrive, Bruchsal, Germany
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

PM synchronous motor
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 $du/dt$-effects for motor insulation stress via inverter output filter

**$du/dt$-filter**

$L$-C-combination with resonance frequency above double switching frequency $f_{\text{res}} > 2f_T$

$\Rightarrow$ Steep $du/dt$-slopes reduced

$\Rightarrow$ Current switching ripple still active (magnetic noise, add. losses, ...)

**Sine-wave filter**

$L$-C-combination with resonance frequency above fundamental frequency $f_{\text{res}} > f_s$

$\Rightarrow$ Nearly sinusoidal line-to-line voltage

$\Rightarrow$ Current switching ripple removed

**BUT:** Much bigger size than $du/dt$-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

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

Summary:
System design of inverter drives coping with big $du/dt$

- 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 $du/dt$-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
High frequency effects in inverter-fed AC electric machinery

That´s all, folks!

Thank you for your attention!