Interactions Between Electrical Machine and Power Electronics

Prof. Dr.-Ing. Ralph Kennel
(ralph.kennel@tum.de)
Technische Universität München
Arcisstraße 21
80333 München
Additional Losses

Prof. Dr.-Ing. Ralph Kennel
(ralph.kennel@tum.de)
Technische Universität München
Arcisstraße 21
80333 München
Additional Losses

Current Harmonics

with increasing switching frequency the current harmonics caused by the inverter decrease
Iron Losses under Inverter Supply

Quelle: PTB
2 pole squirrel cage induction machine 3 kW, 380 V, Y connection
rated frequency 50 Hz, slip 4.5 %, torque 10 Nm
voltage source inverter 8.3 kVA, 400 V

<table>
<thead>
<tr>
<th></th>
<th>mains supply</th>
<th>inverter supply</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_s$ / Hz</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>$f_T$ / Hz</td>
<td></td>
<td>2400</td>
</tr>
<tr>
<td>$f_p = 2f_T$ / kHz</td>
<td>4.8</td>
<td>9.6</td>
</tr>
<tr>
<td>$\eta$ (Motor)</td>
<td>81.9 %</td>
<td>81.3 %</td>
</tr>
<tr>
<td>$\eta$ (Umrichter)</td>
<td>-</td>
<td>96.9 %</td>
</tr>
<tr>
<td>$\eta$ (gesamt)</td>
<td>81.9 %</td>
<td>78.8 %</td>
</tr>
</tbody>
</table>

at frequency 9.6 kHz motor efficiency is high (less temperature rise)
the overall efficiency, however, is the same as at Frequency 4.8 kHz
At frequency 19.2 kHz motor current harmonics are low, but switching losses increase
EMC

Prof. Dr.-Ing. Ralph Kennel
(ralph.kennel@tum.de)
Technische Universität München
Arcisstraße 21
80333 München
Electro Magnetic Compatibility

E  even

M  more

C  confusion
Cabinet Design
with Modern Servo Drives

signal electronics

power electronics
Shielding and Grounding
following these requirements and advice

there is „conductive EMI“ only
when using power electronics inverters
(... usually no „radiation EMI“)
Travelling Waves

Prof. Dr.-Ing. Ralph Kennel
(ralph.kennel@tum.de)
Technische Universität München
Arcisstraße 21
80333 München
Wanderwellen
typischer Spannungsverlauf
am Ausgang eines PWM-Pulsumrichters
Travelling Waves

typical „voltage step“
at the output of a PWM voltage source inverter
Travelling Waves
... „it depends“ ... on what?
... which case is it?
→ adaptation
→ „loose“ end
→ „fix“ end

... „it depends“ on what?
... which case is it?
→ adaptation
→ „loose“ end
→ „fix“ end

... whether we consider currents or voltages !!!

... in our case: → voltages

... for voltages the motor is a „loose“ end
... what now?
... which case is it?

→ adaptation
→ „loose“ end
→ „fix“ end

... for voltages the inverter is a „fix“ end
... if the inverter output voltage did not change meanwhile, the wave is inverted and travels back again
... on the inverter side the \textit{voltage} remains constant (fix end !)

... on the motor side \textit{voltage oscillations} occur up to the \textbf{double} value of DC link voltage (loose end !)
Travelling Waves

... so far ... so good

... the matter, however, is getting much worse, as soon as the inverter switches simultaneously „into“ the back travelling voltage wave.

... on the inverter side the voltage remains constant

(fix end !)

... on the motor side voltage oscillations occur up to the double value of DC link voltage

(loose end !)
Travelling Waves
... until here everything is like before ...
... what now?

→ „fix“ end

... in case the inverter has switched the voltage at its output meanwhile,
the wave travels back with amplification

Travelling Waves
Travelling Waves
Travelling Waves

... on the inverter side
the voltage is „impressed“
(fix end !)

... what is so critical ?

... on the motor side
voltage oscillations occur
up to 2.7 times
the DC link voltage
(loose end !)
Voltage Flashover within Winding

... what is so critical?
„Horror“ Picture

... the danger is real ...
- behind such pictures, however, there is a commercial interest !!

... what is so critical ?
Compatibility between Inverter and Motor

... these are realistic values for modern inverters !!!

Extract from IEC paper IEC 2 (CD) 566
1991 (in Germany) : appendix to IEC 34

as long as you supply standard induction motors by inverters with

• voltage peaks **below 1000 V**
• voltage rise times **below 500 V/µs**

you should not expect any danger for the motor

---

A... \( \dot{U} = 1000V; \frac{dU}{dt} \leq 500 \text{ V/µs} \) according to IEC guideline
B... standard motors with \( U_N \leq 660V \)
C... motors with „improved“ winding insulation
D... motors with insulation of special quality and formed winding coils
E... real values of a 0,55kW standard motor measured at the Technical University of Dresden
Insulation of Wire

Reasoning

• the critical voltage resulting in a flashover does not depend at all on the diameter of the wire

• doubling the thickness of wire insulation increases the critical voltage by 15 % 
   (the most significant effect results from covering faults of the first layer by the second layer)
   ➔ that is „state of the art“ today !!!

• increasing the operation temperature to 155 °C lowers the critical voltage by 15 %
Voltage Stress on Partial Coils

Prof. Dr.-Ing. Ralph Kennel
(ralph.kennel@tum.de)
Technische Universität München
Arcisstraße 21
80333 München
Voltage Stress on (Partial) Coils

![Graph showing voltage stress over time]

- Voltage in V
- Time in s

- Voltage values: 0, 4e-06, 8e-06, 1.2e-05, 1.6e-05, 2e-05
Voltage Stress on (Partial) Coils
Voltage Stress on (Partial) Coils

![Graph showing voltage stress over time on partial coils.](image)
... to explain this effect, the representation as a simple equivalent circuit containing a serial connection of concentrated inductances is not sufficient!

... in this case, the motor winding has to be represented – like an electric cable – by a serial network of two-ports.
Voltage Stress on (Partial) Coils

... voltage “waves“ spread out within ther motor windings – as in an electrical cable – according to the laws of cable equation
Voltage Stress on (Partial) Coils

... the motor windings only has inductive behaviour, if the rising time of the voltage edge is significantly larger than the group delay of the complete motor winding.

if the rising time of the voltage edge is smaller than the group delay of the complete motor winding, the capacitive behaviour is predominant !!!
Voltage Stress on (Partial) Coils

![Graph showing voltage stress over time on partial coils. The graph plots voltage in volts against time in seconds. The diagram includes a schematic representation of the coils and their connections.]
Voltage Stress on (Partial) Coils
... that is alarming !!!
the first voltage pulse
appears nearly completely at the entrance coil
Voltage Stress on (Partial) Coils

... using cost effective winding processes
the single wires are distributed randomly in the slot!!

... therefore the insulation of the single wire
must be designed with respect to
the full voltage stress !!!
Voltage Stress on (Partial) Coils

... using cost effective winding processes
the single wires are distributed randomly in the slot !!

... remember:

... on the motor side entstehen
voltage oscillations occurr
up to 2,7 times
the DC link voltage

... therefore the insulation of the single wire
must be designed with respect to
the full voltage stress !!!