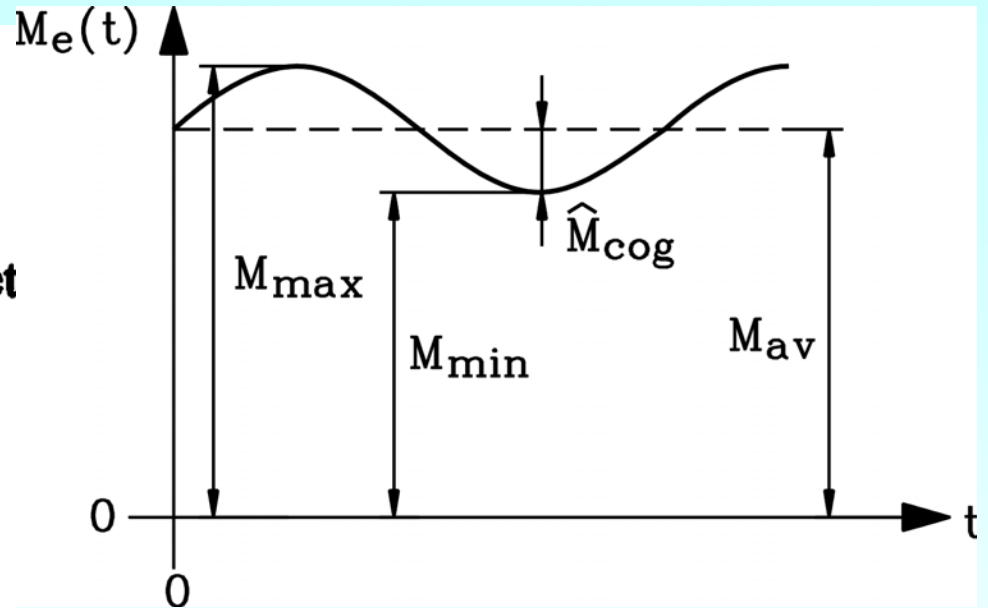
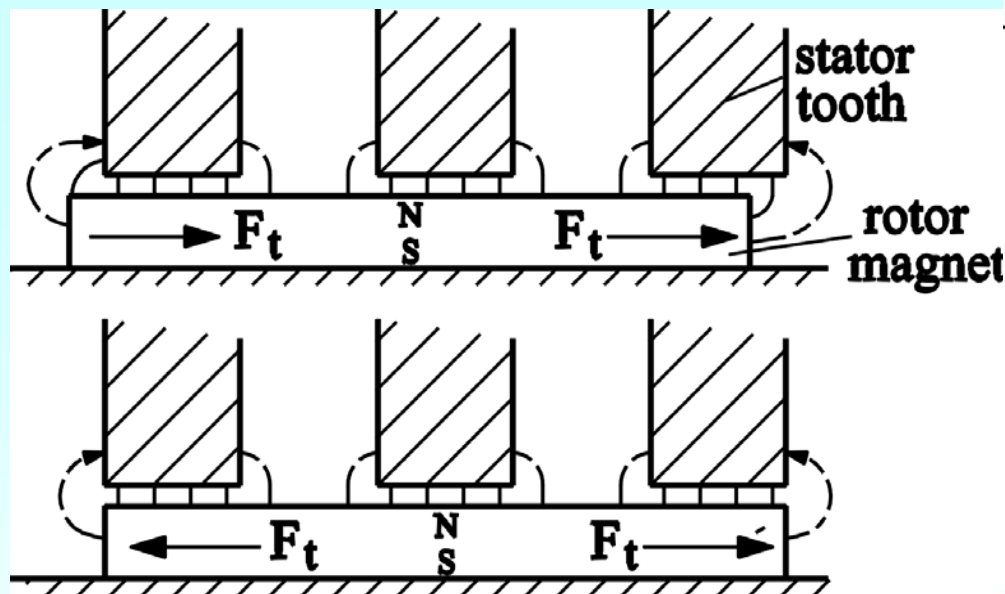


6. Momentenwelligkeit

Torque ripple of brushless DC motors

- **Cogging torque:** No-load torque ripple due to rotor magnets and stator slot openings
- **Pulsating torque at ideal sine wave current:** Torque variation at load due to interaction between stator and rotor field. Step-like stator mmf distribution due to distributed stator winding may be regarded as FOURIER sum of space harmonics, causing pulsating torque components with rotor magnet field.
- **Pulsating torque due to current ripple:** Inverter switching causes current ripple = current time harmonics. Each current harmonic causes a stator fundamental field, which interacts with rotor PM field.

Cogging torque M_{cog} and pulsating load torque



Cogging effect at no-load ($i_s = 0$):

Unaligned position: rotor tangential magnetic pull F_t on stator tooth sides generates torque,

Aligned position: sum $F_t = 0$, no torque

Typical good values: $\hat{w}_{M0} \sim 0.5\% \dots 1\%$

Pulsating load torque:

Quantification of torque ripple from measured torque time function, e.g. measured with strain gauge torque-meter:

$$\hat{w}_M = \frac{\hat{M}_{\text{cog}}}{M_{\text{av}}} = \frac{(M_{\text{max}} - M_{\text{min}}) / 2}{(M_{\text{max}} + M_{\text{min}}) / 2}$$

Determination of load torque ripple

- Internal power varies with time, leading to torque and speed variation
- Speed variation much smaller than torque variation due to rotor inertia, hence we assume CONSTANT speed
- Internal power gives electromagnetic torque:

$$m_e(t) = \left(u_{p,U}(t) \cdot i_U(t) + u_{p,V}(t) \cdot i_V(t) + u_{p,W}(t) \cdot i_W(t) \right) / (2\pi n)$$

- **Ideal sine wave current feeding:** NO inverter current ripple:

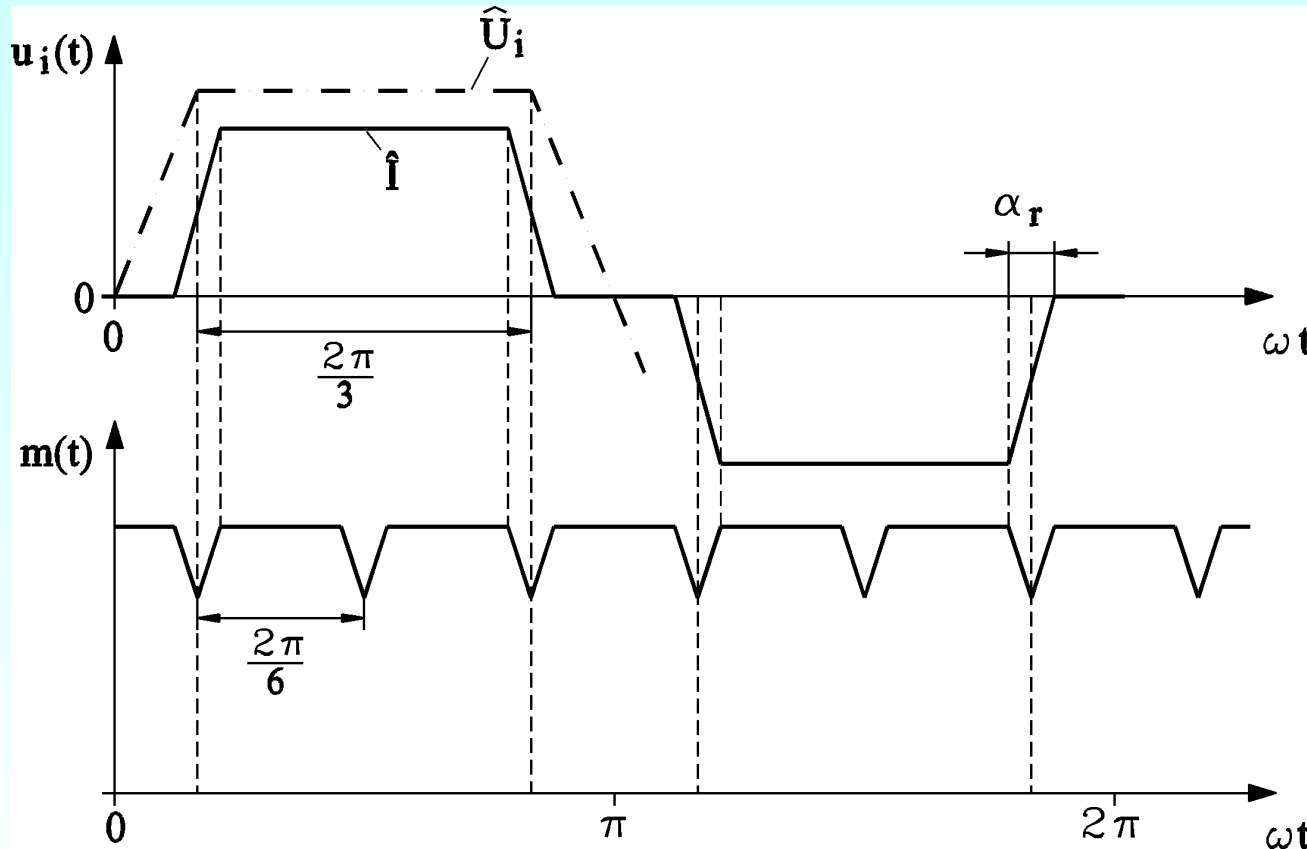
$$p_\delta(t) = \hat{U}_p \cos(\omega t) \cdot \hat{I} \cos(\omega t) + \hat{U}_p \cos(\omega t - 2\pi/3) \cdot \hat{I} \cos(\omega t - 2\pi/3) + \hat{U}_p \cos(\omega t - 4\pi/3) \cdot \hat{I} \cos(\omega t - 4\pi/3)$$

$$p_\delta(t) = \frac{\hat{U}_p \hat{I}}{2} \cdot [\cos(2\omega t) + 1] + \frac{\hat{U}_p \hat{I}}{2} \cdot \left[\cos\left(2\omega t - \frac{4\pi}{3}\right) + 1 \right] + \frac{\hat{U}_p \hat{I}}{2} \cdot \left[\cos\left(2\omega t - \frac{8\pi}{3}\right) + 1 \right]$$

$$p_\delta(t) = m \frac{\hat{U}_p \hat{I}}{2} = \text{const.} \quad M_e = \frac{(3/2) \cdot \hat{U}_p \cdot \hat{I}}{2 \cdot \pi \cdot n} = \text{const.}$$

No load torque ripple occurs due to current time function !

Load torque ripple in block commutated brushless DC machines



Generation of load torque ripple due to block current commutation with finite current rise time t_r (corresponding angle α_r)

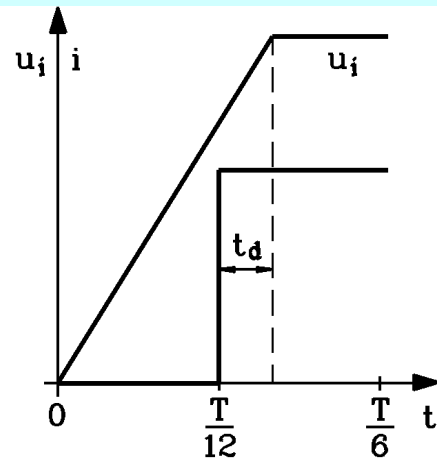
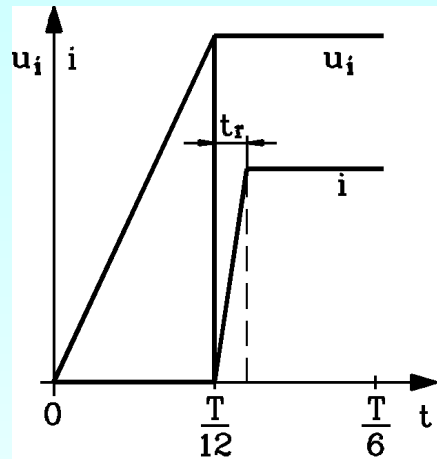
Typical block commutation torque ripple values:

$$\hat{w}_M \sim 4\% \dots 5\%$$

Facit:

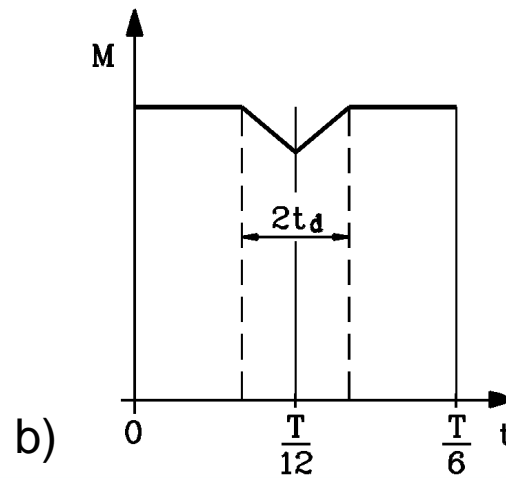
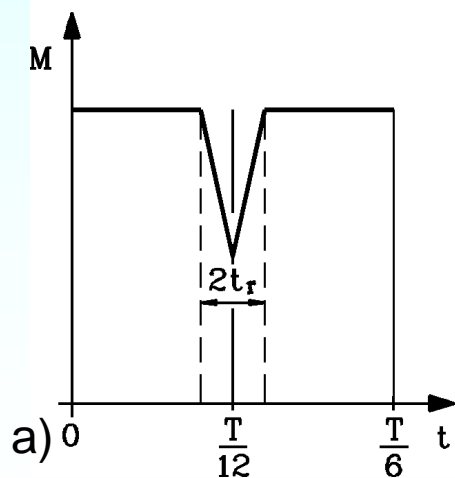
The generated load torque ripple is with six times fundamental frequency.

Two typical reasons for load torque ripple with block commutated brushless DC motors



a) deviation of block current from ideal **rectangular** shape (finite rise time t_r),

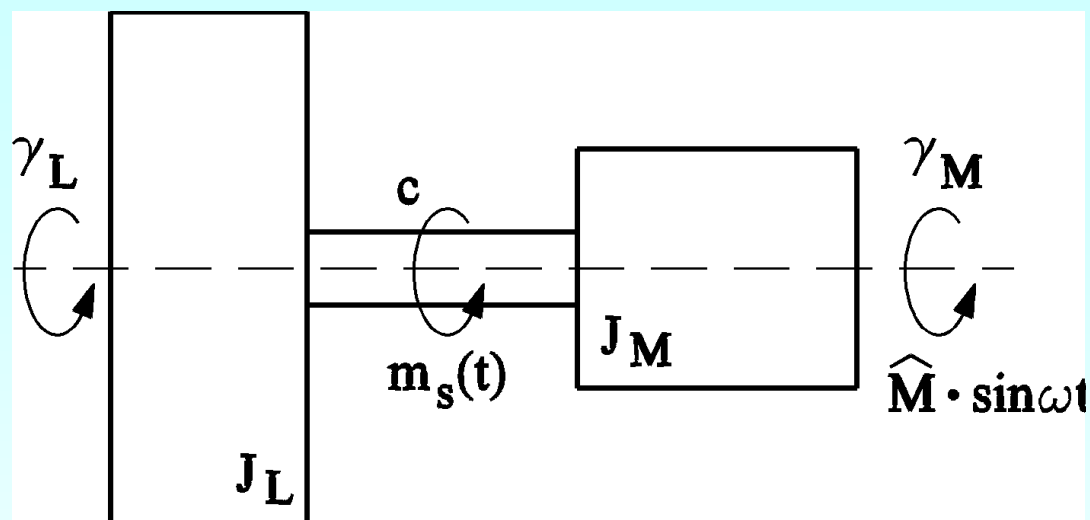
b) deviation of **trapezoidal** back EMF from ideal shape (slope increased by t_d)



Facit:

The sine wave commutated motor has a lower load dependent torque ripple ($\sim 1\%$) than the block commutated brushless DC drive (ca. 4 ... 5%).

Torsional resonance



Rotor of motor coupled to rotating load via an elastic coupling

coupling stiffness c

inertia of motor and load J_M, J_L

$$J_L \ddot{\gamma}_L - m_s = 0 \quad , \quad J_M \ddot{\gamma}_M + m_s = m_{e,c} \quad , \quad m_s = c \cdot (\gamma_M - \gamma_L)$$

$$\ddot{\gamma}_L = m_s / J_L \quad , \quad \ddot{\gamma}_M = (m_{e,c} - m_s) / J_M \quad \Rightarrow \quad \ddot{\gamma}_M - \ddot{\gamma}_L = -\left(\frac{1}{J_M} + \frac{1}{J_L}\right) m_s + \frac{m_{e,c}}{J_M}$$

Differential equation:

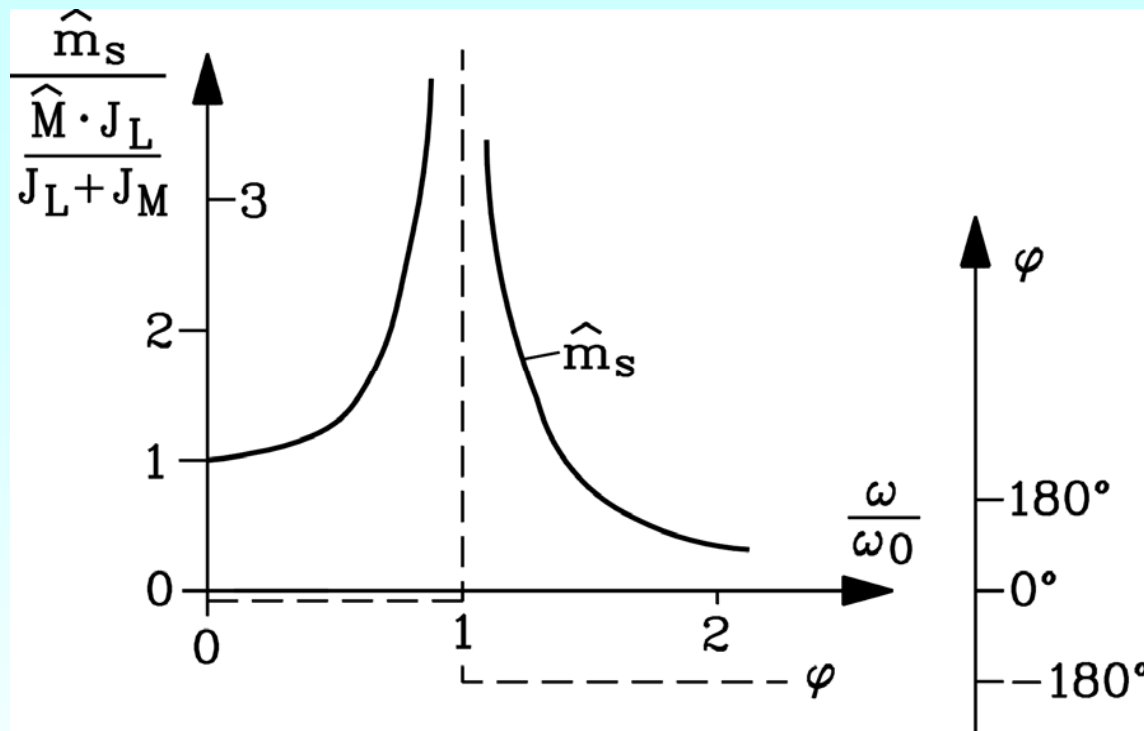
$$\ddot{\gamma} + \frac{c \cdot (J_M + J_L)}{J_M \cdot J_L} \cdot \gamma = \frac{m_{e,c}}{J_M}$$

Homogeneous solution leads to

torsional resonance frequency:

$$f_0 = \omega_0 / (2\pi) = \frac{1}{2\pi} \cdot \sqrt{c \cdot \frac{J_M + J_L}{J_M \cdot J_L}}$$

Excitation of torsional vibrations



Pulsating torque excites torsional vibrations:

$$m_{e,c}(t) = \hat{M} \cdot \sin(\omega t)$$

$$\omega = k \cdot (2\pi \cdot n \cdot p)$$

Solution of differential equation with exciting torque ripple yields vibration angle γ and oscillating shaft torque m_s :

$$\gamma(t) = \frac{\hat{M}}{J_M} \cdot \frac{1}{\omega_o^2 - \omega^2} \cdot \sin(\omega t)$$

$$m_s(t) = c \cdot \gamma(t) = \frac{\hat{M}}{J_M} \cdot \frac{c}{\omega_o^2 - \omega^2} \cdot \sin(\omega t)$$

It must be avoided that the dominant cogging torque frequency excites the torsion resonance of the drive system. This can be achieved by designing the drive with a stiff coupling (c : high value) to stay with cogging torque frequency below the resonance.

Speed ripple due to torque pulsation

Speed ripple definition: $n(t) = n + \Delta n(t)$

From solution of torsional oscillation we know oscillation angle:

$$\text{Angular acceleration is: } \ddot{\gamma}_M(t) = \frac{m_e(t) - m_s(t)}{J_M} = \frac{\hat{M}}{J_M} \cdot \left(1 - \frac{c / J_M}{\omega_o^2 - \omega^2}\right) \cdot \sin(\omega t)$$

Speed ripple: $\Delta n(t) = \dot{\gamma}_M(t) / (2\pi)$

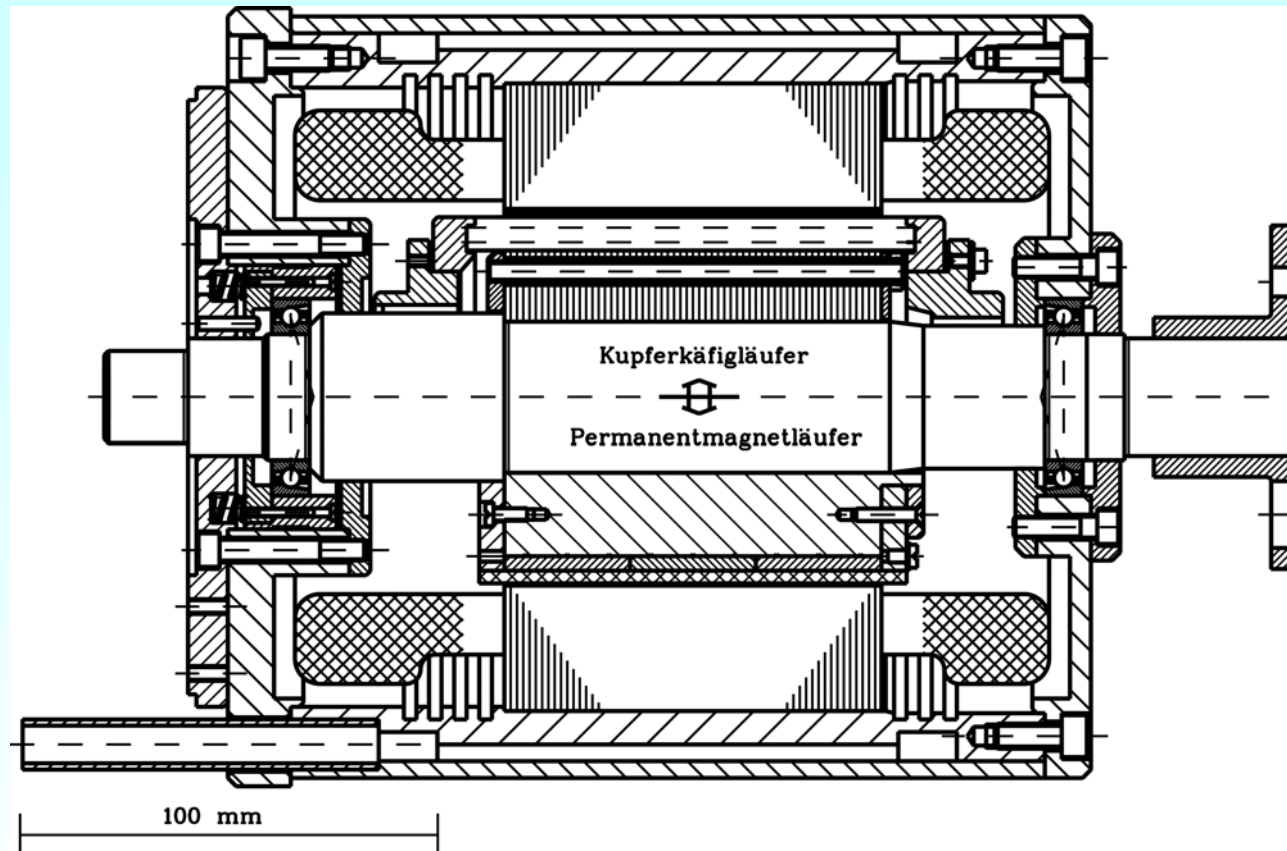
$$\Delta n(t) = \dot{\gamma}_M(t) / (2\pi) = -\frac{\hat{M}}{2\pi \cdot \omega \cdot J_M} \cdot \left(1 - \frac{c / J_M}{\omega_o^2 - \omega^2}\right) \cdot \cos(\omega t)$$

Staying below the resonance $\omega \ll \omega_0$, we observe that especially at low speed the speed ripple amplitude, expressed as percentage of actual speed, increases with DECREASING speed:

$$\left| \frac{\Delta n}{n} \right| = \left| \frac{\hat{M}}{(2\pi)^2 \cdot k \cdot p \cdot n^2 \cdot J_M} \cdot \left(1 - \frac{c / J_M}{\omega_o^2 - \omega^2}\right) \right| \approx \frac{\hat{M}}{(2\pi)^2 \cdot k \cdot p \cdot n^2 \cdot (J_M + J_M)} \sim \frac{1}{n^2}$$

7. Zusatzverluste in umrichter gespeisten PM-Synchronmaschinen

Vergleich Asynchron-/Synchronmaschine: 30 kW, 24000/min



Identische Ständerausführung, Wassermantelkühlung, Spindellager:

Asynchronmaschine mit Kupfer-Ovalstab-Kurzschlusskäfig,

Synchronmaschine: PM-Läufer ($\text{Sm}_2\text{Co}_{17}$ -Oberflächenmagnete) und Glasfaserhülse

Hi-Speed-Läufer: PM-Synchron- vs. Asynchron-Technik



AC-Läufer: 24000/min

30 kW, $d = l_{Fe} = 90$ mm

25 kW/dm³ dauernd

Vierpoliger PM-Läufer,
geblechtes Joch, VOR dem
Aufpressen der Glasfaser-Hülse



Vierpoliger Asynchron-
Kupferkäfig-Läufer mit
Ovalstäben:

Masse/Stab: 23 Gramm

Fliehkraft/Stab: 0.6 Tonnen

Sinusbetrieb 800 Hz: Vergleich Asynchron-/PM-Synchron

Motor	Asynchron, Kupferkäfig	PM-Synchron, $\text{Sm}_2\text{Co}_{17}$
U_s (verkett.), I_s , $\cos\varphi$	330 V, 72.8 A, 0.77	311 V, 62.2 A, 0.95
Drehzahl, Schlupf	23 821 /min, 0.008	24 000 /min, 0.0
Abgabeleistg. P_{out}	29 933 W	30 157 W
$P_{Cu,s}$, $P_{Cu,r}$	537 W, 251 W	353 W, 0 W
P_{Fe} , P_R , P_z	650 W, 480 W, 49 W	660 W, 440 W, 100 W
Kühlwassertemp.	ein: 41.5 °C, aus: 47.5 °C	ein: 44.4 °C, aus: 48.1 °C
Kühlwasserstrom	3.25 l/min	3.25 l/min
Erwärmung: Wickelkopf / Nut *)	84.5 K / 68.5 K	42 K / 36 K
Wirkungsgrad	93.7 %	95.1 %

*) Erwärmung über Wasseraustrittstemperatur

PM-Synchron: deutlich niedrigere Verluste und Erwärmung

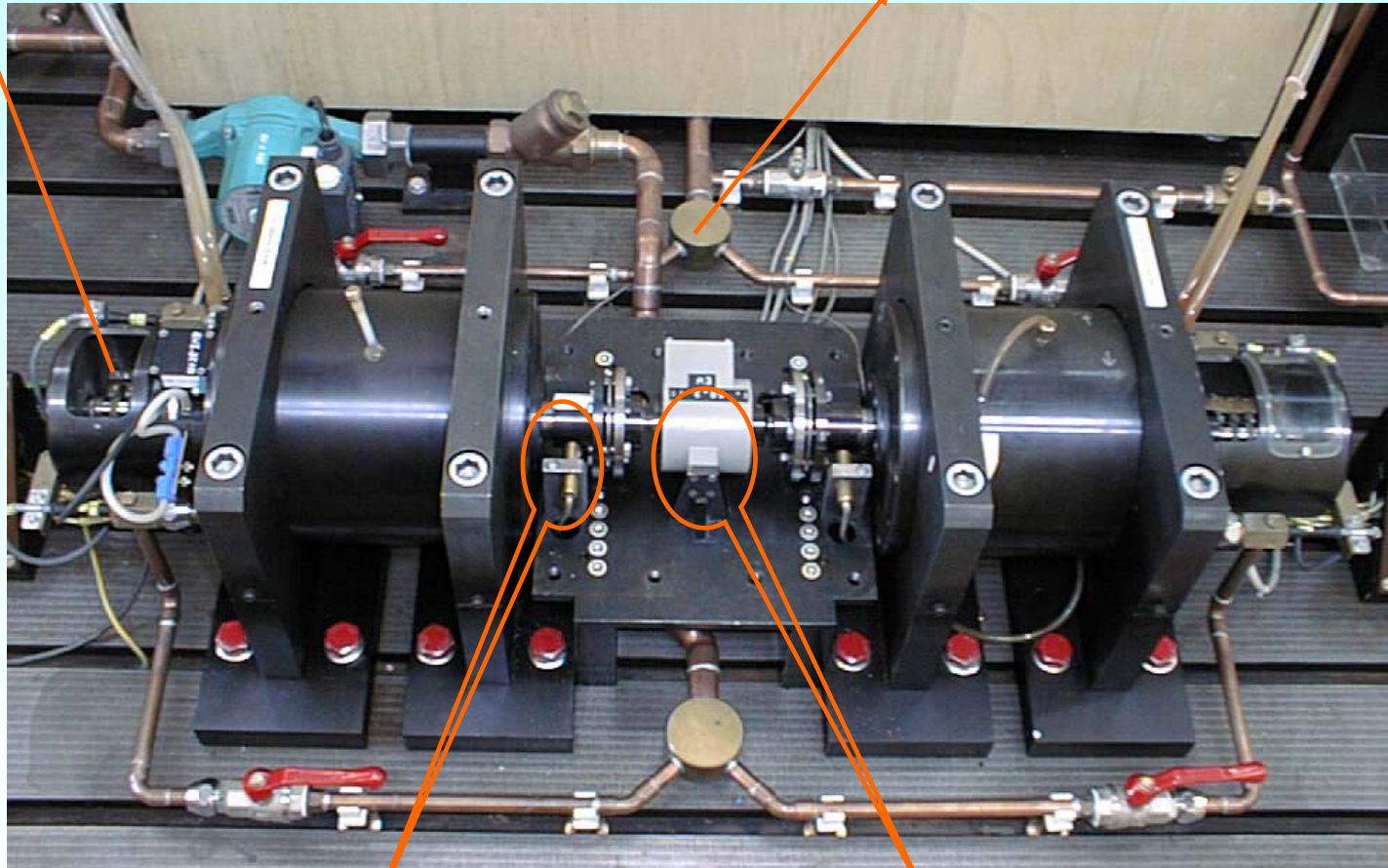
Motorenprüfstand für 24 000/min, 30 kW

Rotortemperatur-Messung

Wasserkühlkreislauf

**PM-
Synchron
Test-Motor**

- 30 kW
- 24 000 rpm
- 12 Nm
- 800 Hz



**ASM
Last**

Drehzahlmessung

Drehmomentmesswelle

Umrichterspeisung

- Zum Vergleich: **Sinusumformer** (bis 800 Hz, 40 kVA)
- **PWM-IGBT-Spannungszwischenkreisumrichter**: 90 kVA, bis 1400 Hz (Schaltfrequenz 12 kHz)
- **Blocktaktung, variable Zwischenkreisspannung** 0 ... 520 V, 50 kVA, Transistor-Wechselrichter

Umrichter-Ausgangsspannung \Rightarrow Oberschwingungen im Strom \Rightarrow Zusätzliche Luftspaltfelder \Rightarrow Zusätzliche Motor-Verluste \Rightarrow **Erhöhte Erwärmung**

Abhilfe:

Stromglättung durch Ausgangsdrossel bzw. Sinusfilter

Umrichterspeisung vs. Sinusspeisung

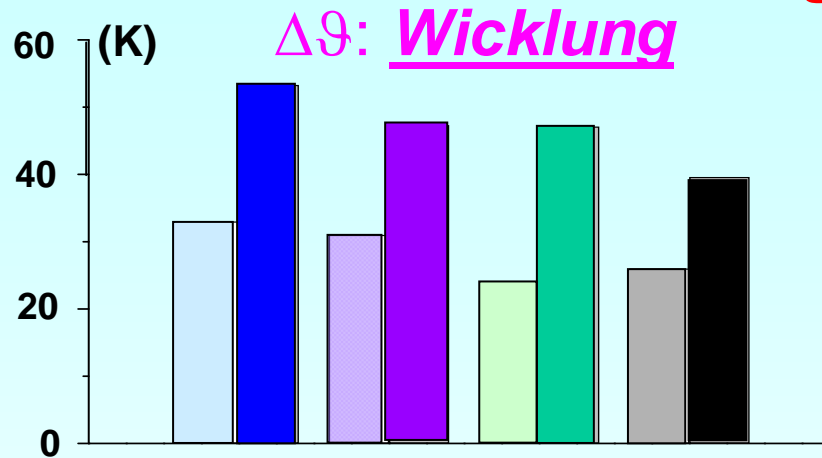
Permanent magnet synchronous motor: magnets $h_M = 3.5$ mm, $d_B = 2.8$ mm, $\delta = 0.7$ mm		
Fundamental voltage, current, power factor	<i>Ideal sine wave operation</i>	<i>Voltage six step inverter operation</i>
$U_{s,(l)}$ (line to line), I_s , $\cos\varphi_{(l)}$	301 V, 67.4 A, 0.89	309 V, 71.9 A, 0.84
Motor output power P_{out}	30 144 W	30 159 W
P_{Fe}	560 W	560 W
P_{fr}	440 W	440 W
$P_{Cu,s}$	430 W	522 W
$P_{M+Fe,r}$	50 W	520 W
Efficiency	95.3 %	93.65 %

Gemessene Verluste in einer PM Synchronmaschine mit Oberflächenmagneten und massivem Rotorjoch

Abhilfe:

Stromglättung durch Ausgangsdrossel bzw. Sinusfilter

PM-Synchronmotor: Gemessene Erwärmung in Ständerwicklung und Läufermagneten

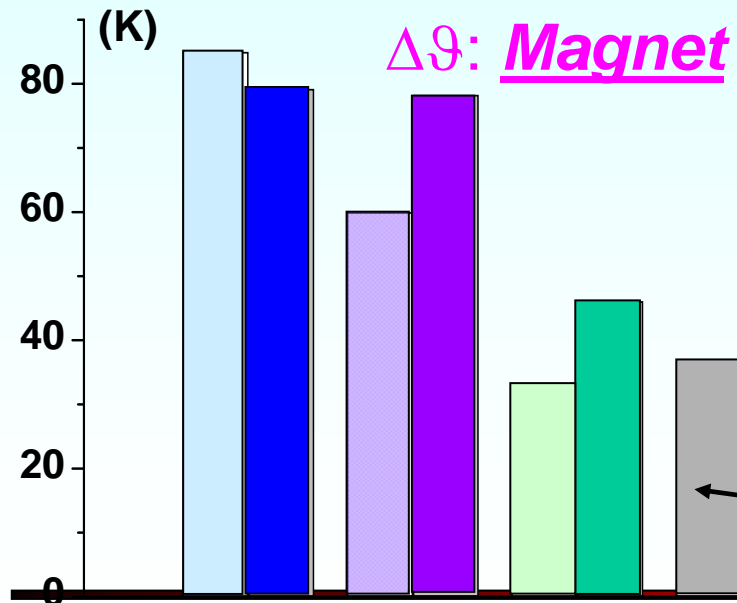


PWM mit Ausgangsdrossel +

Blockspannung ++

PWM mit Sinusfilter +++

Sinusumformerspeisung +++



(PWM ohne Filter: $\Delta\vartheta$ zu hoch)

Bei 30 kW, 24 000 /min

Bei Leerlauf, 24 000 /min

Numerische Berechnung der Zusatzverluste im Läufer

Wassermantel

Ständerblechpaket

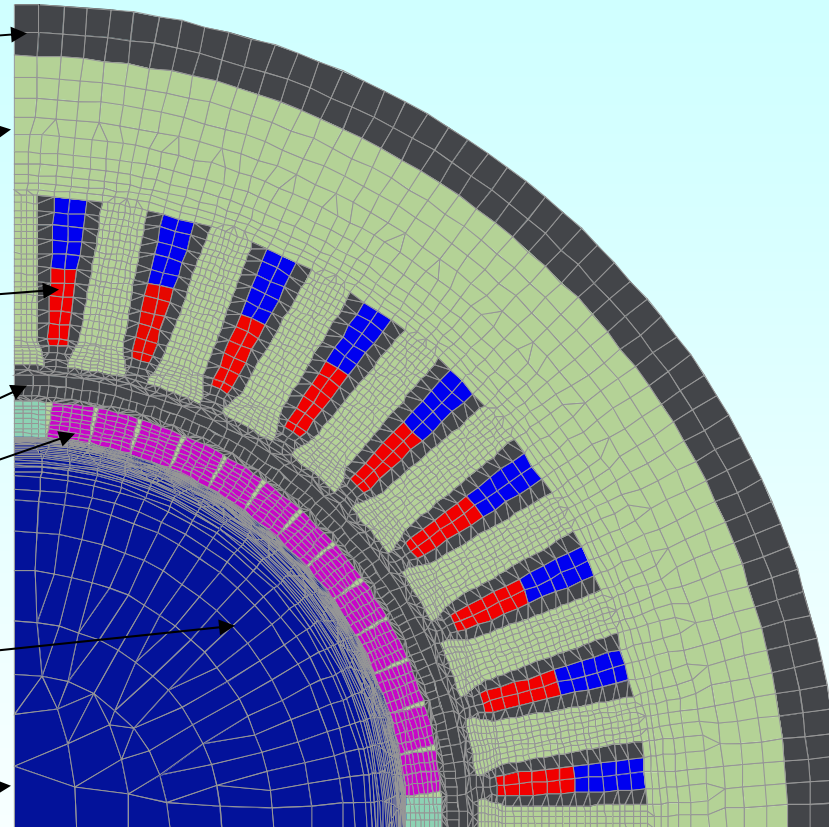
Zweischicht-Drehstrom-
wicklung

Luftspalt und Bandage

Läufermagnete

Läuferjoch

Läuferwelle



Ergebnis: **Massives** Läuferjoch: Zu hohe Verluste bei Blockspannungsspeisung; Abhilfe: Geblechtes Joch oder Sinusfilter