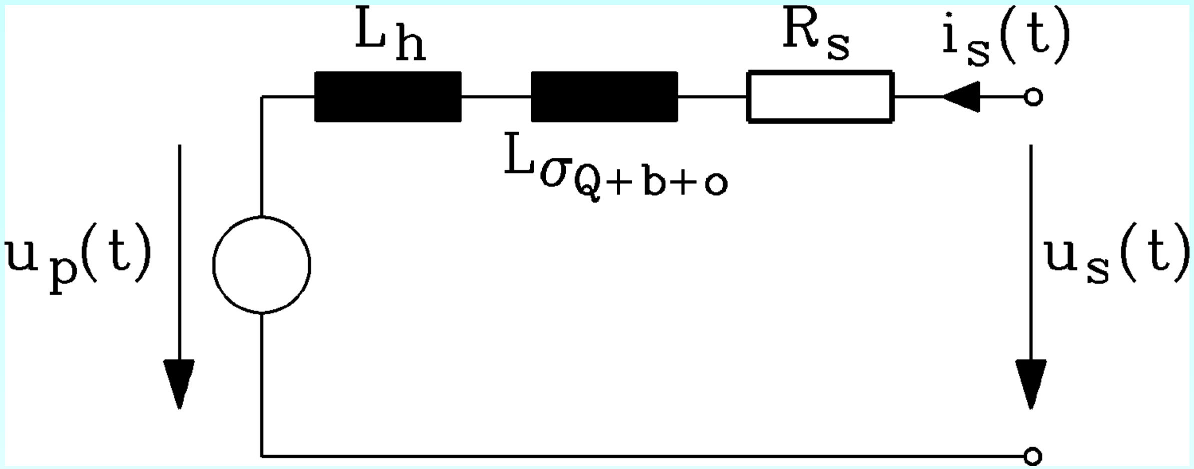
2. Ansteuerung von PM-Maschinen

Equivalent circuit of PM synchronous machines



Voltage equation per phase:

- back EMF $u_p(t)$
- self-induced voltage ~ $\mathrm{d}i_s/\mathrm{d}t$
- resistive voltage drop
- voltage from feeding inverter: $u_s(t)$

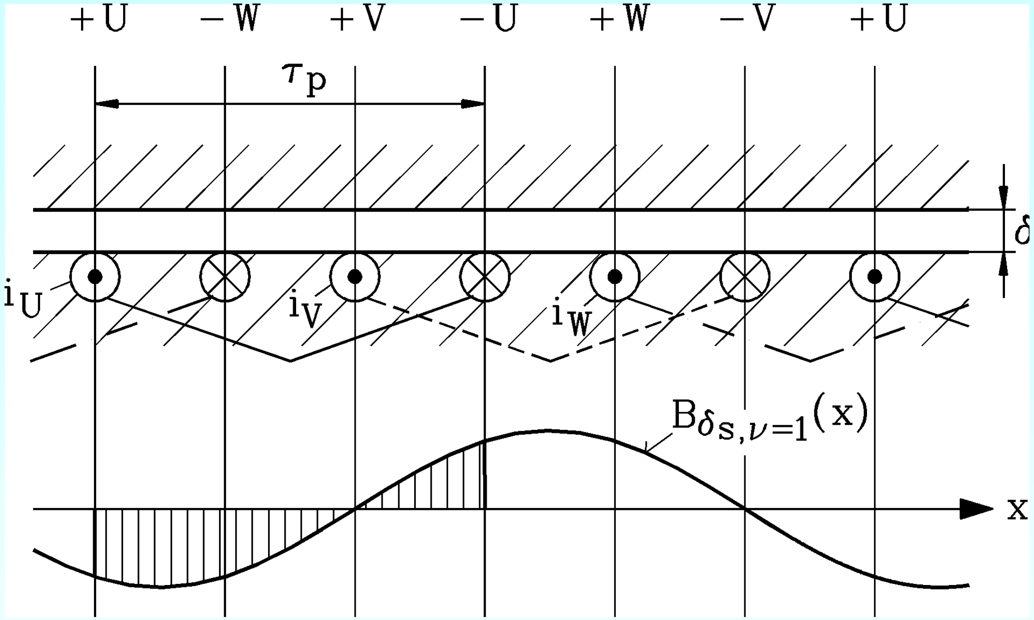
$$u_s(t) = R_s \cdot i_s(t) + L_d \frac{di_s(t)}{dt} + u_p(t)$$

$$L_d = L_h + L_\sigma$$

Synchronous inductance: main and leakage inductance:

Leakage: Q: slot; b: overhang, o: harmonic

Air gap flux density excited by the distributed stator winding



Resulting air-gap:

$$\delta_{res} = \delta + h_B + h_M$$

mechanic air gap

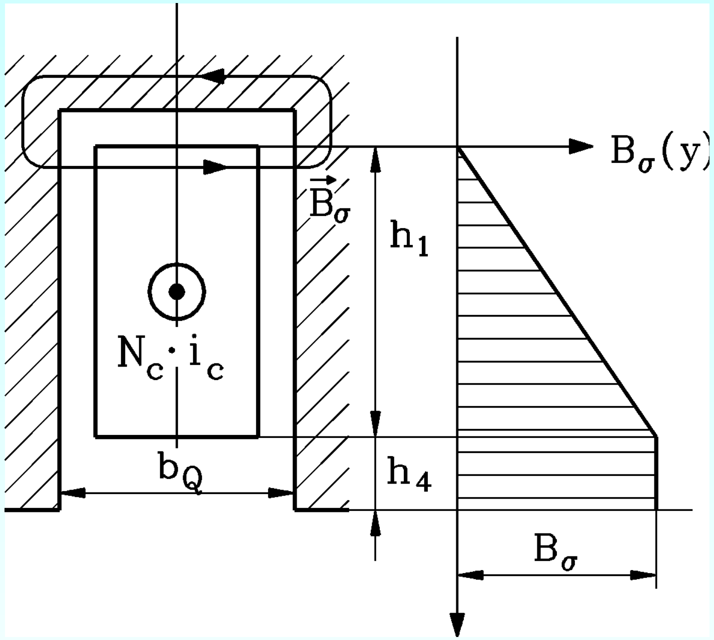
bandage thickness

magnet height

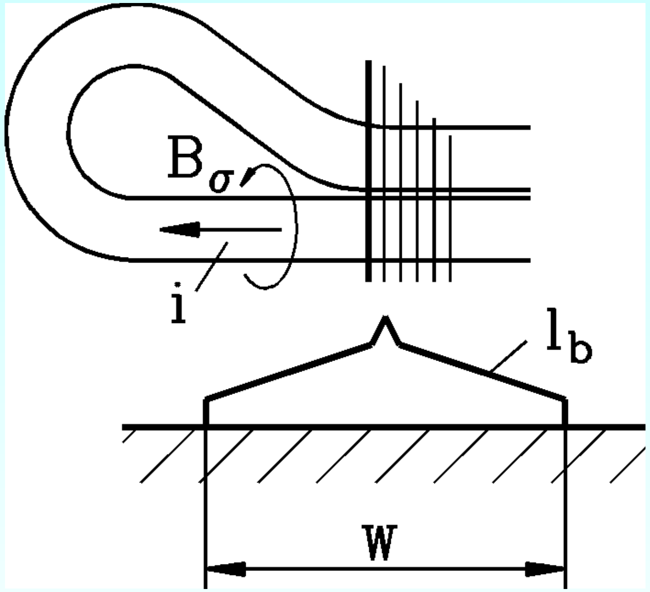
Fundamental of this flux density induces back into stator winding, thus linking phases U, V, W, generating a self-inductance (main inductance) L_h, which is equal for all three phases (here is shown flux excited by phase V, linked with coil of phase U)

$$L_h = \frac{U_{s,s}}{\omega_s \cdot I_s} = \mu_0 \cdot (N_s \cdot k_{ws})^2 \cdot \frac{2m_s}{\pi^2 \cdot p} \cdot \frac{\tau_p l_{Fe}}{\delta_{res}}$$

Schematic drawing of stray flux lines



a)



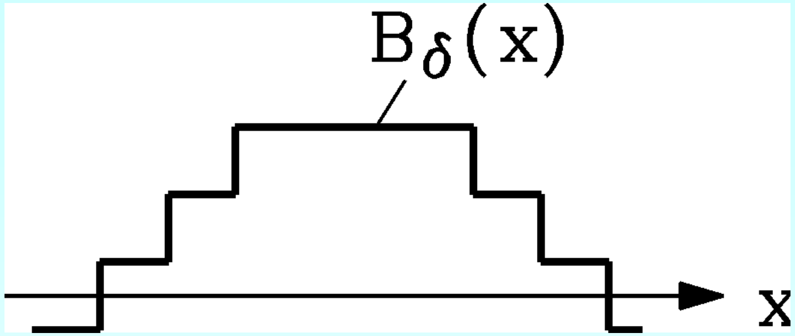
b)

a) Slot leakage flux, rising linear from bottom to top of slot according to *Ampere´*s law,
b) leakage flux density of winding overhangs

Harmonic leakage inductance

Harmonic inductance: Step-like air gap flux density distribution: *Fourier* analysis

$$B_\delta(x,t) = \sum_{\nu=1,-5,7,\ldots}^{\infty} B_{\delta\nu} \cdot \cos(\nu\pi x/\tau_p - \omega_s t)$$

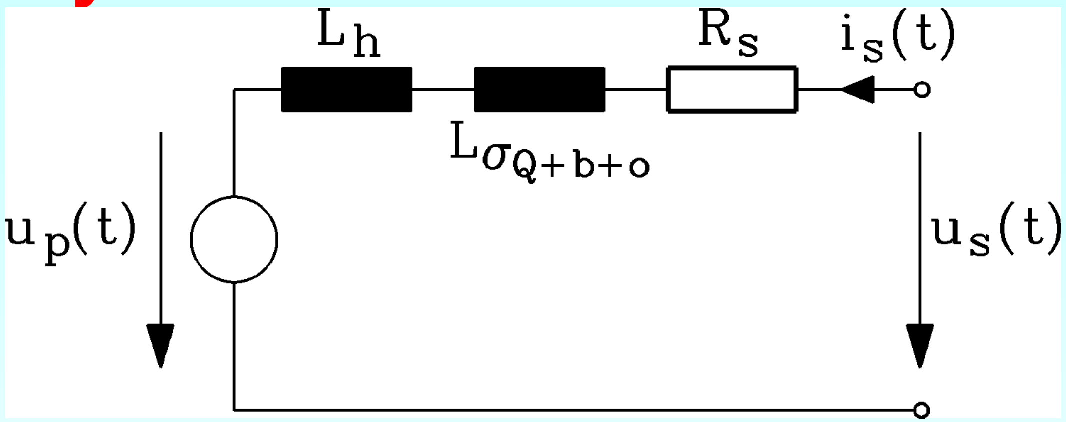


Each harmonic induces stator winding with stator frequency, thus adding up induced voltage.

$$\Delta\underline{U}_{hs} = \sum_{|\nu|>1} \underline{U}_{h\nu} = \sum_{|\nu|>1} jX_{h\nu} \cdot \underline{I}_s$$

$$\Delta\underline{U}_{hs} = \sum_{|\nu|>1} jX_{h\nu} \cdot \underline{I}_s = jX_{h,\nu=1} \cdot \underline{I}_s \cdot \sum_{|\nu|>1} \left(\frac{k_{ws\nu}}{\nu \cdot k_{ws1}} \right)^2 = jX_{\sigma,Os} \cdot \underline{I}_s$$

Equivalent circuit per phase of synchronous PM machine

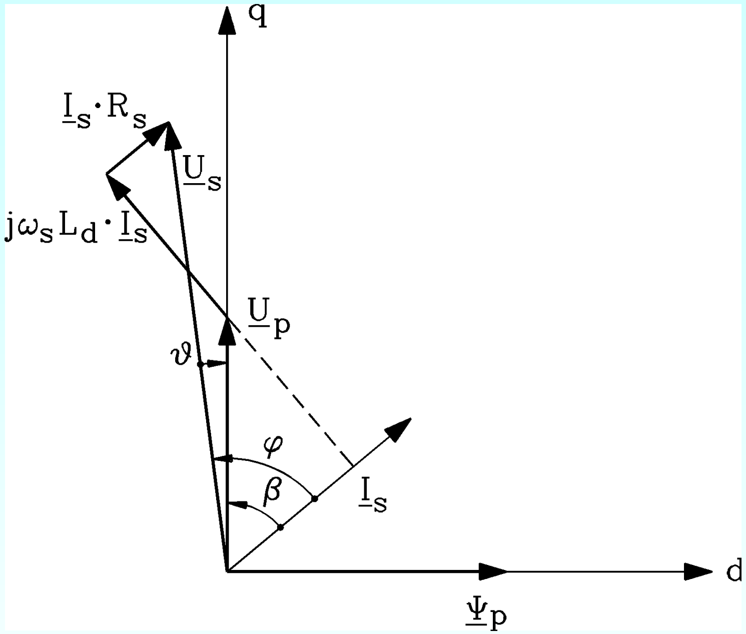


$$u_s(t) = R_s \cdot i_s(t) + L_d \frac{di_s(t)}{dt} + u_p(t)$$

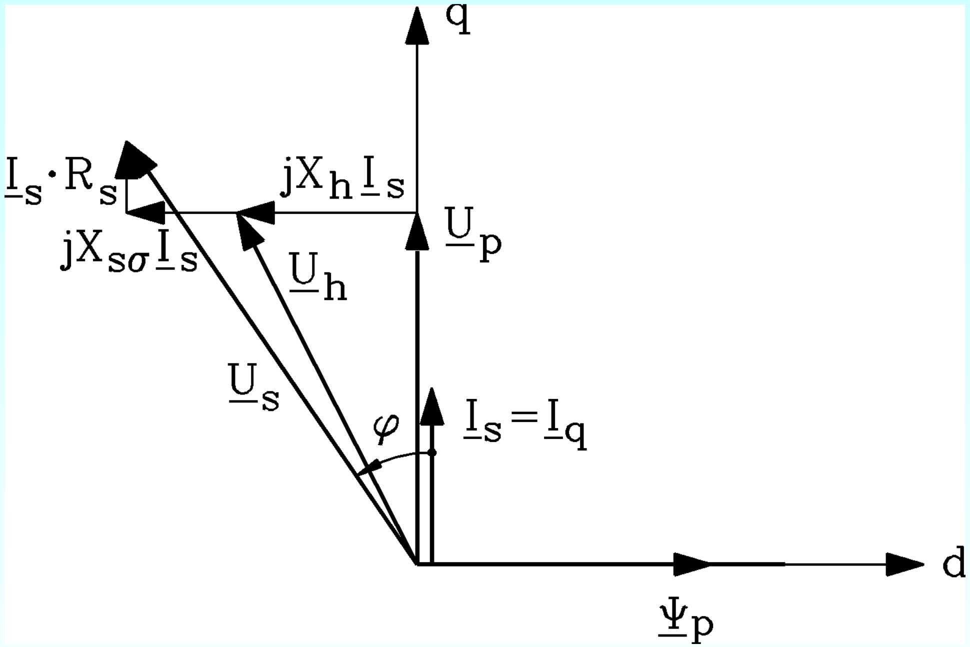
- Considering only time fundamentals = use complex phasors $\underline{U}_s$, $\underline{U}_p$ and $\underline{I}_s$!
- Field oriented operation = current in phase with back EMF: ***q*-axis current I_q.**
- Surface magnets: inductivity for *d*- and *q*-axis identical ($L_d = L_q = L_s$)

$$\underline{U}_s = R_s \underline{I}_s + j\omega L_d \underline{I}_s + \underline{U}_p$$

Phasor diagram per phase of synchronous PM machine at operation with sinusoidal voltage and current



a)

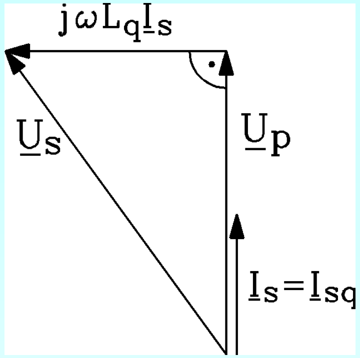


b)

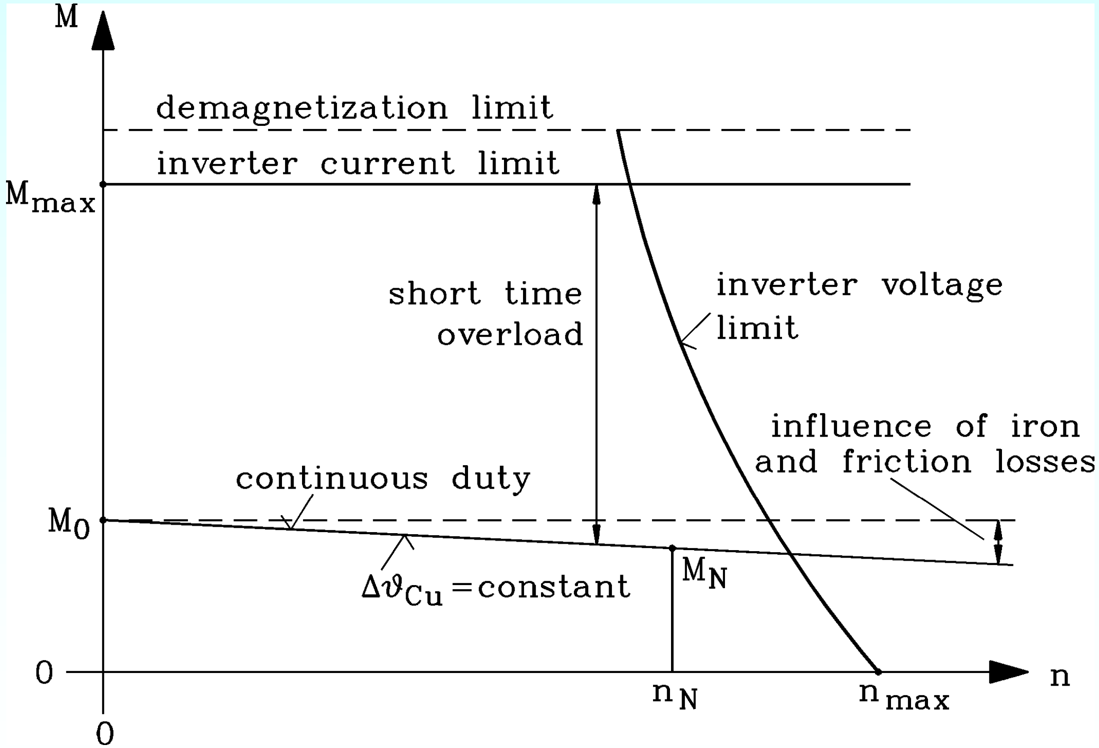
a) arbitrary current phase shift,

b) field-oriented control = current **in phase** with back EMF U_p **("brushless DC drive"). Load angle ϑ equals phase shift φ.**

Operating limits of brushless DC drive



Phasor diagram per phase of synchronous PM machine at high speed with neglected stator resistance; field-oriented control with current in phase with back EMF, no saliency assumed $L_d = L_q$



Speed-torque curve limit for synchronous PM machine with field-oriented control (current in phase with back EMF)

Operation limits for brushless DC drive

- **Steady state torque:** temperature limit of insulation material of stator winding.

  E.g.: Temperature limit (IEC 34-1): 105 K for insulation class F (ambient temperature 40°C).

  Stand-still torque: M_0 at $n = 0$: only resistive losses

  Rated torque an rates speed: M_N at n_N: Resistive losses, friction and iron losses, additional losses.

  For constant temperature and self-cooled machine: Total losses must be constant $\Rightarrow$ Resistive losses must decrease at n_N, hence current decreases: $M_N < M_0$.

- **Dynamic torque (Overload** up to about $4M_0$ **): A**ccelerating and braking: short time operation (several seconds). Temperature rise according to thermal time constant T_{th} of the motor winding stays below temperature limit. So **dynamic torque** overload up to about $4M_0$ is only possible for.

- **Maximum torque: inverter current limit**.

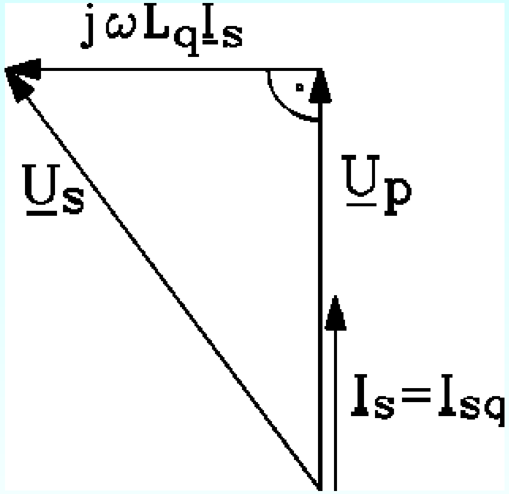
- **Demagetization limit:** Inverter current limit must be below the critical motor current which would cause irreversible demagnetization of the hot rotor magnets (at 150°C).

- **Mechanical maximum speed limit** n_{max} > rated speed n_N !

- **Inverter voltage limit:** Internal motor voltage reaches inverter voltage limit, hence current input and torque decreases

Voltage limit for brushless DC drive

- *Inverter-output voltage* U_{max} defines maximum possible motor speed n_{max}.



At high speed neglect $R_s << X_q$:

$$I_{s,\lim} = \frac{1}{\omega_s L_d} \cdot \sqrt{U_{s,\max}^2 - (\omega_s \Psi_p / \sqrt{2})^2}$$

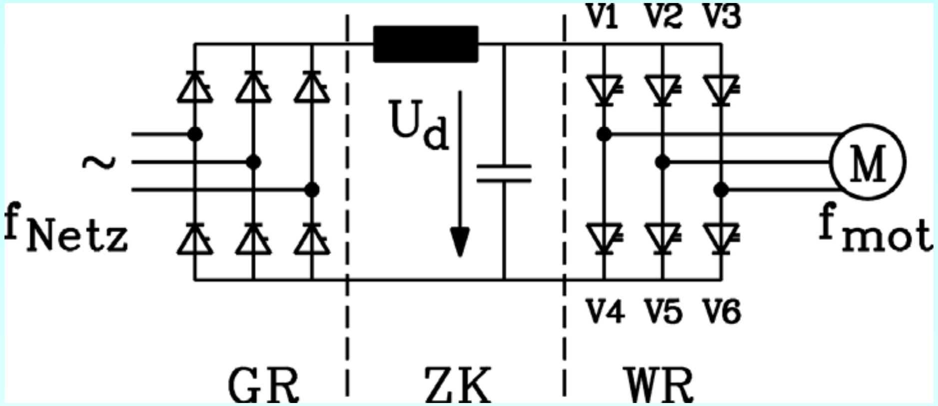
$$M_{\lim} = m \cdot p \cdot \frac{\Psi_p}{\sqrt{2}} I_{\lim}(n)$$

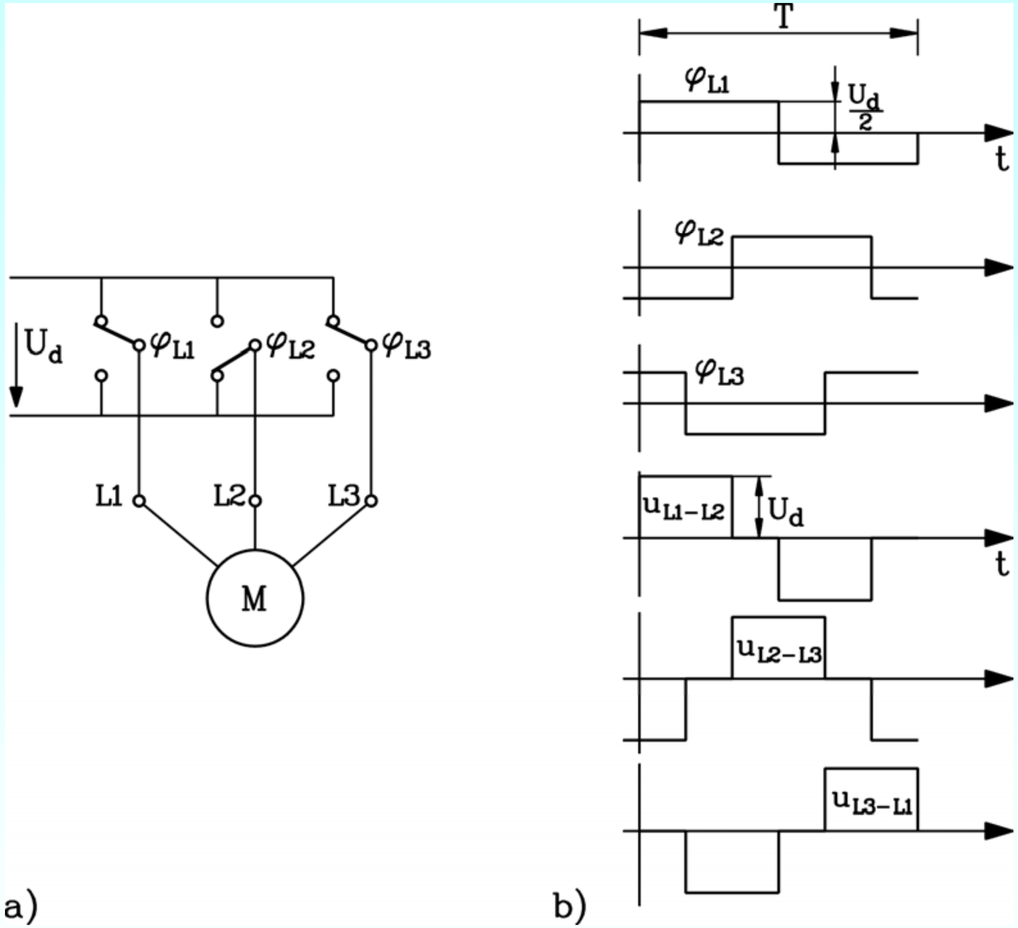
- **Maximum possible motor speed** = No-load speed at voltage limit:

$$U_{s,\max} = \omega_{s,\max} \cdot \Psi_p / \sqrt{2}$$

$$n_{\max} = n_N \frac{U_{\max}}{U_{pN}}$$

Blockspannungs-Taktung

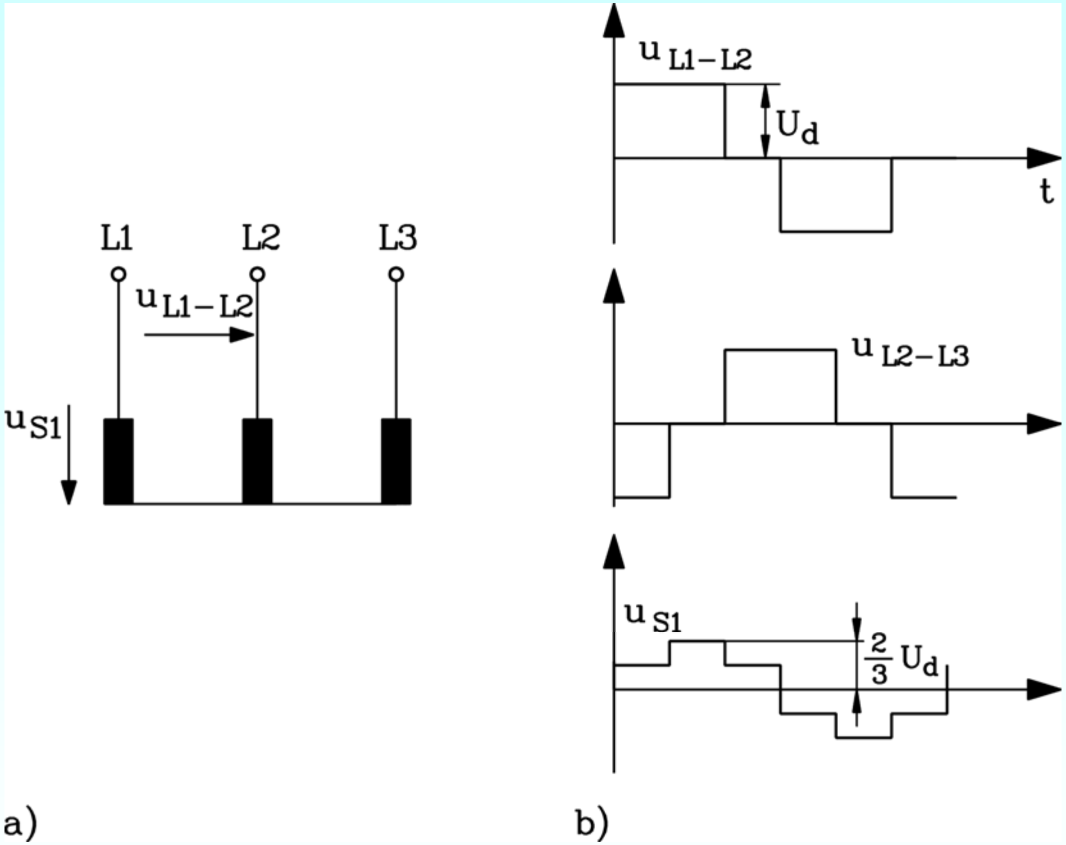




- Gesteuerter Netzgleichrichter GR (Steuerwinkel α) erzeugt variable Gleichspannung U_d im Zwischenkreis ZK; Glättung mit Kondensator: .
- Wechselreichter WR erzeugt daraus **blockförmige** verkettete Ausgangsspannung zwischen den Klemmen L1, L2, L3.
- Zwischenkreisspannung U_d wird **proportional** zur Ausgangsfrequenz f_{mot} verändert.
- Netzseitig: Ab $\alpha > 90°$: Leistung im Zwischenkreis ist negativ: Rückspeisung erfolgt ins Netz.

Oberschwingungen bei Blockspannungs-Taktung

- **Die Strangspannung u_S:** Aus $u_{S1} - u_{S2} = u_{L1-L2}; \quad u_{S2} - u_{S3} = u_{L2-L3}; \quad u_{S1} + u_{S2} + u_{S3} = 0;$



folgt: $$u_{S1} = \frac{2u_{L1-L2} + u_{L2-L3}}{3}$$

- Blockförmige verkettete Spannung: zeitliche *FOURIER*-Reihe:

$$u_L(t) = \sum_{k=1,-5,7,..}^{\infty} \hat{U}_{L,k} \cdot \cos(k \cdot \omega_s t)$$

$$k = 1 + 6g, \qquad g = 0, \pm 1, \pm 2, ...$$

$\Rightarrow$ k = 1, -5, 7, -11, 13, ...

$$\hat{U}_{L,k} = \frac{2}{\pi} \sqrt{3} \frac{U_d}{k}$$

Die Maschine erhält ein Gemisch unterschiedlich-frequenter Sinusspannungen. Nur die Grundschwingung k = 1 ist erwünscht. Die Oberschwingungen |k| > 1 bewirken Oberschwingungsströme mit zusätzlichen Verlusten.

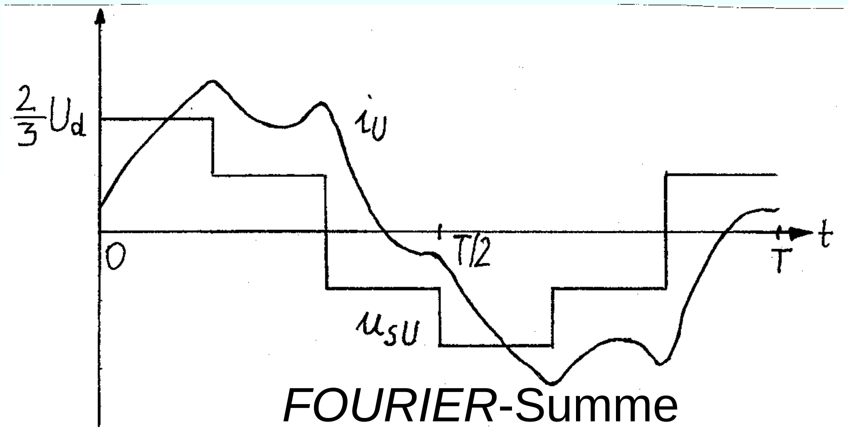
Beispiel: Stromoberschwingungen bei Blocktaktung

- Amplituden der Strangstromober-schwingungen bei Blockspannungsbetrieb: (U_p wirkt nur für Grundschwingung !)

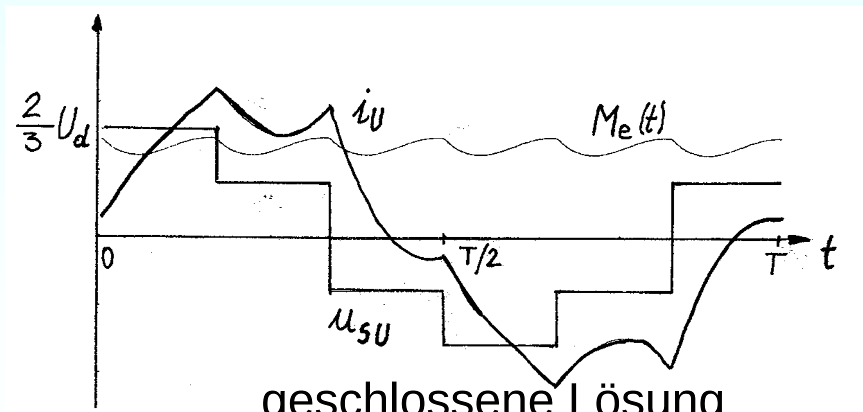
$$I_{s,k} \approx \frac{U_{s,k}}{|k|\omega_s(L_{s\sigma}+L_{sh})} \sim \frac{1}{|k|^2}$$

k	1	-5	7	-11	13
$\left\|\hat{U}_{Lk}/\hat{U}_{L1}\right\|$	1	0.2	0.14	0.1	0.08
$I_{s,k}/I_{s,k=1}$	1	0.04	0.02	0.008	0.006

- *Die Stromoberschwingungen sinken wesentlich rascher mit steigender Ordnungszahl als die Spannungsoberschwingungen, weil die Streuinduktivität den Stromverlauf* ***"glättet"****.*

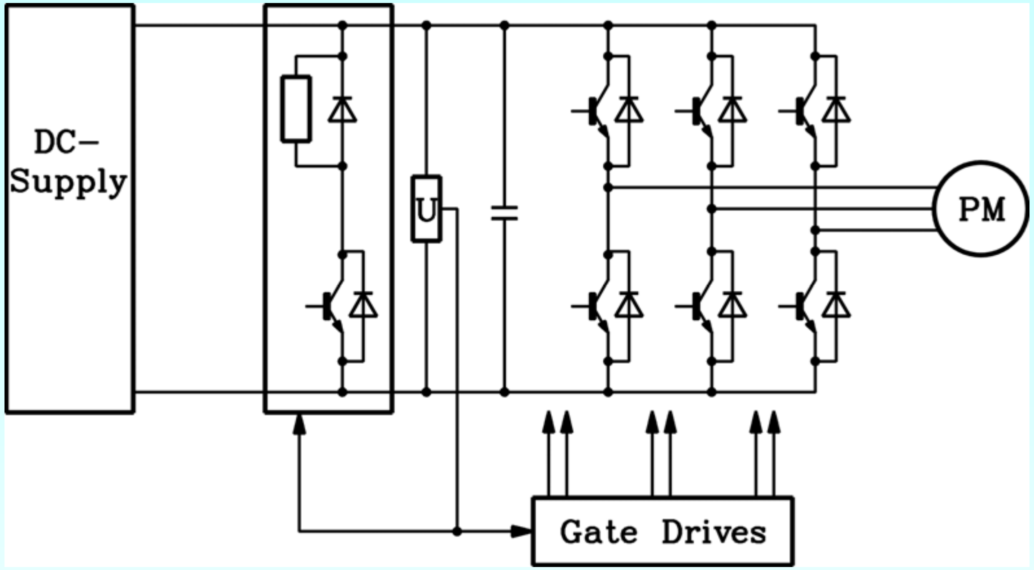


FOURIER-Summe



geschlossene Lösung

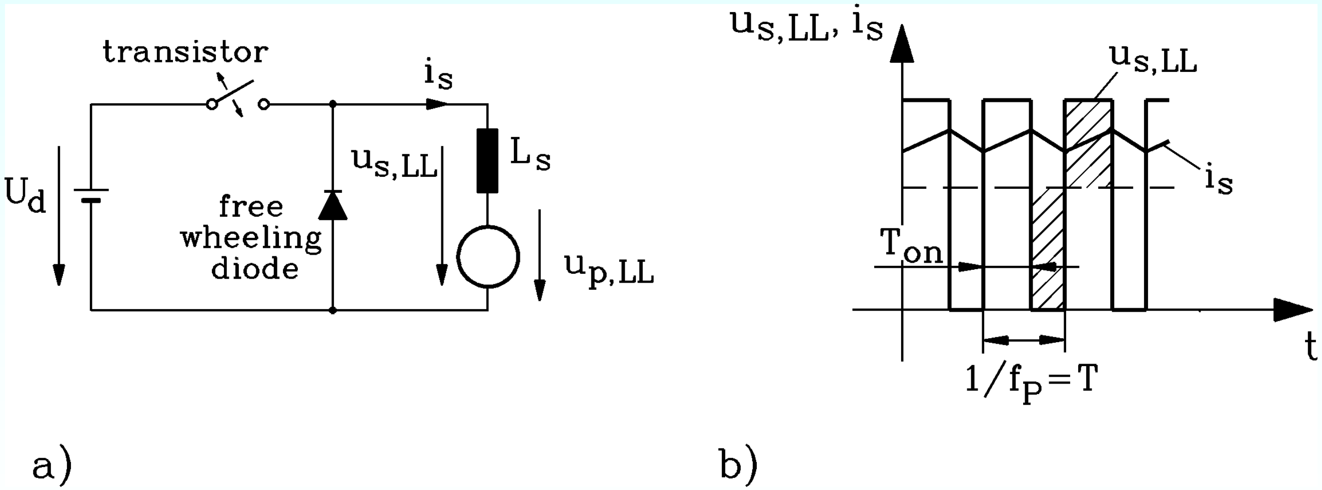
PWM: Stator current generation



$\color{blue}{\text{DC link voltage source inverter}}$ with switching transistors and free-wheeling diodes

R_s neglected:

$$U_d - U_{p,LL} \approx L_s \cdot di_s / dt$$

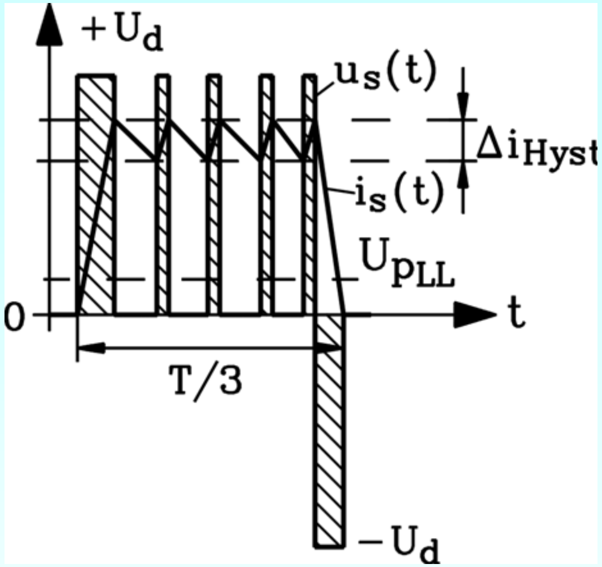


a) Equivalent switching scheme of DC link voltage source inverter, connected to the two phases with switching transistor and free-wheeling diode,

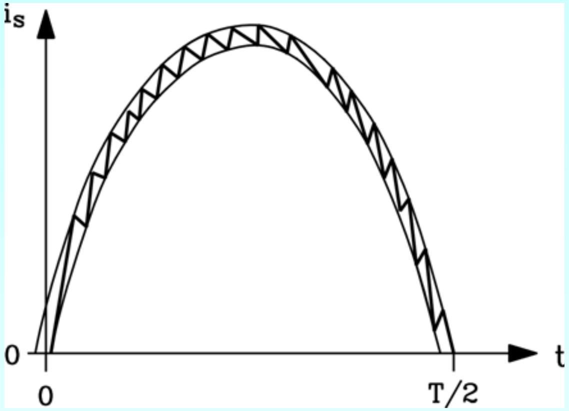
b) Current ripple and chopped inverter voltage

Hysteresis band current control

block commutation



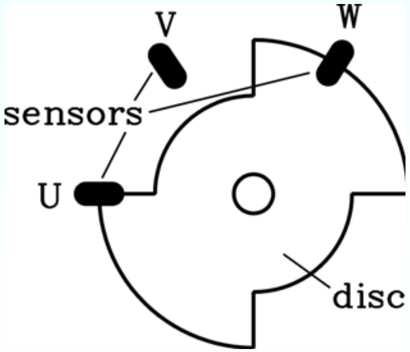
sine wave commutation



Shaping of current with hysteresis band

Current commutation from phase U to V etc.:

Determination of current phase shift (= firing angle) by encoder fo get rotor position. Current shall be in phase with back EMF !



Block commutation: Six step encoder:

A rotor disc and three stator-fixed sensors U, V, W, spaced by 120°/p (p: number of pole pairs), are sufficient for rotor position sensing for block commutation (here: $2p = 4$)

Measuring rotor position for sine wave commutated synchronous PM machine

Optical incremental encoder,

to be mounted on motor non-drive shaft end *(Heidenhain)*

Rotor position must be known at every moment, as frequency might change at every moment, hence changing sine wave shape !

Position measurement:

a) Resolver: Continuous measurement of position (analogue electromagnetic device)

b) Incremental encoder: High resolution necessary (e.g. 1024 x 4 counts per revolution), hence optical sensors !

Steady state torque of block and sine commutated motors

For same **thermal limit**, only copper losses, same stator geometry, identical winding, identical magnet material and magnet height:

Sine wave and block commutated motors give for the same copper losses the same output power.

PM machine	*Block commutation (B)*	*Sine wave commutation (S)*
Air gap flux density amplitude	$B_\delta = B_p$	$B_{\delta,1} = \frac{4B_p}{\pi}\cdot\sin\left(\frac{\alpha_e\pi}{2}\right)$
Back EMF	$\hat{U}_{pB} = 2N_s\cdot 2f\tau_p\cdot B_p\cdot l_{Fe}$	$\hat{U}_{pS} = 2\pi f\cdot N_s\cdot k_w\cdot\frac{2}{\pi}\tau_p l_{Fe} B_{\delta,1}$
Stator copper losses	$P_{Cu} = 2\cdot R_s\cdot\hat{I}_{sB}^2$	$P_{Cu} = (3/2)\cdot R_s\cdot\hat{I}_{sS}^2$
Air gap power	$P_{\delta B} = 2\cdot\hat{U}_{pB}\cdot\hat{I}_{sB}$	$P_{\delta S} = (3/2)\cdot\hat{U}_{pS}\cdot\hat{I}_{sS}$

Equal copper losses:

$$\hat{I}_{sS}/\hat{I}_{sB} = 2/\sqrt{3}$$

$$\frac{P_{\delta S}}{P_{\delta B}} = \frac{(3/2)\cdot\hat{U}_{pS}\cdot\hat{I}_{sS}}{2\cdot\hat{U}_{pB}\cdot\hat{I}_{sB}} = \frac{\sqrt{3}\cdot 2}{\pi}\cdot k_w\cdot\sin\left(\frac{\alpha_e\pi}{2}\right)$$

Comparison of block and sine wave commutated motors

Example:

Winding factor k_w = 0.933, pole coverage ratio α_e = 0.85:

$$\frac{P_{\delta S}}{P_{\delta B}} = \frac{\sqrt{3}\cdot 2}{\pi}\cdot 0.933\cdot \sin\left(\frac{0.85\cdot\pi}{2}\right) = 1.00035$$

Example:

Operation at inverter current limit $I_{s,max}$: Block or sine wave commutated motor delivers the higher short term torque ?

$$\frac{M_{e,S}}{M_{e,B}} = \frac{P_{\delta S}}{P_{\delta B}} = \frac{(3/2)\cdot \hat{U}_{pS}\cdot \hat{I}_{s,\max}}{2\cdot \hat{U}_{pB}\cdot \hat{I}_{s,\max}} = \frac{\sqrt{3}\cdot 2}{\pi}\cdot k_w\cdot \sin\left(\frac{\alpha_e\pi}{2}\right)\cdot\frac{\sqrt{3}}{2} = \frac{1}{1.15}$$

The block commutated motor is able to deliver at the SAME current amplitude 15% higher maximum torque, whereas for the same copper losses the thermal steady state torque for block and sine wave commutated PM machine is equal.

Block commutated brushless DC drive systems

- permanent magnet motor with three phase, single layer winding, skewed slots and 100% pole coverage ratio for the rotor magnets

- simple rotor position sensor with rotor disc according to pole number,

- brushless DC tachometer for speed measurement,

- encoder with high resolution for precise positioning,

- voltage source inverter system (power transistors), speed and current control, implemented in a micro-computer system; motor current measurement devices such as shunts or DC transformers with *Hall*-sensors,

- motion control system, implemented in a second microcomputer. It allows position control, but also different motion control such as special velocity profiles according to the needs of the driven load.

Sine commutated brushless DC drive systems

- permanent magnet motor with three phase, double layer winding (or special single layer winding with non-integer *q*), skewed slots and 80%...85% pole coverage ratio for the rotor magnets,

- high resolution rotor position sensor (optical encoder or magnetic resolver), which acts also speed sensor and sometimes as position sensor for precise positioning,

- voltage source inverter system (power transistors), speed and current control, implemented in a micro-computer system and motor current measurement devices such as shunts or DC transformers with *Hall*-sensors,

- motion control system, which is implemented in a second microcomputer and allows position control, but also different motion control such as special velocity profiles according to the needs of the driven load.

Block and sine commutated brushless DC drives

Advantages

Block commutation

- cheap rotor position and speed sensor,
- cheap motor winding
- 15% higher overload at inverter current limit

Sine commutation

- 10% ... 15% reduced amount of magnets,
- very low torque ripple below 1%,
- reduced additional losses at high speed,
- reduced torque ripple sensitivity to misalignment of rotor position sensor.

Disadvantages

Block commutation

- extra encoder for accurate drive positioning,
- higher minimum torque ripple (2% ... 4% at low speed,
- increased additional losses in the motor due to extra eddy currents especially in the rotor due to the rapid chance of stator flux at commutation.

Sine commutation

- expensive encoder for current commutation and speed measurement,
- expensive stator winding, if two layer winding is used,
- 15% lower overload capability at inverter current limit,
- more complex mathematical model for motor control.