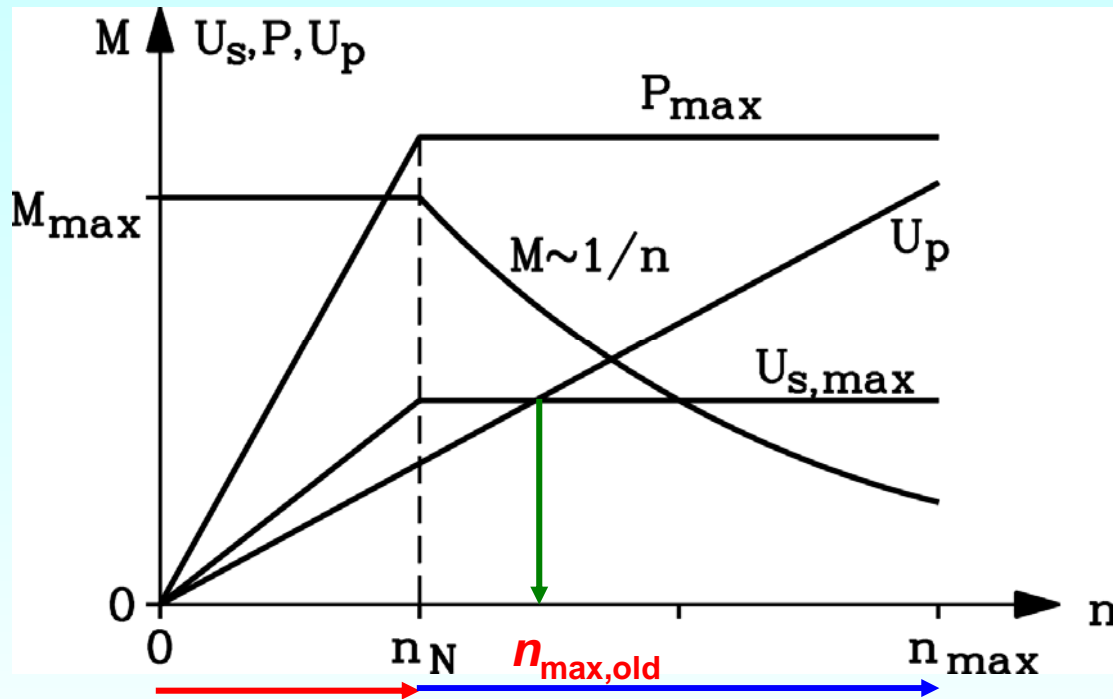


3. Feldschwächung von PM-Maschinen

Flux weakening with negative d-current



Constant torque Flux weakening range

- At **rated speed n_N** the voltage limit $U_{s,max}$ is reached.
- By introducing a **negative d-current** a voltage component opposite to the back EMF U_p is induced, so that remains U_s constant.
- This d-current **does not generate any torque** with the rotor permanent flux !
- At constant resulting current due to the required d-current the q-current must be reduced. Hence **torque M decreases !** („Flux weakening range“)

Instead of $n_{max,old}$ (at $U_s = U_p$) now a higher speed n_{max} is reached, but at a reduced torque, which is not any longer proportional to stator current I_s !

Phasor diagrams of PM machine with field weakening

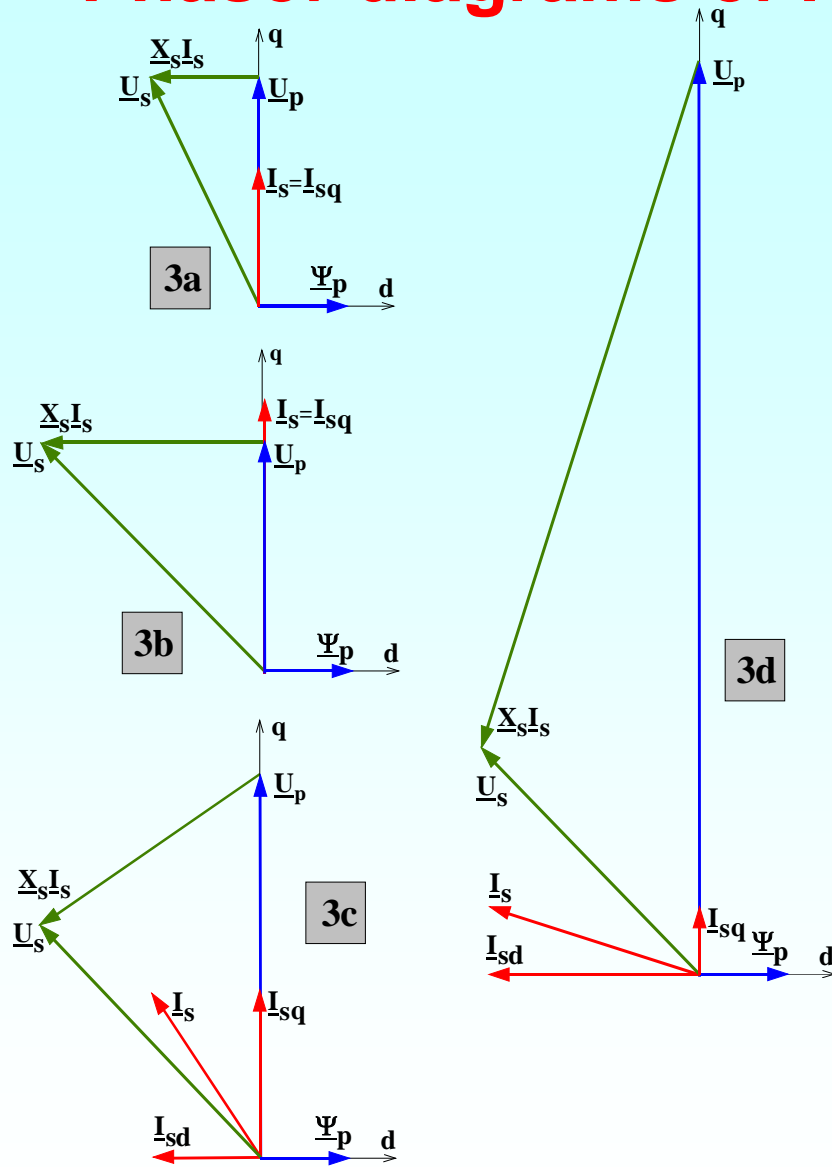
- stator resistance R_s is neglected

a) rated speed, rated torque,

b) rated speed, overload torque,

c) speed at 170% rated speed, decreased torque, flux weakening by negative I_d current,

d) very high speed (400%) can only be reached by strong field weakening; nearly the whole current consists of flux weakening component I_d , whereas torque-producing component I_q is very small.



Demands for flux weakening

	Voltage u_s	Current i_s	d -axis i_{sd}	q -axis i_{sq}	Power	Speed n	$\cos \varphi$
a)	0.8	1.0	0	1.0	P_N	n_N	0.89 ind
b)	1.0	2.0	0	2.0	$2P_N$	n_N	0.7 ind
c)	1.0	1.5	-0.8	1.27	$2P_N$	$1.7n_N$	0.98 ind
d)	1.0	1.7	-1.6	0.5	$2P_N$	$4n_N$	0.89 cap

Big field weakening: $U_p \gg U_{s,max}$, we may neglect $U_{s,max}$ and R_s .

$$I_{s,d} \cong U_p / X_s = \Psi_p / L_s = \Psi_p / L_d$$

The necessary field weakening current must be smaller than the inverter current limit !

$$I_{s,d,max} < I_{s,max}$$

Steady state short circuit current of PM machine

$$I_{s,k} = U_p / \sqrt{R_s^2 + X_s^2} \cong U_p / X_s = \Psi_p / L_s = \Psi_p / L_d < I_{s,max}$$

Demand for infinite field weakening:

If the short-circuit current $I_{s,k}$ of the PM machine is smaller than the inverter current limit $I_{s,max}$, an infinite field weakening is theoretically possible.

Motor and system design for high field weakening:

- synchronous d -axis inductance L_d is big, e.g. big leakage inductance
- permanent magnet flux linkage with stator winding Ψ_p is small
- inverter current limit is high
- inverter voltage limit is high.

$$L_d = L_h + L_\sigma$$

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

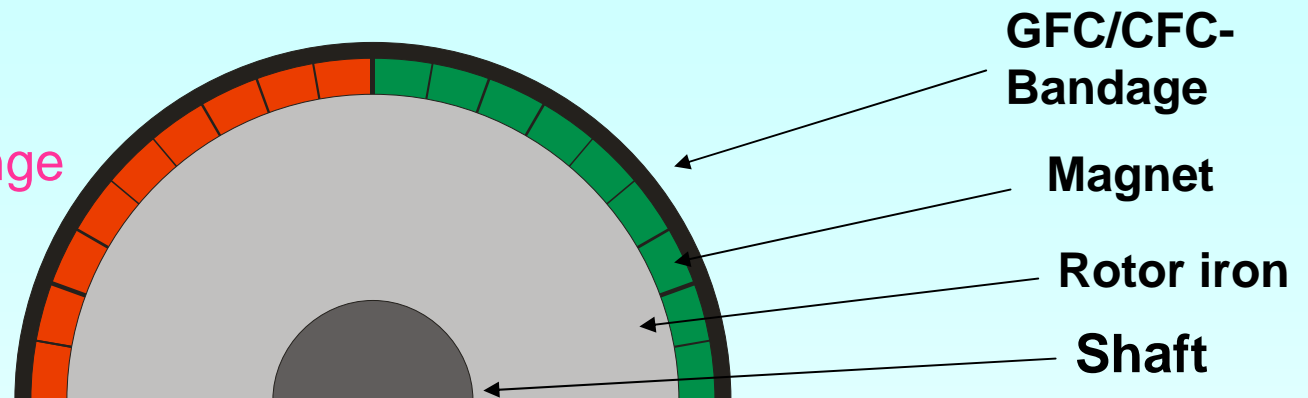
Rotor configurations of PM Synchronous Machines

Surface magnets:

small L_h , big $I_{s,k}$,
small flux weakening range

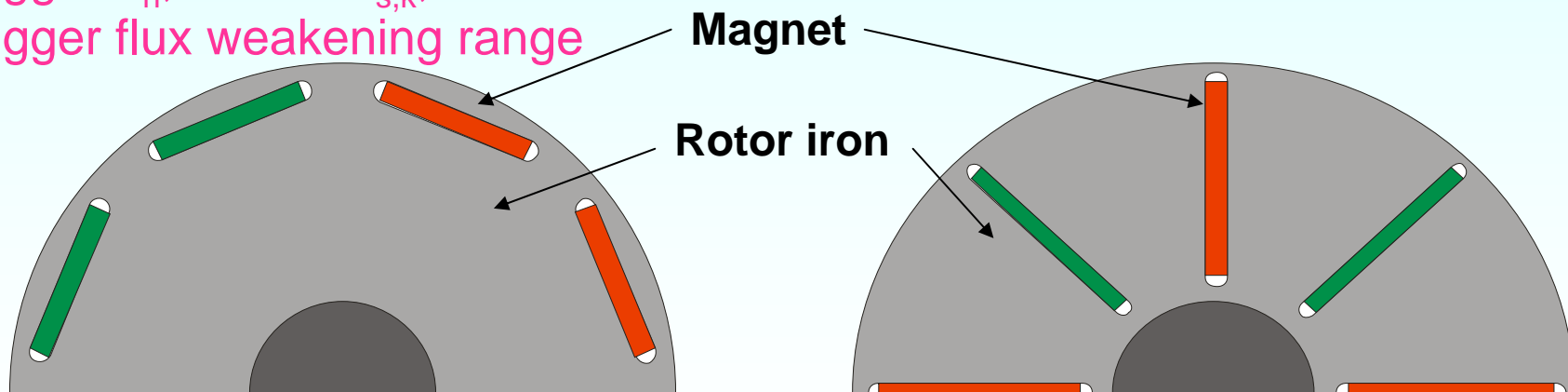
GFC: Glass fiber composite

CFC: Carbon fiber composite



Buried magnets:

bigger L_h , smaller $I_{s,k}$,
bigger flux weakening range



No flux concentration

Applied flux concentration

Example: Two different machines for flux weakening

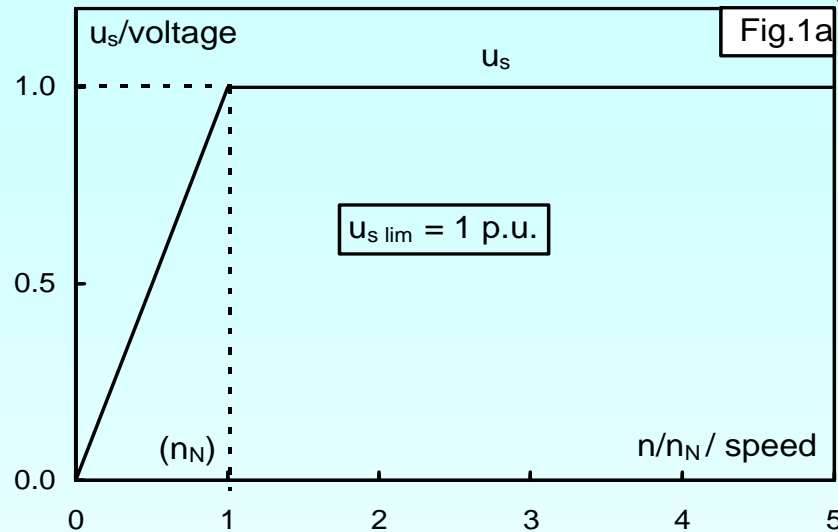
Example:

Two PM motors A and B are compared with different voltage drop and different back EMF, but the same inverter voltage and current limit $U_{s,\text{lim}}$ and $I_{s,\text{lim}}$. Numbers are given in per unit-values of $U_{s,\text{lim}}$ and $I_{s,\text{lim}}$, e.g. $u_s = U_s / U_{s,\text{lim}}$, $i_s = I_s / I_{s,\text{lim}}$.

$$I_{s,k} / I_{s,\text{lim}} = i_{s,k} = U_p / (X_s I_{s,\text{lim}})$$

PM machine	A	B
$U_p / U_{s,\text{lim}}$ at n_N	0.6	0.8
$X_s I_{s,\text{lim}} / U_{s,\text{lim}}$ at n_N	0.8	0.6
$U_{s,\text{lim}}$ at n_N	$\sqrt{0.6^2 + 0.8^2} = 1$	$\sqrt{0.8^2 + 0.6^2} = 1$
Short circuit current $I_{s,k}$	$0.6 / 0.8 = 0.75 < 1$	$0.8 / 0.6 = 1.33 > 1$
Field weakening ?	Unlimited	Limited

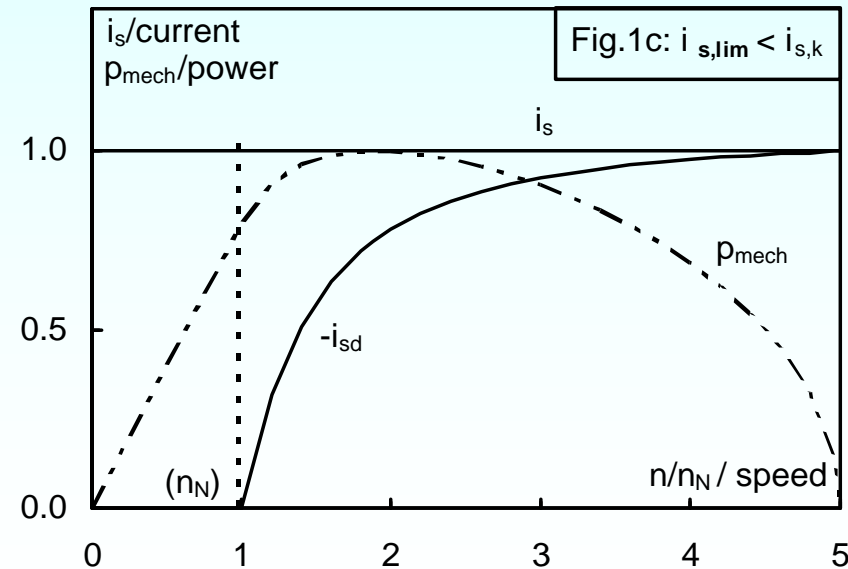
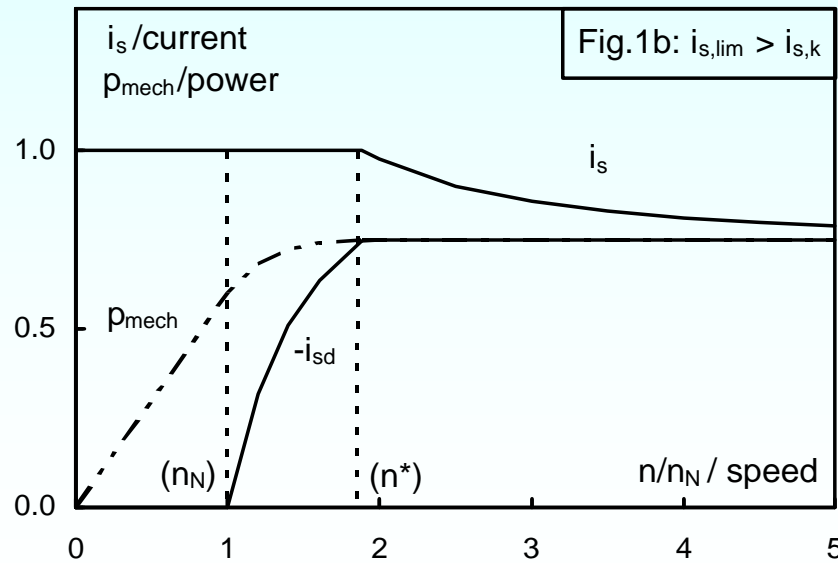
Comparison of two different PM machines concerning field weakening



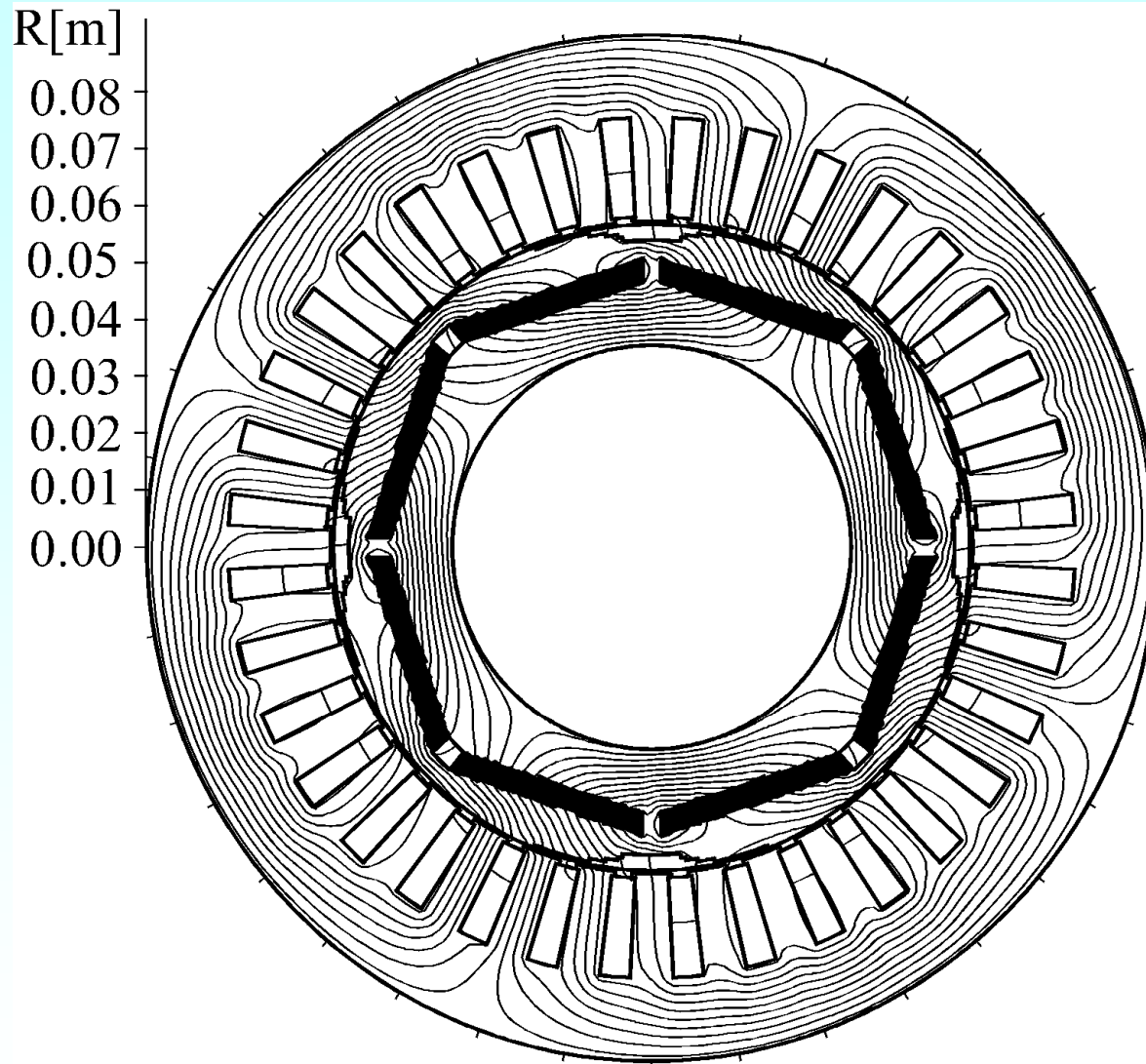
a) voltage characteristic of inverter with voltage limit

b) Motor A with inverter current limit $i_{s,lim} > i_{s,k}$

c) Motor B with inverter current limit $i_{s,lim} < i_{s,k}$



Buried magnet rotor at rated flux and current



4-pole machine

small magnetic air gap

sinusoidal air gap contour

rotor iron above magnets

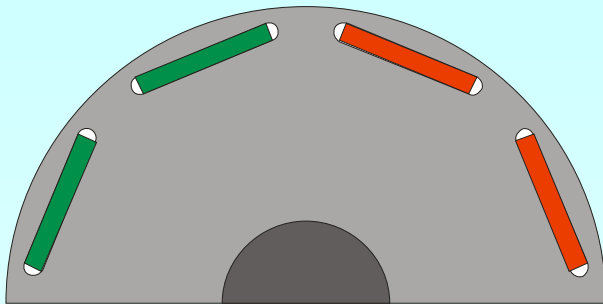
for big L_d

interpole gaps to reduce L_q

Application:

High speed spindle drive for tooling machine (milling)

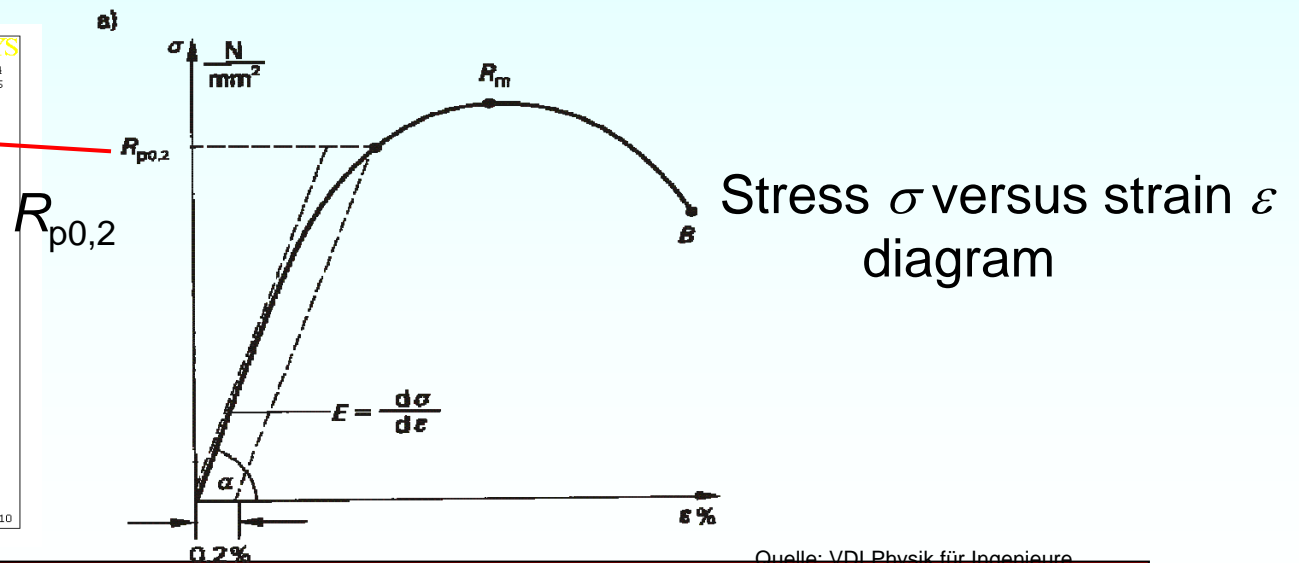
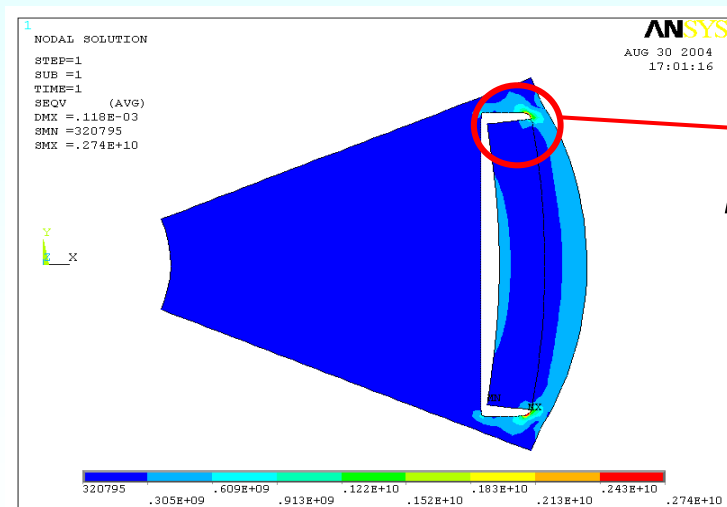
Fixing buried magnets at high speed - rotor sheet strength



Magnets are fixed by rotors sheet:

- no bandage
- small magnetic air gap
- less magnet material in case of flux concentration

- Detailed mechanical calculation necessary, requires Finite Element Calculation
- max. tensile strength must stay below 0,2%-deformation limit of sheet $R_{p0,2}$



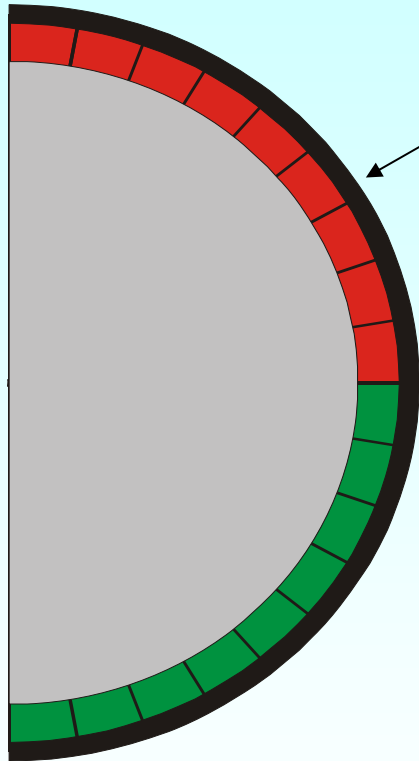
Quelle: VDI Physik für Ingenieure

Surface mounted magnets

Fixing of magnets by bandage:

Fiber and resin ("matrix") = „Bandage“

Pre-fabricated bandage is pressed onto rotor with force.



PM-Rotor

**40 kW,
40000/min**

*Magnetic
bearings*

*Carbon fiber
bandage*

*Outer diameter:
ca. 90 mm*

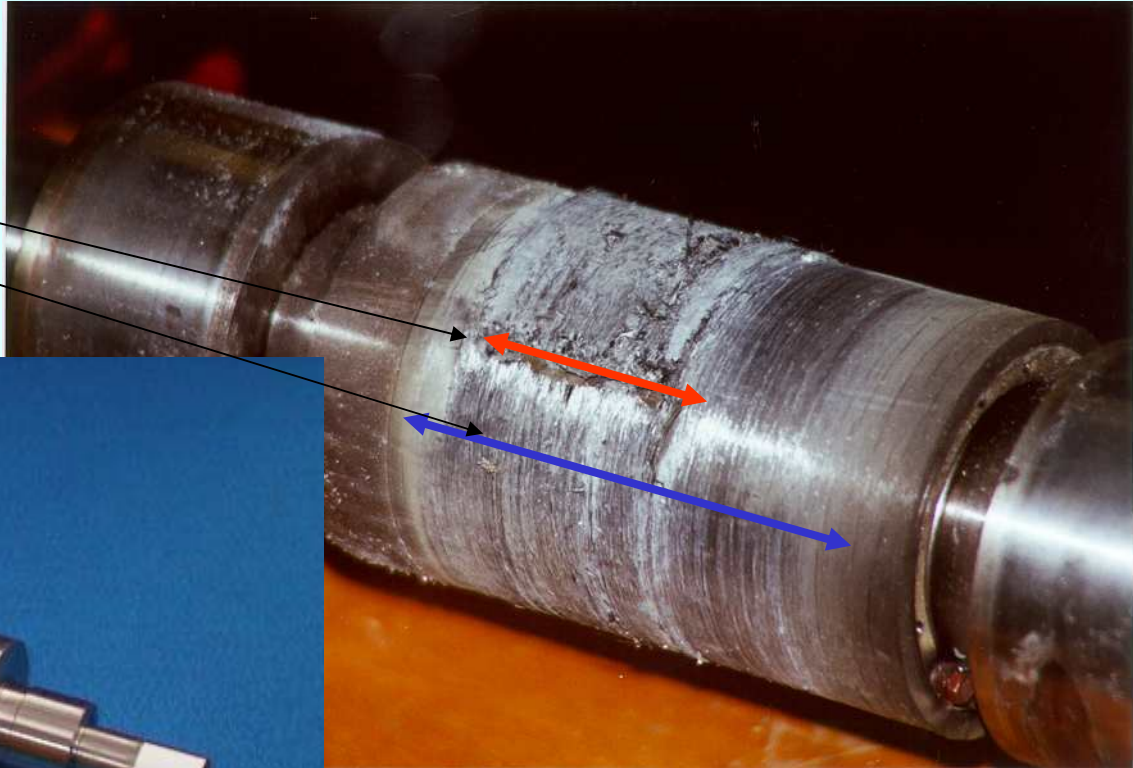
(TU Darmstadt)

Damaged Rotor M1 and New Rotor M2

First Rotor M1:

Breaking at 35000/min

- Break length
- Total active length



New Rotor M2

Example: Magnetically levitated PM drive 40 kW, 40000/min

4-pole PM-Synchronous machine, surface magnets ($\text{Sm}_2\text{Co}_{17}$)

16 magnet segments / pole, carbon fiber bandage, radial magnetic bearings

P_N = 40 kW

d_a = 88.6 mm rotor diameter

n_N = 40.000 min^{-1}

$v_{u,schl} = 222 \text{ m/s}$ rotor surface velocity at over-speed

α_e = 0.87 (pole coverage ratio)

stator with water jacket cooling



Magnetic bearing stator

magnetic bearing rotor

Source:

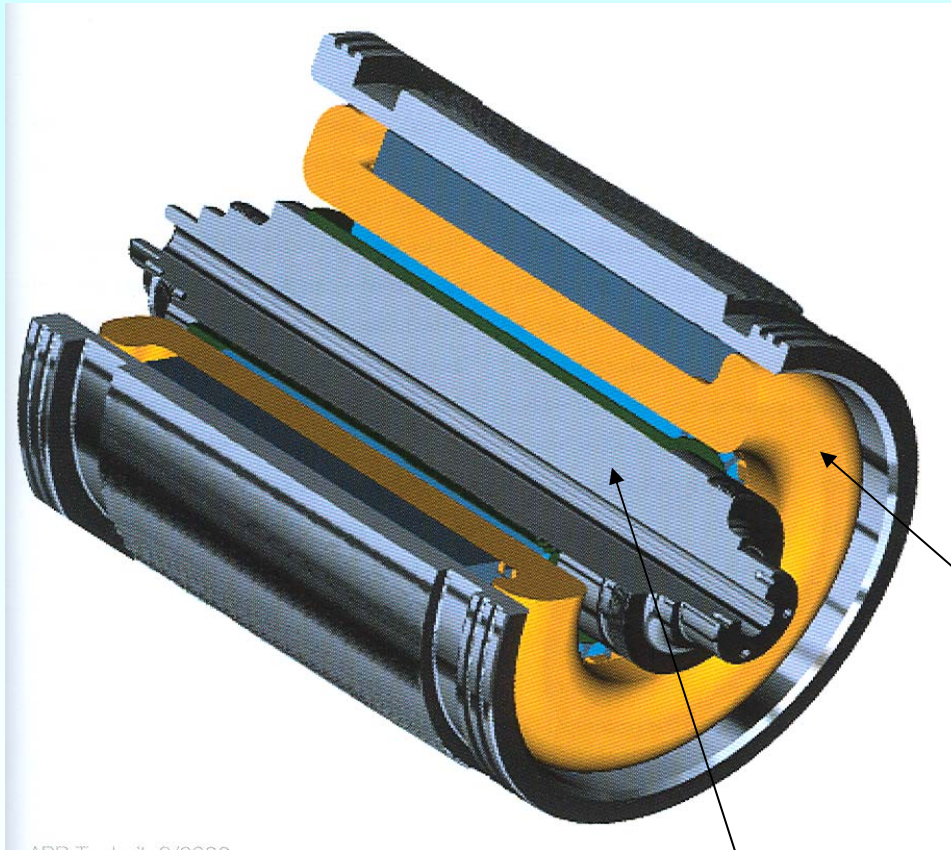
TU Darmstadt

rotor with CFC-bandage

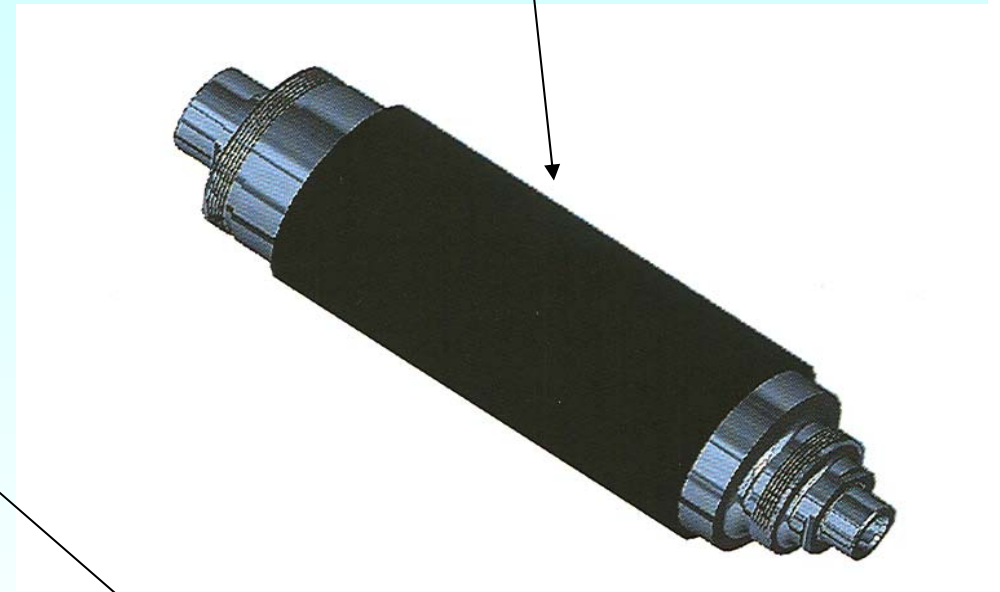
Radial distance sensors (eddy current principle)

Gearless high speed PM generator

70000/min, 2300 Hz, four pole PM-rotor, Carbon fiber bandage



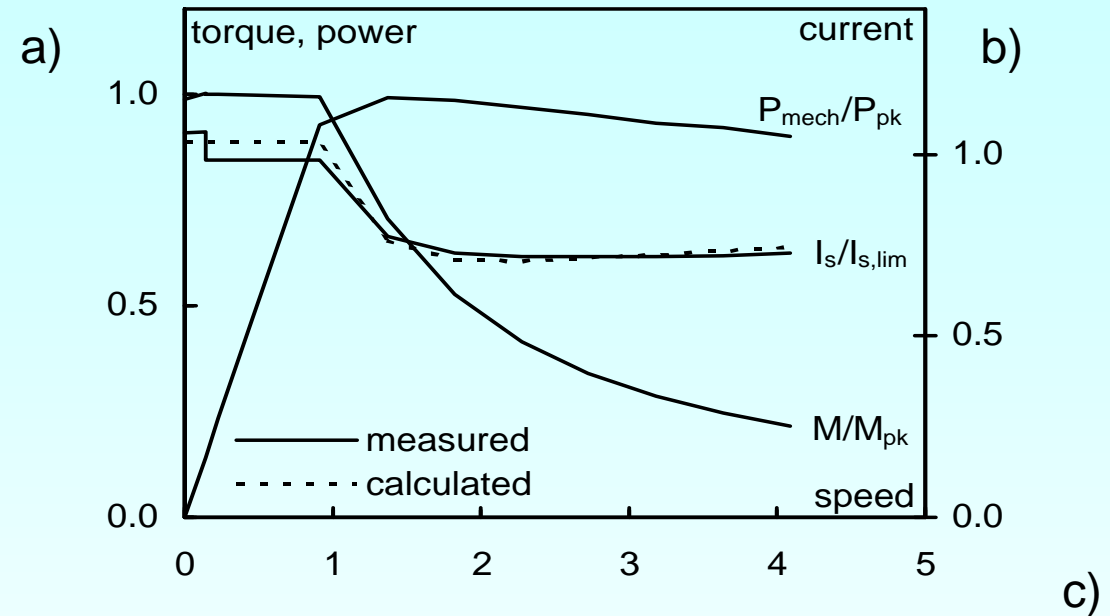
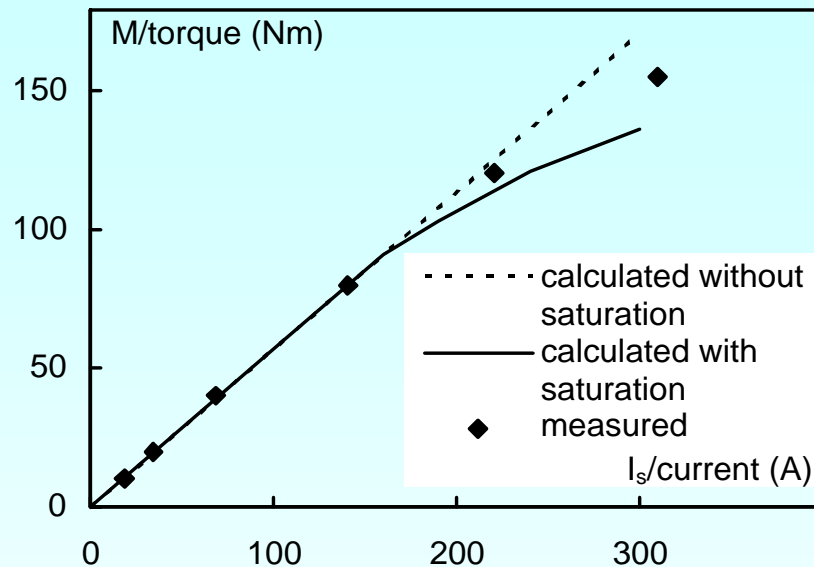
Massive rotor iron, special bearings



Stator with four pole three phase winding, fully encapsulated in resin for good heat transfer to iron

Source: ABB

“Mild high speed”: Motors for electric or hybrid-electric cars



Propulsion for electric car:

- a) Torque-Current-Characteristic for propulsion motor,
- b) Measured torque-speed drive characteristic at 132V DC link voltage = battery voltage,

$$M_{pk} = 156Nm, P_{pk} = 35kW, I_{s,lim} = 315A$$

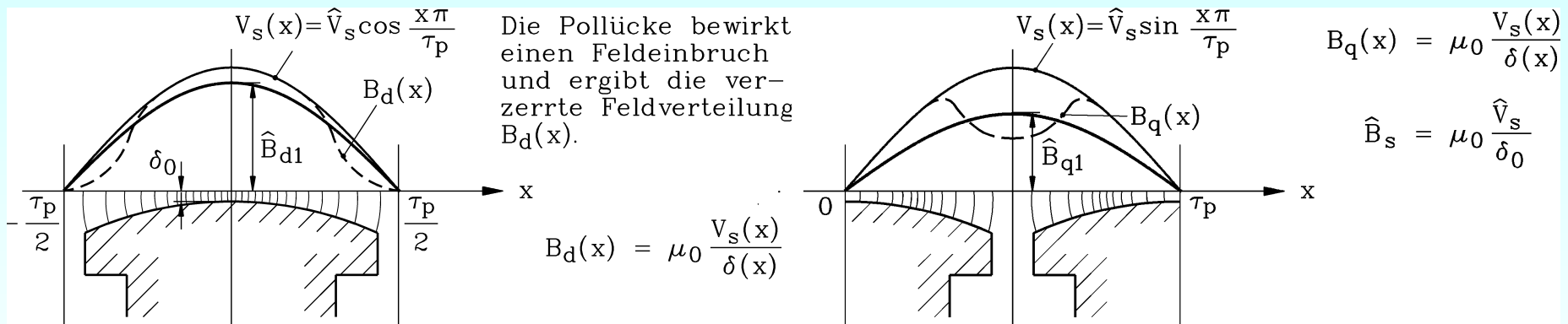
- c) Prototypes of fuel cell powered cars NECAR (New Electric Car) of DaimlerChrysler with electric drive system



4. Reluktanzmoment

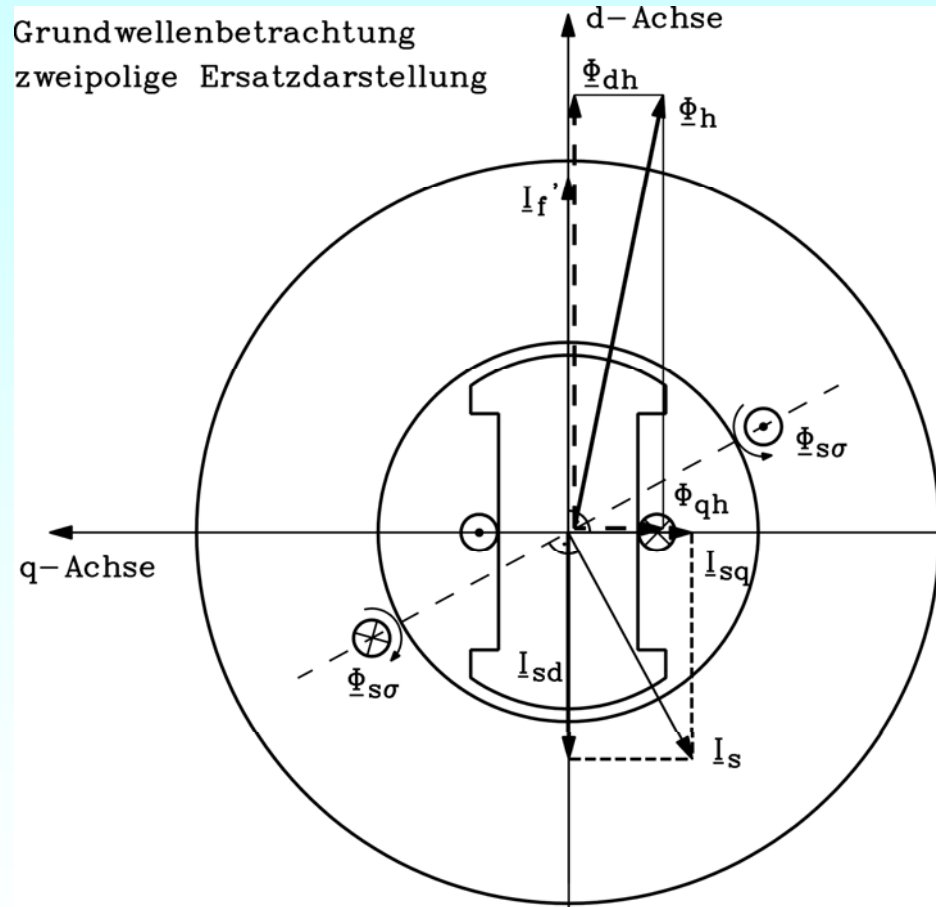
Schenkeligkeit der Synchronmaschine

- Ständerwicklung:** Drehfeldwicklung, ABER „magnetische Leitfähigkeit“ in der Längs- und Querachse (d- und q-Achse) unterschiedliche ! Z.B.: Luftspalt ist in der **q-Achse durch eine Pollücke GRÖßER** als in der **Polachse (d-Achse)**. Daher ist bei gleicher magnetischer Spannung V_s (Grundwelle $\nu = 1$) das zugehörige Luftspaltfeld in der q-Achse **KLEINER** als in der d-Achse.



- Ständerfeld in d-Achse:** Grundwellenamplitude etwas kleiner als bei konstantem Luftspalt δ_0 : $c_d = \hat{B}_{d1} / \hat{B}_s < 1$ **ca. 0.95, daher:** $L_{dh} = c_d \cdot L_h$
- Ständerfeld in q-Achse:** Grundwellenamplitude viel kleiner als bei konstantem Luftspalt δ_0 : $c_q = \hat{B}_{q1} / \hat{B}_s \ll 1$ **ca. 0.4 ... 0.5** $L_{qh} = c_q \cdot L_h$

Ständerstrom I_s : d - und q -Komponente



- **Ständerstrom-Zeiger** \underline{I}_s in d - und q -Komponente gedanklich zerlegt:

$$\underline{I}_s = \underline{I}_{sd} + \underline{I}_{sq}$$

\underline{I}_{sd} ist in Phase/Gegenphase mit fiktivem Strom \underline{I}'_f und erregt daher ein Ständer-Luftspaltfeld in d -Achse (Polachse). Gemeinsam mit dem Läuferfeld bildet es den Luftspaltfluß Φ_{dh} .

\underline{I}_{sq} ist 90° zu \underline{I}_{sd} phasenverschoben und erregt daher ein Ständer-Luftspaltfeld in q -Achse (Pol-Lücke). Der zugehörige Luftspaltfluß ist Φ_{qh} .

- **Selbstinduktionsspannung:** Zwei um 90° phasenverschobene Komponenten:

$$j\omega_s L_{dh} \underline{I}_{sd}, \quad j\omega_s L_{qh} \underline{I}_{sq}$$

Hinzu kommt Selbstinduktion durch Ständerstreuungsfeld:

$$j\omega_s L_{s\sigma} \underline{I}_s$$

Ständer-Spannungsgleichung der Schenkelpolmaschine

- Mit Berücksichtigung der Ständerstreuinduktivität $L_{s\sigma}$ und des Strangwiderstands R_s folgt die **Ständerspannungsgleichung je Strang**:

$$\underline{U}_s = R_s \underline{I}_s + j\omega_s L_{s\sigma} \underline{I}_s + j\omega_s L_{qh} \underline{I}_{sq} + j\omega_s L_{dh} \underline{I}_{sd} + \underline{U}_p$$

oder

$$\underline{U}_s = R_s \underline{I}_s + j\omega_s L_{s\sigma} (\underline{I}_{sd} + \underline{I}_{sq}) + j\omega_s (L_{qh} \underline{I}_{sq} + L_{dh} \underline{I}_{sd}) + \underline{U}_p$$

- X_d : **"synchrone Reaktanz der Längsachse"**: $X_d = X_{s\sigma} + X_{dh} = \omega_s L_{s\sigma} + \omega_s L_{dh}$
- X_q : **"synchrone Reaktanz der Querachse"**: $X_q = X_{s\sigma} + X_{qh} = \omega_s L_{s\sigma} + \omega_s L_{qh}$
- Es ist $X_d > X_q$ (typisch: $X_q = (0.5 \dots 0.6) \cdot X_d$), wenn eine Pollücke vorhanden ist.
- Wenn die Sättigung in der d-Achse durch das Läufer-PM-Feld dominiert, und die Magnete in der d-Achse liegen, ist $X_d < X_q$.

Drehmoment der Schenkelpolmaschine ($U_s = \text{konst.}$, $R_s = 0$)

- **VORGABE** durch "starre" Spannung des Umrichters: $\underline{U}_s = \text{konstant}$

Gewählt: d -Achse = Re-Achse, q -Achse = Im-Achse:

$$\underline{U}_s = U_{sd} + jU_{sq} \qquad \underline{I}_s = I_{sd} + jI_{sq} \qquad \underline{U}_p = jU_p$$

$$R_s = 0: \quad \underline{U}_s = jX_d I_{sd} + jX_q I_{sq} + \underline{U}_p \quad \Rightarrow \quad \underline{U}_s = jX_d I_{sd} - X_q I_{sq} + jU_p$$

- **Wirkleistung P_e :** $P_e = m_s U_s I_s \cos \varphi = m_s \cdot \text{Re} \left\{ \underline{U}_s \underline{I}_s^* \right\} = m_s (U_{sd} I_{sd} + U_{sq} I_{sq})$

$$P_e = m_s (-X_q I_{sq} I_{sd} + X_d I_{sd} I_{sq} + U_p I_{sq})$$

- **Elektromagnetisches Drehmoment:**

$$M_e = \frac{P_m}{\Omega_{syn}} = \frac{P_e}{\Omega_{syn}} = \frac{m_s}{\Omega_{syn}} \cdot (U_p \cdot I_{sq} + (X_d - X_q) \cdot I_{sd} \cdot I_{sq})$$

- **Zwei Drehmomentanteile:**

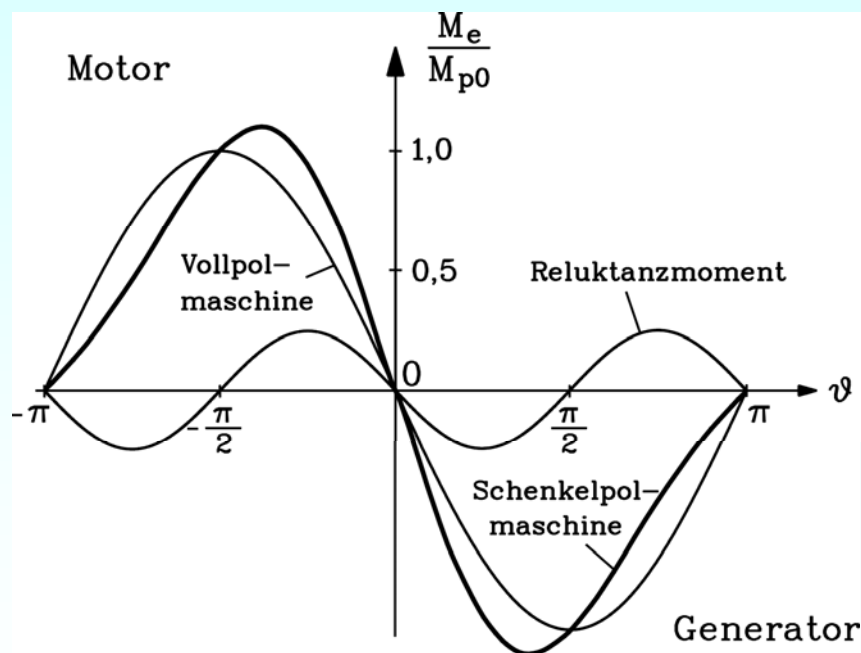
a) prop. U_p wie bei Vollpolmaschine

b) "**Reluktanz**"moment wegen $X_d \neq X_q$. Dafür ist KEINE Läufererregung erforderlich = robuster Läuferaufbau OHNE Wicklung ist möglich (**Reluktanz-Synchronmaschine**)

Drehmoment-Polradwinkel-Kurve $M_e(\vartheta)$

- Darstellung des Drehmoments wie bei Vollpolmaschine: I_{sd} , I_{sq} durch U_s , ϑ ausgedrückt:

$$M_e = -\frac{p \cdot m_s}{\omega_s} \left(\frac{U_s U_p}{X_d} \sin \vartheta + \frac{U_s^2}{2} \left(\frac{1}{X_q} - \frac{1}{X_d} \right) \sin 2\vartheta \right)$$

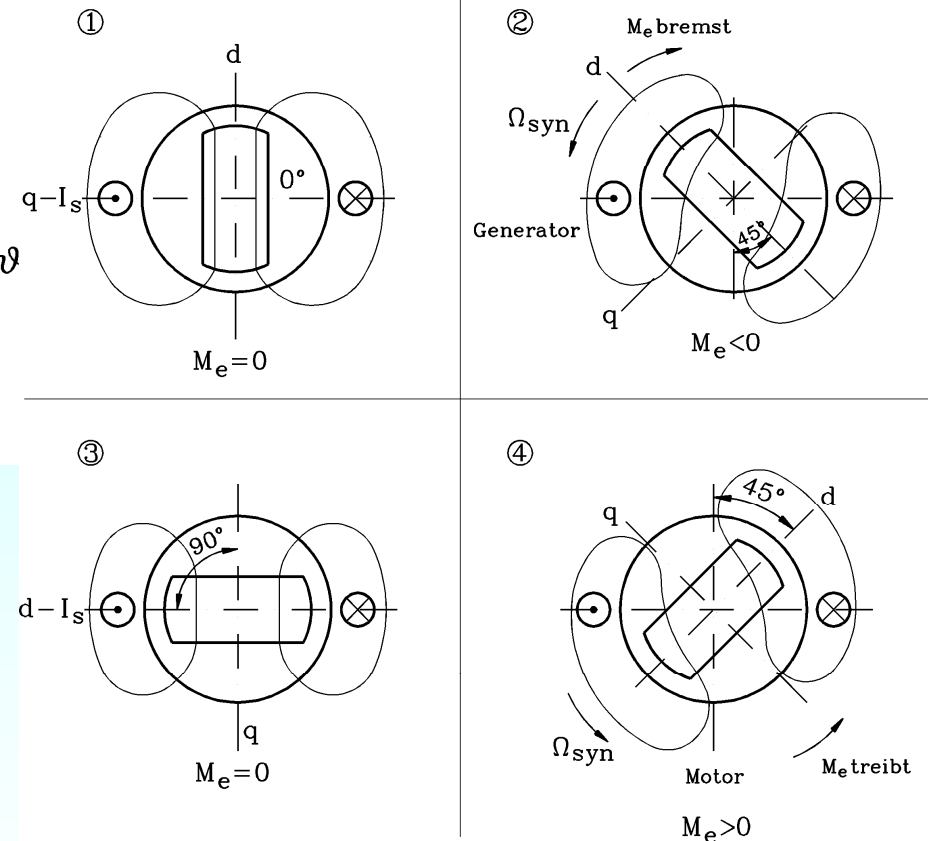
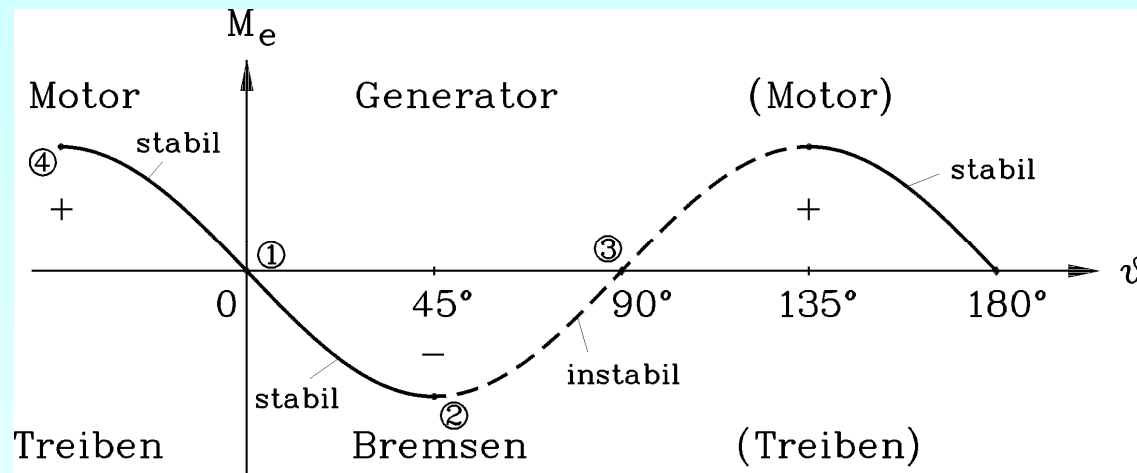


Betrag des Kippwinkel $< 90^\circ$,
da Kippmoment des Reluktanzmoments
bei $\pm 45^\circ$.

Betrag des Kippmoments durch
Reluktanzmoment erhöht.

Ersatz-Drehfederkonstante c_g
größer als bei Vollpolmaschine,
da Reluktanzmoment
mitwirkt (steilere $M_e(\vartheta)$ -Kennlinie).

Synchron-Reluktanzmaschine



- Läufer **ohne Wicklung**, aber mit **großen Pollücken**: $X_d > X_q$.
- Läufer will sich STETS in die Ständerfeld-Achse drehen, damit Feldlinien möglichst **KURZEN** Weg über den Luftspalt zurück legen müssen = **Reluktanzmoment**.

Reluktanz-Drehmoment

- **a) $X_d > X_q$:**
Der Strom muss so eingeprägt werden, dass I_d **positiv** ist, damit ein positives (antreibendes) Reluktanzmoment entsteht.
- **b) $X_d < X_q$:**
Der Strom muss so eingeprägt werden, dass I_d **negativ** ist, damit ein positives (antreibendes) Reluktanzmoment entsteht.

$$M_e = \frac{P_m}{\Omega_{syn}} = \frac{P_e}{\Omega_{syn}} = \frac{m_s}{\Omega_{syn}} \cdot \left(U_p \cdot I_{sq} + (X_d - X_q) \cdot I_{sd} \cdot I_{sq} \right)$$

$$X_d \neq X_q$$