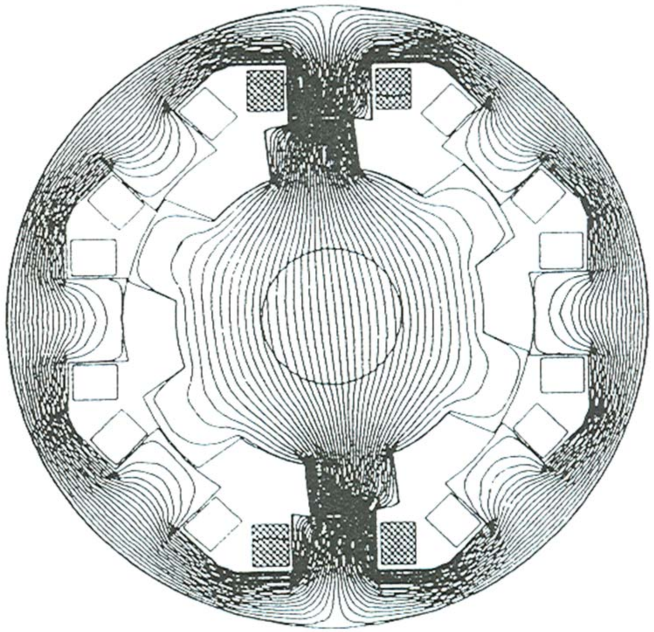
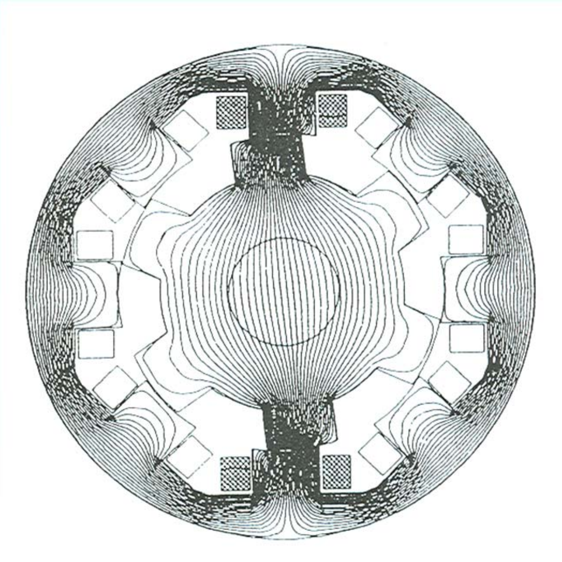
2. Reluctance machines



Source: Omekanda, A, ICEM, 1992

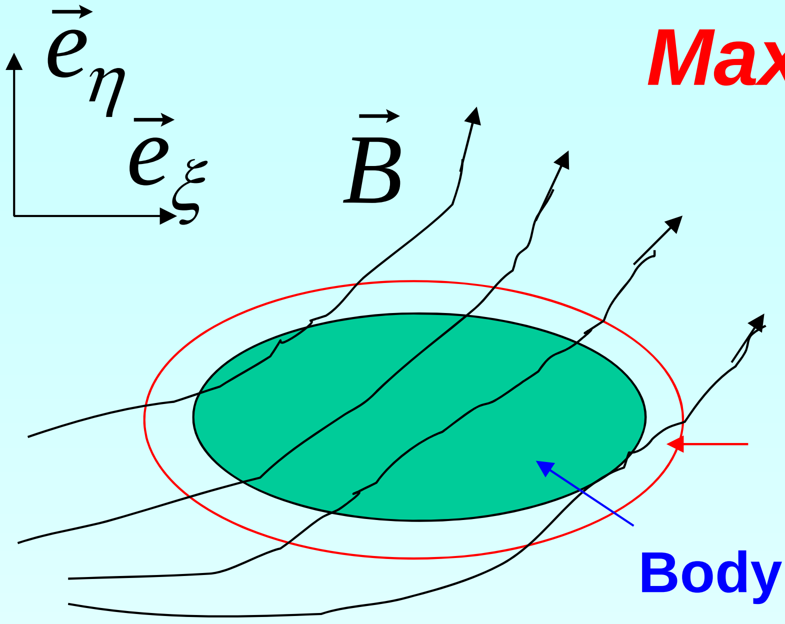
2. Reluctance machines

2.1 Switched reluctance drive



Source: Omekanda, A, ICEM, 1992

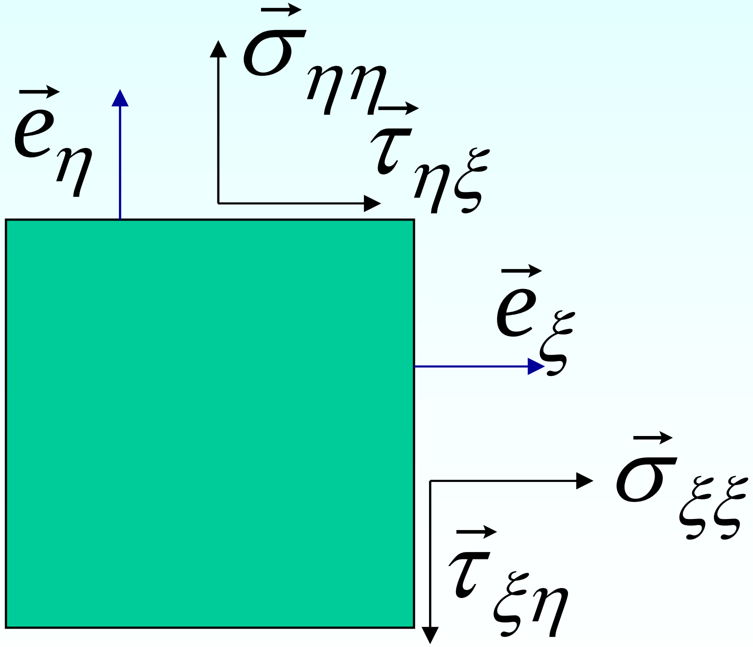
Maxwell stress tensor



- **Total magnetic force on a (magnetized) body is calculated by integrating the 9 components of *Maxwell´s* stress tensor via surface *A*, which encloses the body outside in free space (μ_0)**

- ***Maxwell´s* stress tensor in 2 dimensions ξ, η**

$$\overleftrightarrow{T} = \begin{pmatrix} \sigma_{\xi\xi} & \tau_{\xi\eta} \\ \tau_{\eta\xi} & \sigma_{\eta\eta} \end{pmatrix} = \begin{pmatrix} \dfrac{B_\xi^2 - B_\eta^2}{2\mu_0} & \dfrac{B_\xi B_\eta}{\mu_0} \\ \dfrac{B_\eta B_\xi}{\mu_0} & \dfrac{B_\eta^2 - B_\xi^2}{2\mu_0} \end{pmatrix}$$



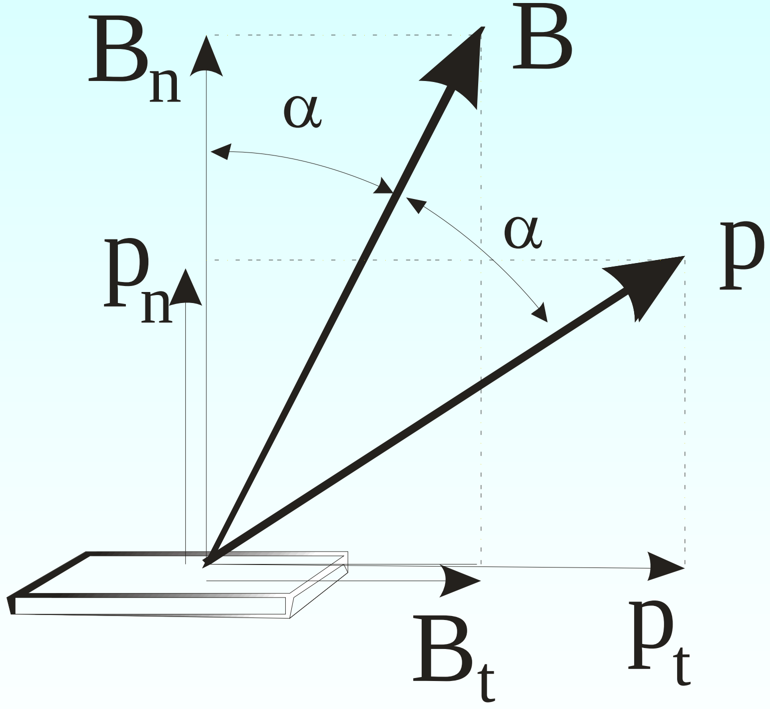
Maxwell stress for force calculation

$$\sigma = \frac{B_n^2 - B_t^2}{2\mu_0} = p_n$$

$$\tau = \frac{B_n B_t}{\mu_0} = p_t$$

$$\left.\right\} \vec{p} = \vec{p}_n + \vec{p}_t$$

$$\vec{F} = \oint_A \vec{p} \cdot d\vec{A}$$



$$\tan\alpha = \frac{B_t}{B_n}$$

$$\frac{p_t}{p_n} = \tan 2\alpha = \frac{2}{\frac{1}{\tan\alpha} - \tan\alpha} = \frac{2B_n B_t}{B_n^2 - B_t^2}$$

Source: Reichert, K., VDE-Kurs El. Maschinen, 2009

Maxwell stress does not allow calculating local forces

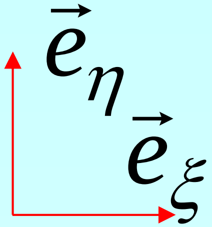
$$\vec{F} = \oint_A \vec{p} \cdot d\vec{A}$$

- Force integration must cover complete body.
- Local value *p·A* has usually no physical meaning.
- In periodic structures the force per period can be determined.

- Usually the magnetic force density is distributed with in the ferromagnetic body according to the field and the permeability distribution. It does NOT correspond to the (equivalent) local surface forces, calculated from the MAXWELL stress.
- Only in ferromagnetic parts with <u>constant</u> permeability the magnetic force density is localized in the body surface, but is usually not equal with the MAXWELL stress components.
- Only in case of infinite iron permeability the magnetic force density, localized in the iron surface, is identical with the MAXWELL stress components.

$$\mu_{Fe} \to \infty : \quad d\vec{F}(x,y)/dA = \vec{p}(x,y)$$

Example: LORENTZ force

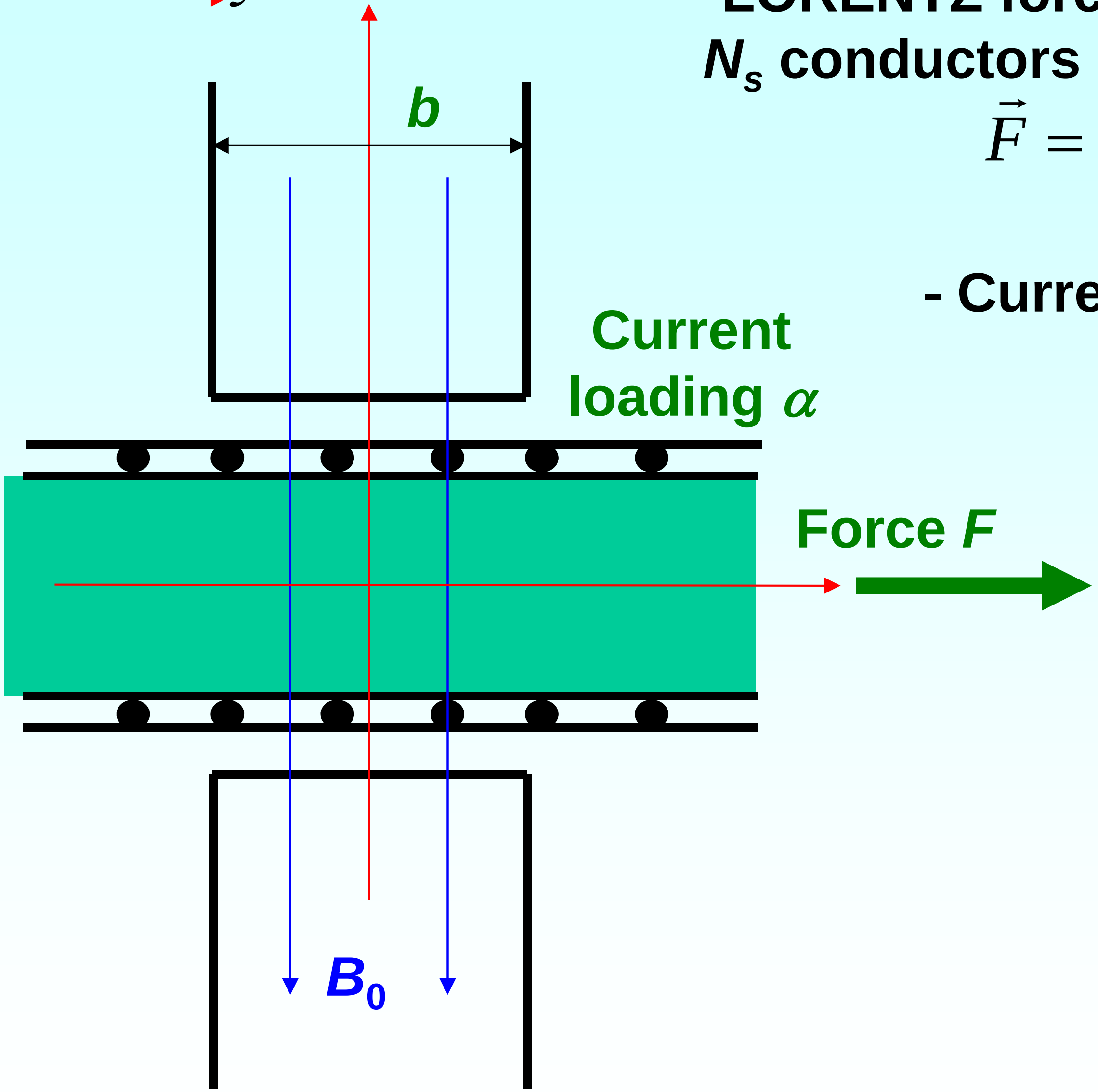


- **LORENTZ force per current *I*:** $\vec{F}_c = I \cdot B_0 \cdot l_{Fe} \cdot \vec{e}_\xi$

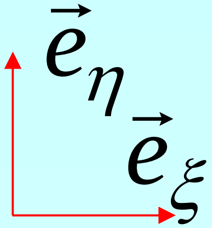
N_s conductors under pole width *b*, total force:

$$\vec{F} = 2N_s \vec{F}_c \Rightarrow F = 2N_s I \cdot B_0 \cdot l_{Fe}$$

- **Current loading:** $\alpha = N_s I / b$

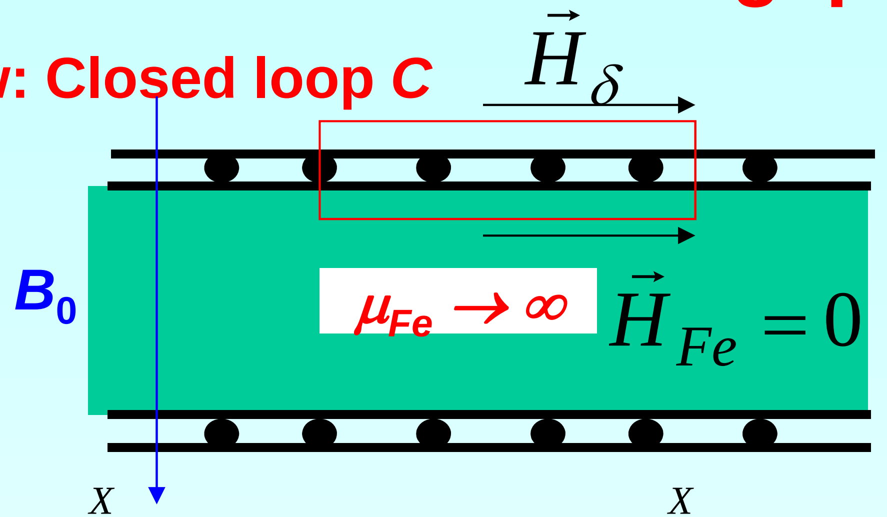


$$F = 2 \cdot \alpha \cdot B_0 \cdot (b \cdot l_{Fe})$$



Magnetic field in the air gap

Ampere´s law: Closed loop C



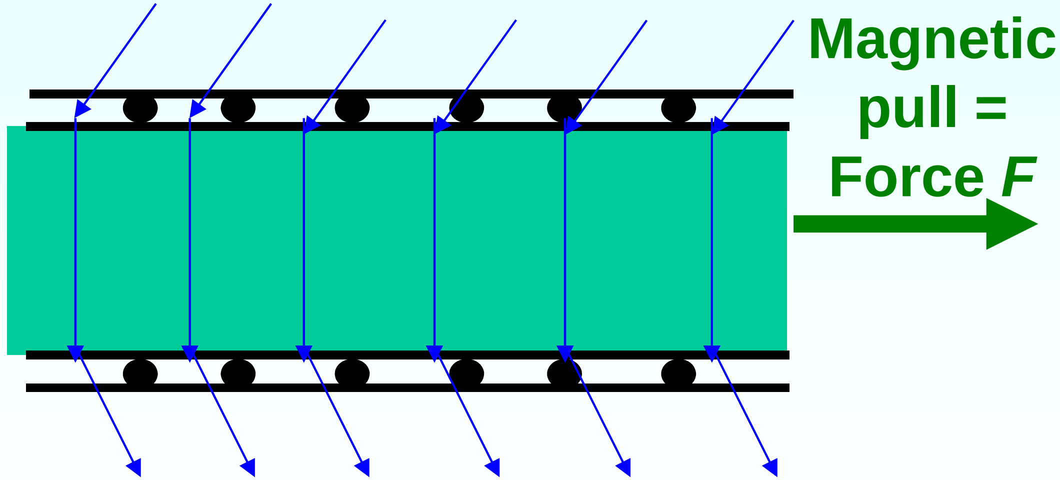
$$\Theta = \int_0^X \alpha(\xi)\cdot d\xi = \oint_C \vec{H}\cdot d\vec{s} = \int_0^X (H_{Fe} - H_\delta)d\xi = -\int_0^X H_\delta d\xi \Rightarrow H_\delta(\xi) = -\alpha(\xi)$$

$$\vec{B}_\xi = \mu_0 H_\delta(\xi)\cdot\vec{e}_\xi = -\mu_0\alpha(\xi)\cdot\vec{e}_\xi$$

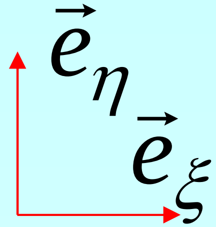
$$\vec{B}_\eta = -B_0\cdot\vec{e}_\eta$$

$$\vec{B} = \vec{B}_\xi + \vec{B}_\eta$$

Resulting flux density *B*



Magnetic pull via *Maxwell* stress



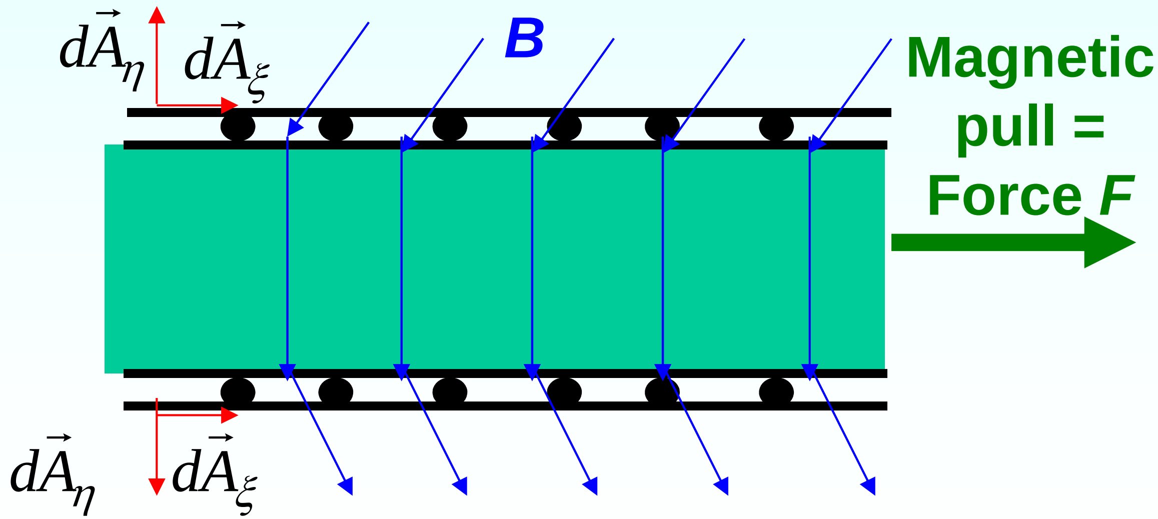
- **Vertical stress component:** $\sigma_{\eta\eta} = \dfrac{B_\eta^2 - B_\xi^2}{2\mu_0}$

$$\vec{F}_\eta = \oint_A \vec{T} \cdot d\vec{A}_\eta = \int_{A_{upper}} \frac{B_\eta^2 - B_\xi^2}{2\mu_0} \cdot d\xi \cdot l_{Fe} - \int_{A_{lower}} \frac{B_\eta^2 - B_\xi^2}{2\mu_0} \cdot d\xi \cdot l_{Fe} = 0$$

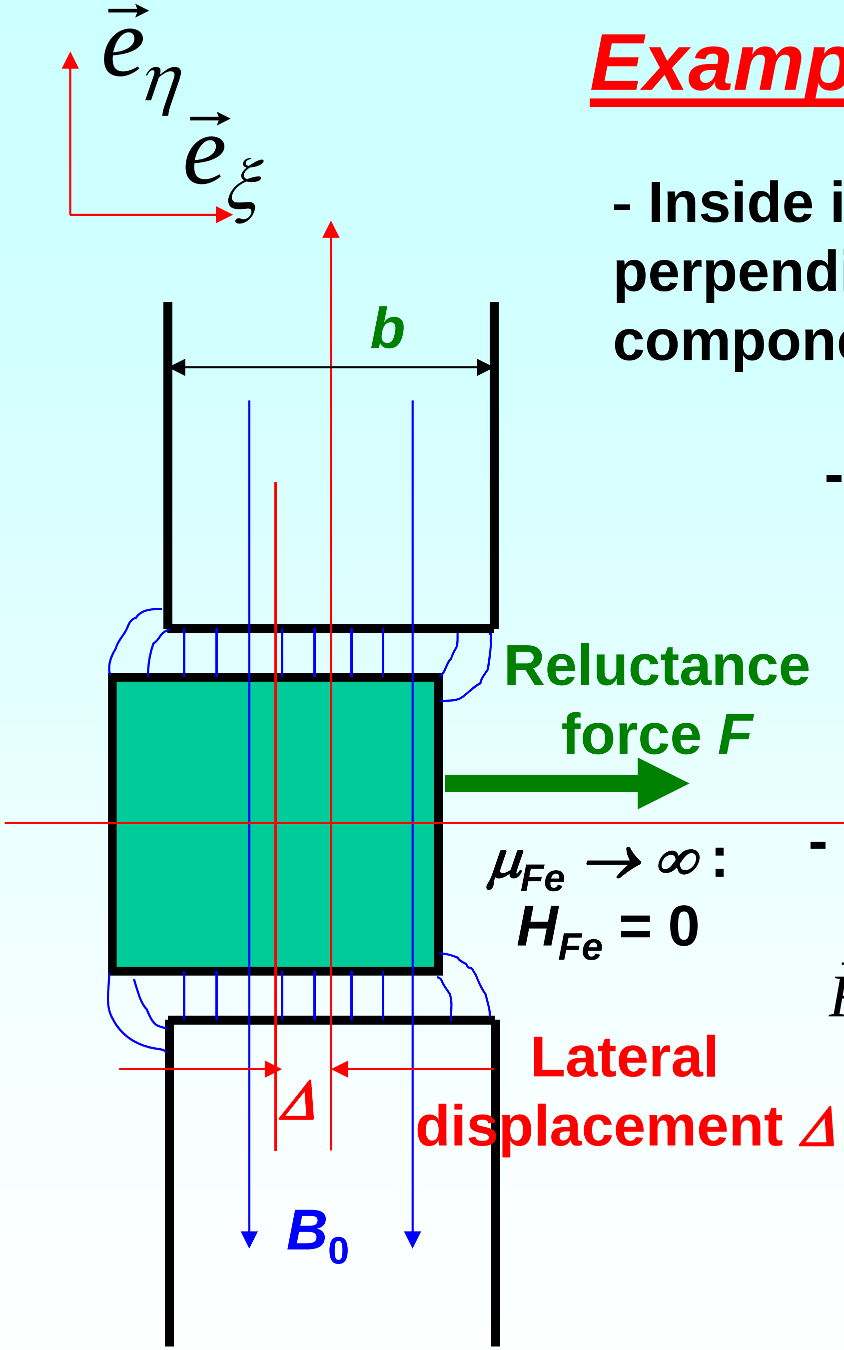
- **Horizontal stress component:** $\tau_{\eta\xi} = \dfrac{B_\eta B_\xi}{\mu_0} = \dfrac{(-B_0)\cdot(-\mu_0\alpha)}{\mu_0} = B_0 \cdot \alpha$

$$\vec{F}_\xi = \oint_A \vec{T} \cdot d\vec{A}_\xi = \int_{A_{upper}} \frac{B_\eta B_\xi}{2\mu_0} \cdot d\xi \cdot l_{Fe} + \int_{A_{lower}} \frac{B_\eta B_\xi}{2\mu_0} \cdot d\xi \cdot l_{Fe} = \vec{F}$$

$$\boxed{\vec{F} = 2 \cdot (B_0 \cdot \alpha) \cdot b \cdot l_{Fe} \cdot \vec{e}_\xi}$$



Example: Reluctance force



- Inside iron: $H_{Fe} = 0$, no current layer = flux lines end perpendicular on iron surface = tangential flux density component ZERO: $\tau_{\eta\xi} = \tau_{\xi\eta} = 0$

- Vertical stress component: $\sigma_{\eta\eta} = \frac{B_\eta^2 - B_\xi^2}{2\mu_0} = \frac{B_\eta^2}{2\mu_0}$

$$\vec{F}_\eta = \oint_A \overleftrightarrow{T} \cdot d\vec{A}_\eta = \left(\int_{A_{upper}} B_\eta^2 \cdot d\xi - \int_{A_{lower}} B_\eta^2 \cdot d\xi \right) \cdot \frac{l_{Fe}}{2\mu_0} = 0$$

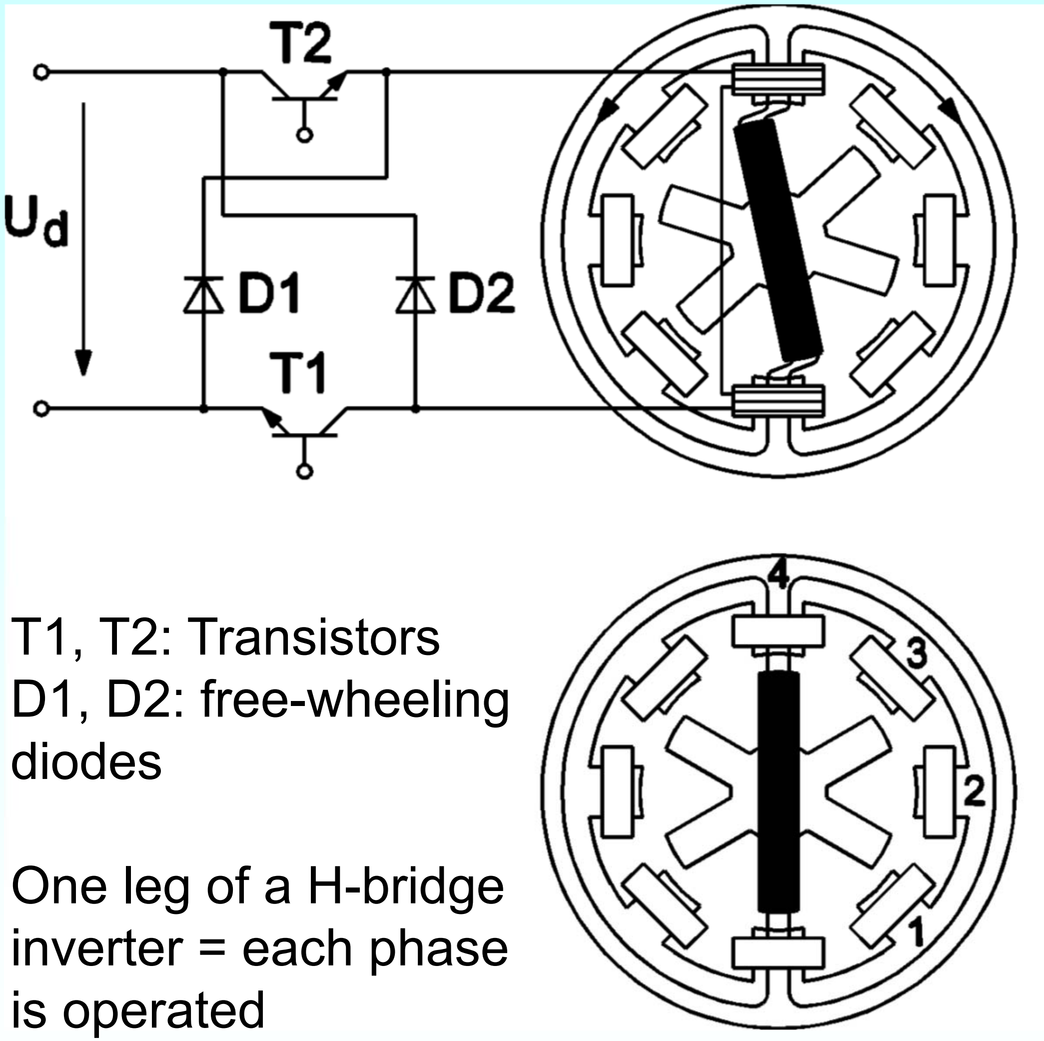
- Horizontal stress component: $\sigma_{\xi\xi} = \frac{B_\xi^2 - B_\eta^2}{2\mu_0} = \frac{B_\xi^2}{2\mu_0}$

$$\vec{F}_\xi = \oint_A \overleftrightarrow{T} \cdot d\vec{A}_\xi = \left(\int_{A_{left}} B_\xi^2 \cdot d\eta + \int_{A_{right}} B_\xi^2 \cdot d\eta \right) \cdot \frac{l_{Fe}}{2\mu_0} = \vec{F}$$

Reluctance force *F*

$$\vec{F} = \int_{A_{right}} B_\xi^2 \cdot d\eta \cdot l_{Fe} / (2\mu_0)$$

Basic function of switched reluctance machine



T1, T2: Transistors
D1, D2: free-wheeling diodes

One leg of a H-bridge inverter = each phase is operated INDEPENDENTLY !

Source: Hopper, E, Elektrotechnik, 1992

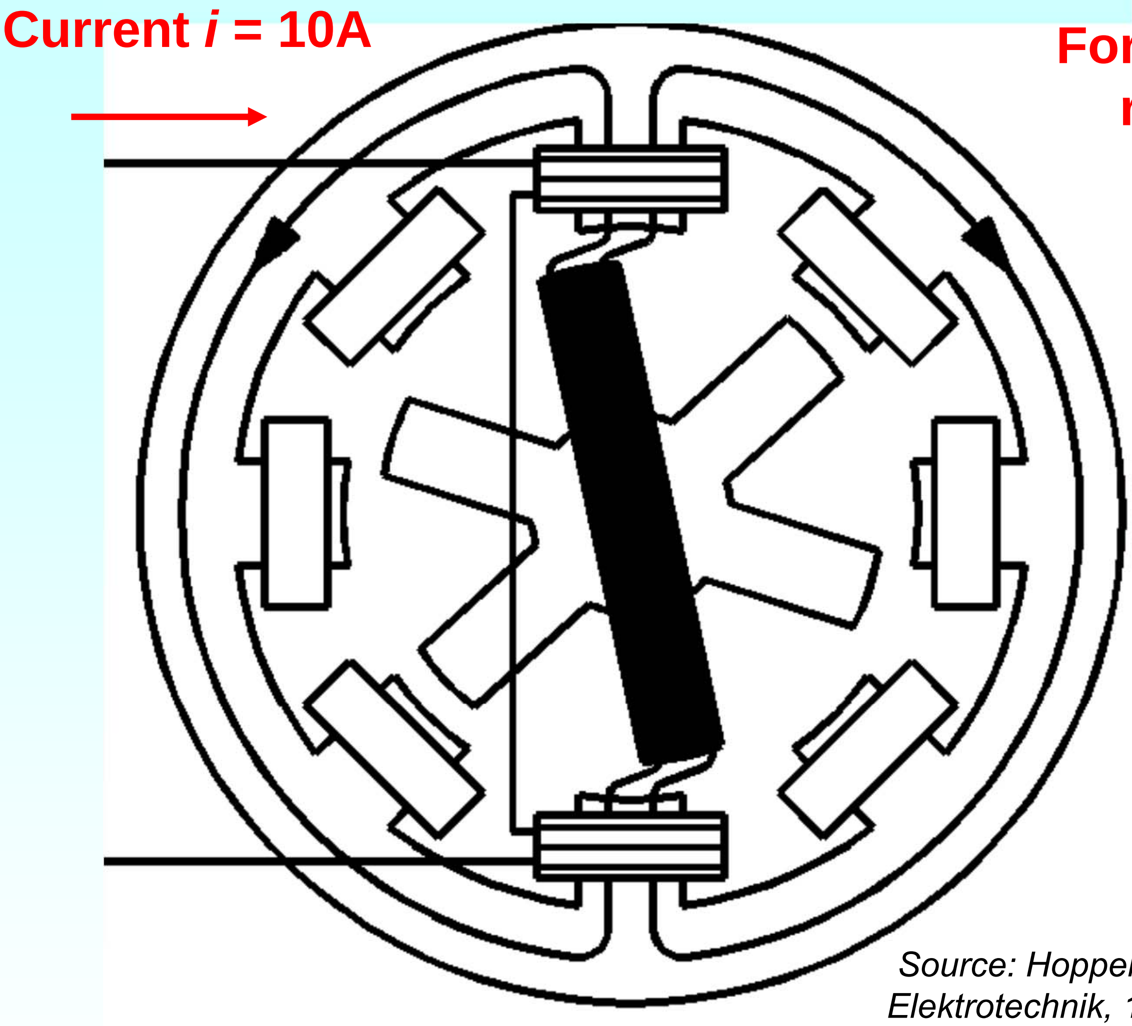
Two pole, four phase switched reluctance machine (cross section):

a)
Phase "4" is energized by H-bridge inverter, fed from DC link U_d

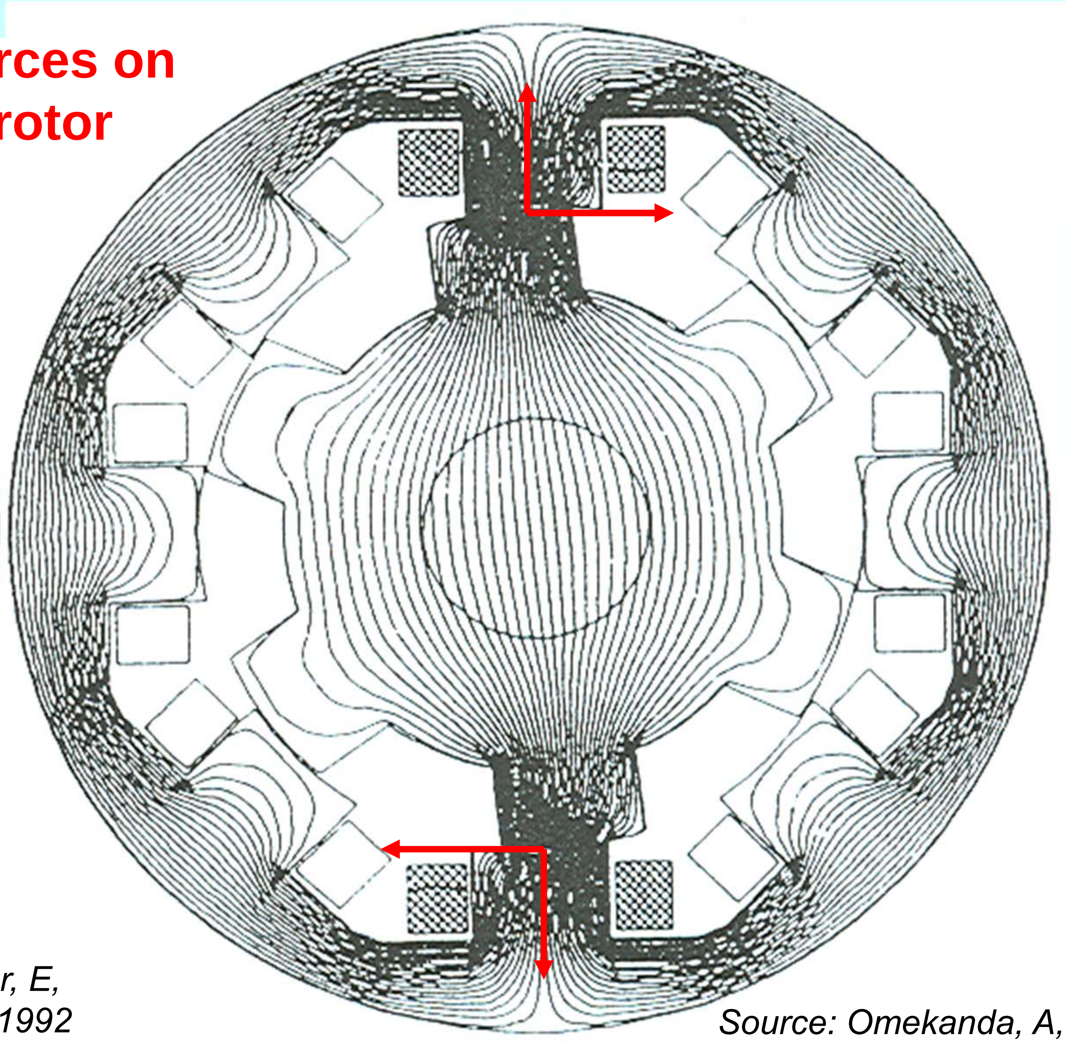
b)
Tangential magnetic pull of flux lines drags next rotor teeth into aligned position with energized stator teeth, thus creating a torque

c)
Next phase to be energized is no.1 to keep direction of rotation !

Torque production in switched reluctance machine



Source: Hopper, E, Elektrotechnik, 1992

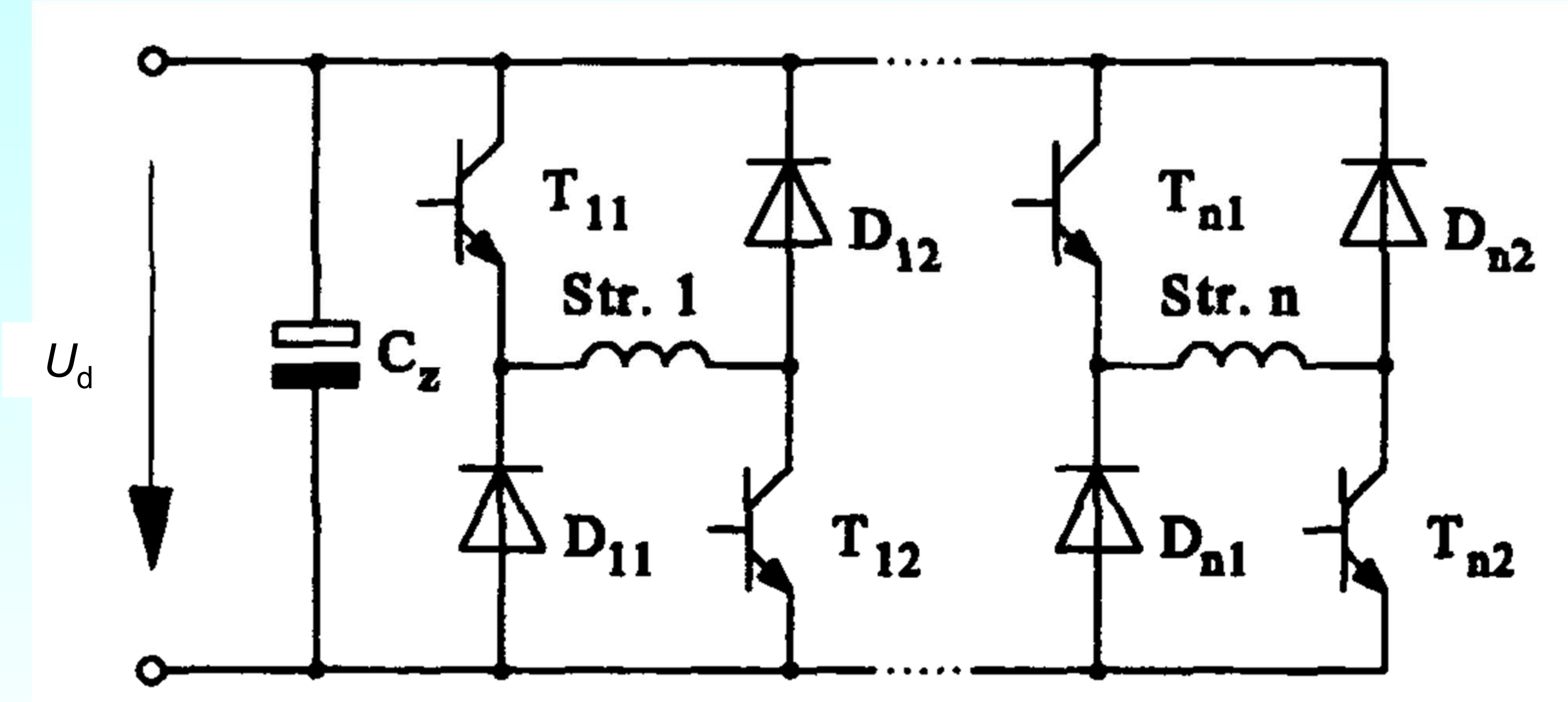


Source: Omekanda, A, ICEM, 1992

Numerical field calculation: Flux lines with energized phase “1”

Data: Outer stator diameter: 320 mm, air gap: 1 mm, iron stack length: 320 mm, shaft diameter: 70 mm, coil turns per tooth: 10, current per turn: 100 A DC

H-Bridge inverter



Voltage DC link   Phase 1 H-Bridge   …   Phase *n* H-Bridge

Source: Schencke, T.: Drehmomentglättung von geschalteten Reluktanzmotoren durch eine angepasste Blechschnittgestaltung, Ilmenau, Technische Universität, Dissertation, 1997

SR machine motor operation

- Torque is generated by **magnetic pull**, which is ~ B^2. **Unipolar** current (= block shaped current of one polarity) sufficient.

- **Reluctance** structure: The flux lines try to pass through the iron teeth with their high permeability and avoid the slot region.

- Stepper motor principle: Rotor moves stepwise without position sensor = cheap drive.

- **”Switched” reluctance motor principle:** With position sensor the rotor movement is completely controllable. No pull-out at overload is possible, as long as the inverter is able to impress current. Speed can be measured by using the rotor position sensor as speed sensor (**speed control**).

Direction of rotation: phases ”1”, ”2”, ”3”, ”4”, ”1”, ... **clockwise**
”4”, ”3”, ”2”, ”1”, ”4”, ... **counter-clockwise**

SR generator operation

Motor mode:

- By switching one phase after the other, the rotor keeps turning = **"switched" reluctance motors**.

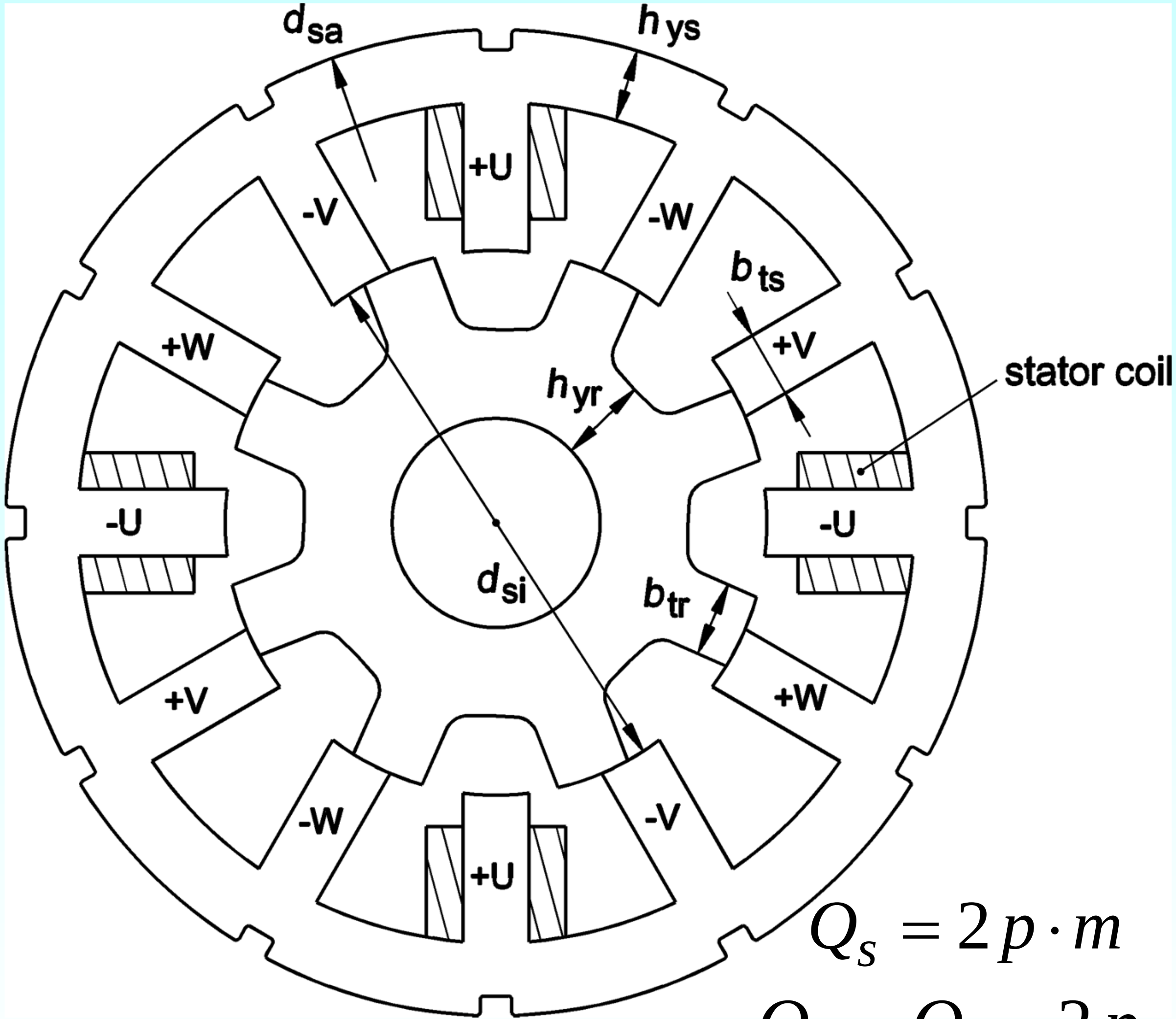
- As rotor movement causes flux change in the stator coils, there a voltage is induced (back EMF).

Generator mode:

- If the rotor is driven mechanically and the stator coils are energized when rotor moves from aligned to unaligned position, then the magnetic pull is **braking** the rotor.

- Back EMF gives - along with the stator current - generated electric power, which is fed to the inverter.

Design features of SR machines



$$Q_s = 2p \cdot m$$

$$Q_r = Q_s - 2p$$

Cross section of a totally enclosed, air cooled 4-pole SR machine:
7.5 kW, 1500/min,
motor current (rms): 12 A,
stator outer/inner diameter:
210 / 120.9 mm, air gap: 0.45 mm

- Very small air gap for big difference of inductance of *d*- and *q*-axis
- Number of stator and rotor teeth NOT equal
- Usually number of rotor slots smaller
- Stator tooth width slightly smaller than rotor tooth width

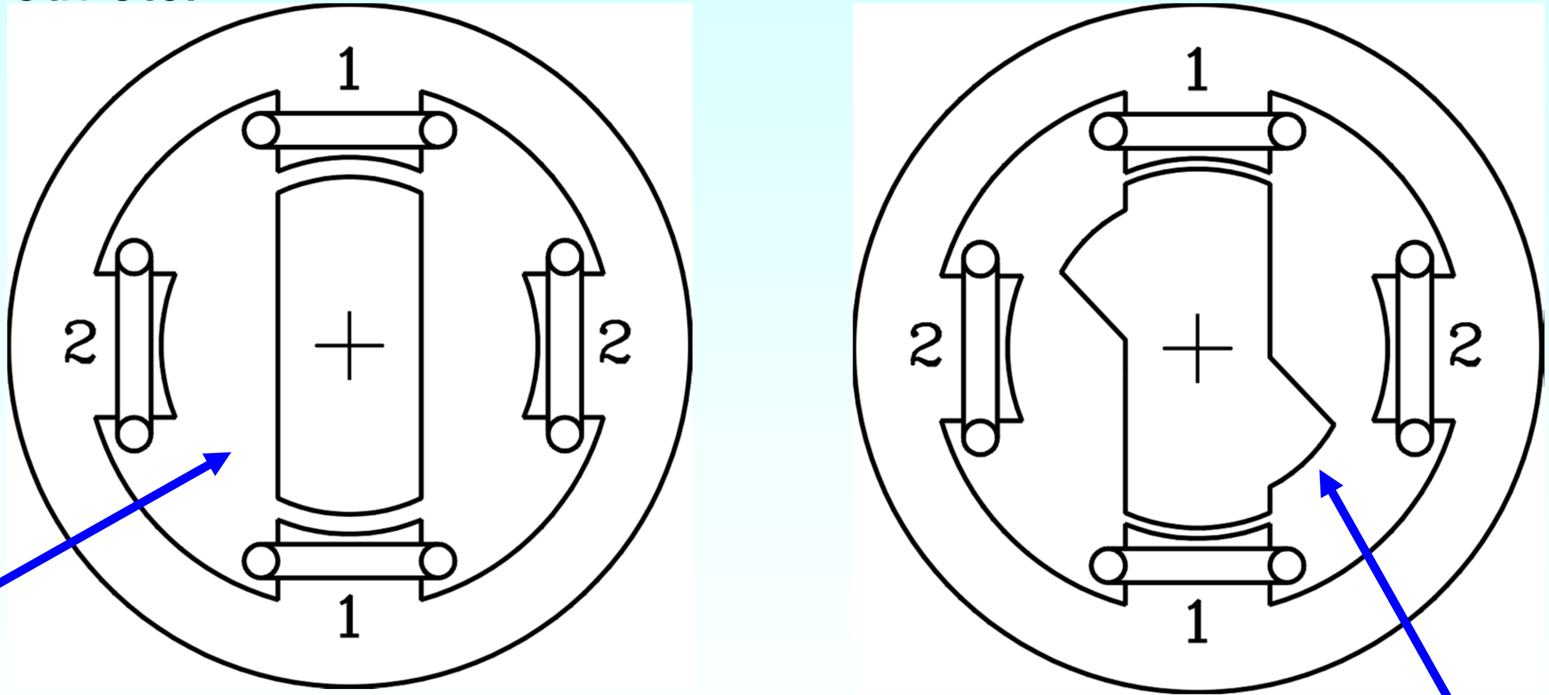
3 phases: 6/4 teeth per pole pair 4 phases: 8/6 teeth per pole pair

One - & Two-phase SR motors are not self starting

Stator and rotor teeth numbers, two phase machine: per pole pair ($2p = 2$):

$m = 2$: $Q_s = 2p \cdot m = 2 \cdot 2 = 4 \qquad Q_r = Q_s - 2p = 4 - 2 = 2$

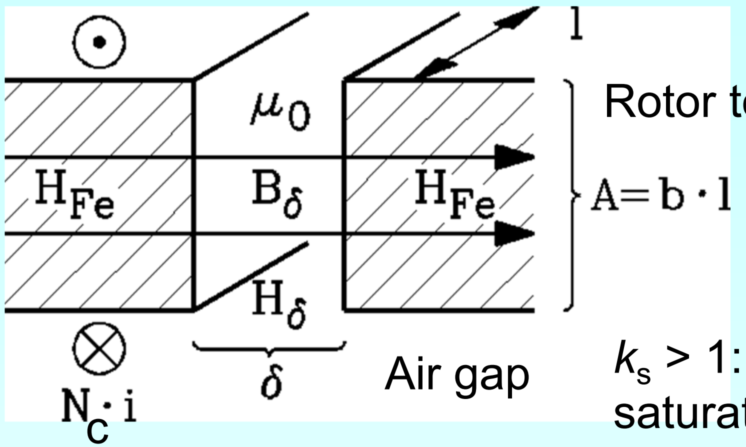
Self starting is only assured, if some special asymmetry is put into the machine e.g. **asymmetric rotor teeth**, additional permanent magnet in on stator tooth etc.



Symmetric rotor cannot start from aligned position

Phase 2 exerts magnetic pull on **asymmetric rotor** to self-start in ccw direction

Flux linkage per phase in SR machines

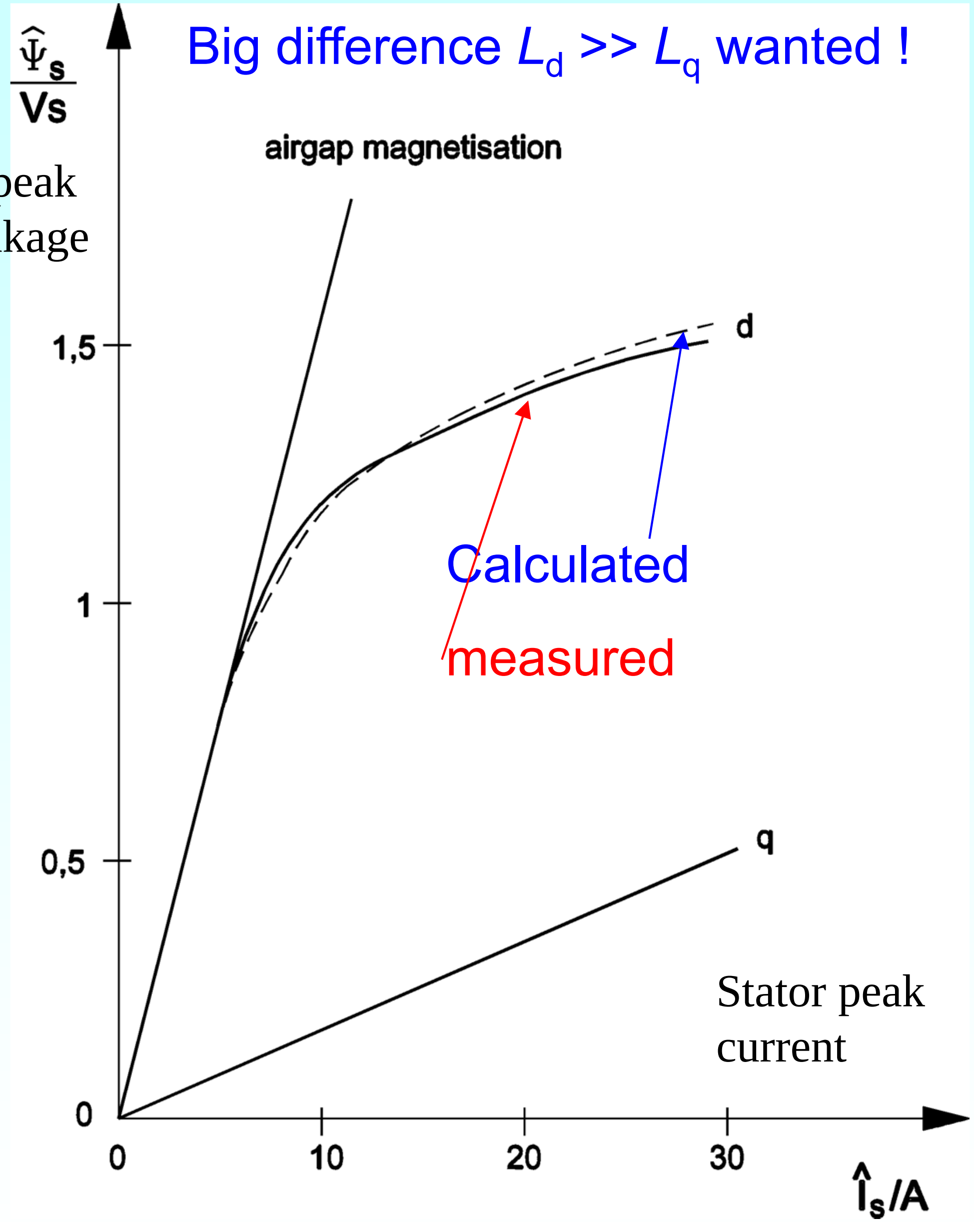


$k_s > 1$:
saturation factor

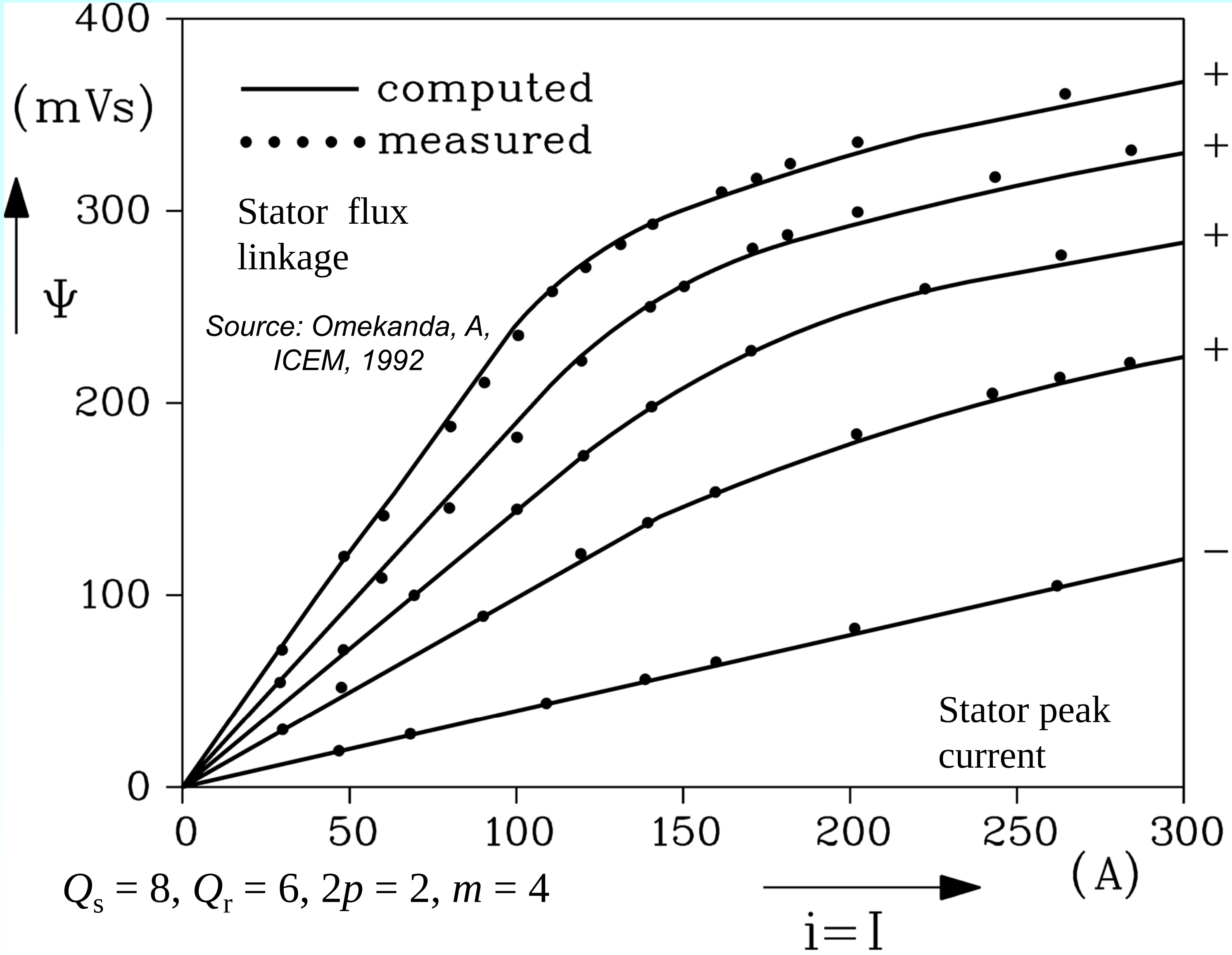
$$L_c = \frac{\Psi}{i} = \frac{N_c \cdot A \cdot B_\delta}{i} = \mu_0 \cdot N_c^2 \cdot \frac{b}{\delta \cdot k_s} \cdot l$$

- Inductance is biggest in aligned position (***d*-position: $L_d = 2pL_{c,d}/a$**) = small air gap δ.
- Unaligned position **(*q*-position: $L_q = 2pL_{c,q}/a$):** Rotor slot opposes stator tooth = big air gap = small inductance.

Facit:
Inductance depends on stator current (= iron saturation) and rotor position .

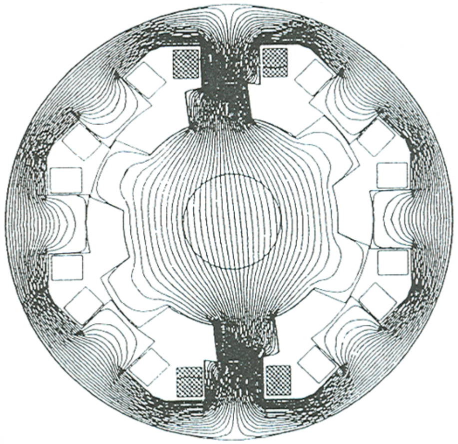


Example: Numerically calculated flux linkage per phase in intermediate positions between *d*- and *q*-position



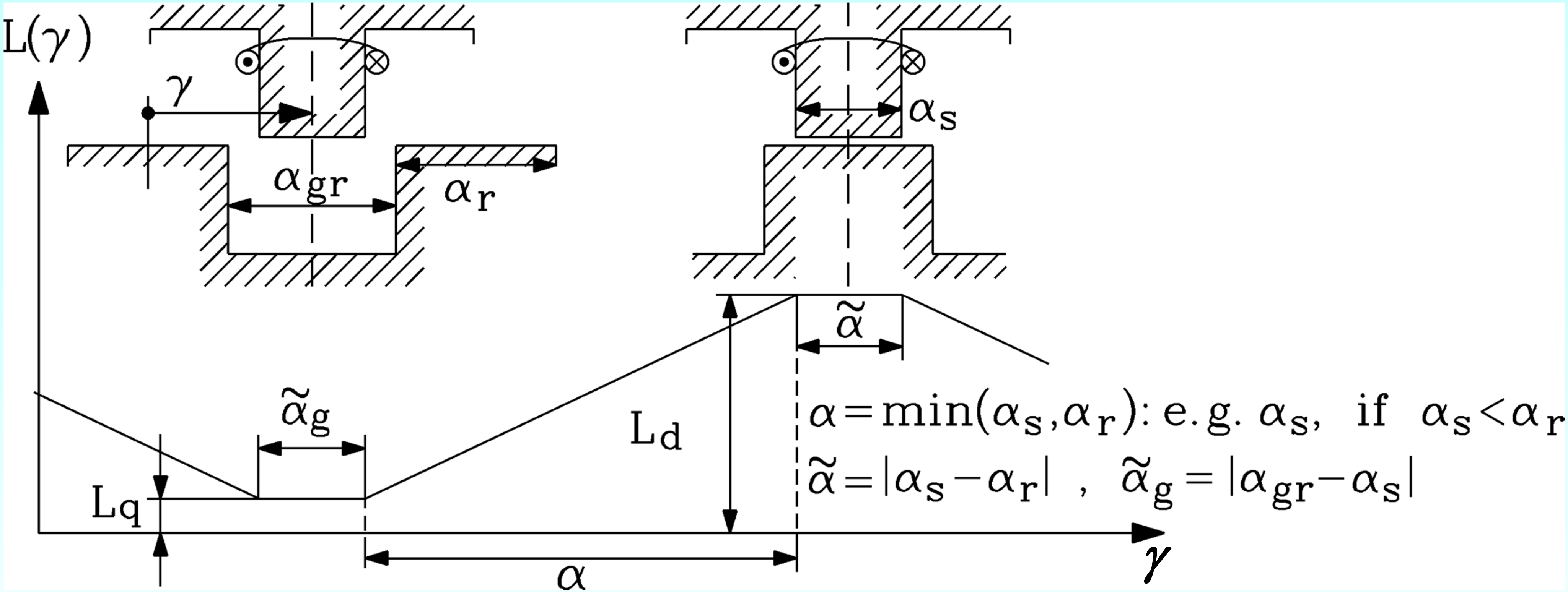
Mech. angle between *d*- & *q*-position:

$$\frac{360°}{2Q_r} = \frac{360°}{2 \cdot 6} = 30°$$



$Q_s = 8,\ Q_r = 6,\ 2p = 2,\ m = 4$

Changing of stator inductance during rotor movement



*- In order to get big torque the difference between d-axis and q-axis flux linkage (inductance) must be very big**, which holds true for all kinds of reluctance machines.***

*- Sign of current polarity does not influence sign of torque, so **uni-polar** current feeding is sufficient.*

Voltage equation per phase of a SR machine

Rotor position angle γ (mech. degrees):
Determines speed and inductance !

$$\Omega_m = \frac{d\gamma}{dt}$$

Flux linkage depends on rotor position angle γ and current *i* (saturation):

$$\psi(\gamma, i) = L(\gamma, i) \cdot i$$

Voltage equation per phase: $u = R \cdot i + \frac{d\psi}{dt} = R \cdot i + \left.\frac{d\psi}{d\gamma}\right|_{i=c.} \cdot \frac{d\gamma}{dt} + \left.\frac{d\psi}{di}\right|_{\gamma=c.} \cdot \frac{di}{dt}$

Induced voltage due to rotor motion ("Back EMF"): $u_i = \left.\frac{d\psi}{d\gamma}\right|_{i=c.} \cdot \Omega_m = i \cdot \frac{dL(\gamma, i)}{d\gamma} \cdot \Omega_m$

Inductive voltage drop: $\left.\frac{d\psi}{di}\right|_{\gamma=c.} \cdot \frac{di}{dt}$

Special case: Saturation neglected: $\psi(\gamma, i) = L(\gamma) \cdot i$

"Back EMF": $u_i = i \cdot \frac{dL(\gamma)}{d\gamma} \cdot \Omega_m$ Inductive voltage drop: $\left.\frac{d\psi}{di}\right|_{\gamma=c.} \cdot \frac{di}{dt} = L \cdot \frac{di}{dt}$

Power balance per phase of a SR machine

Magnetic energy per phase: $W_{mag} = \int_0^{\psi} i \cdot d\psi$

<u>Special case:</u> No iron saturation: $\psi(\gamma, i) = L(\gamma) \cdot i$

$$W_{mag} = \int_0^{\psi} i \cdot d\psi = \int_0^{i} i \cdot L(\gamma) \cdot di = \frac{L(\gamma) \cdot i^2}{2}$$

Change of magnetic energy per phase: $\frac{dW_{mag}}{dt} = \frac{d}{dt} \frac{L(\gamma) \cdot i^2}{2} = \frac{i^2}{2} \cdot \frac{dL(\gamma)}{d\gamma} \cdot \frac{d\gamma}{dt} + \frac{L(\gamma)}{2} \cdot 2 \cdot i \cdot \frac{di}{dt}$

Voltage equation per phase: $u = R \cdot i + \frac{d\psi}{dt} = R \cdot i + L \cdot \frac{di}{dt} + i \cdot \frac{dL}{d\gamma} \cdot \Omega_m$

Power equation per phase: $p_e = u \cdot i = R \cdot i^2 + i \cdot L \cdot \frac{di}{dt} + i^2 \cdot \frac{dL}{d\gamma} \cdot \Omega_m$

General power balance per phase: $p_e = p_{Cu} + \frac{dW_{mag}}{dt} + p_\delta$

Mechanical air gap power ("internal power"): $p_\delta = \frac{1}{2} i^2 \cdot \frac{dL}{d\gamma} \cdot \Omega_m$

Electromagnetic torque per phase: $M_e = p_\delta / \Omega_m = \frac{1}{2} i^2 \cdot \frac{dL}{d\gamma}$

Torque equation of SR machine

Special case: No iron saturation: $\psi(\gamma, i) = L(\gamma) \cdot i$

Electromagnetic torque (γ: mech. degrees):

$$M_e = p_\delta / \Omega_m = \frac{1}{2} \cdot i^2 \cdot \frac{dL(\gamma)}{d\gamma}$$

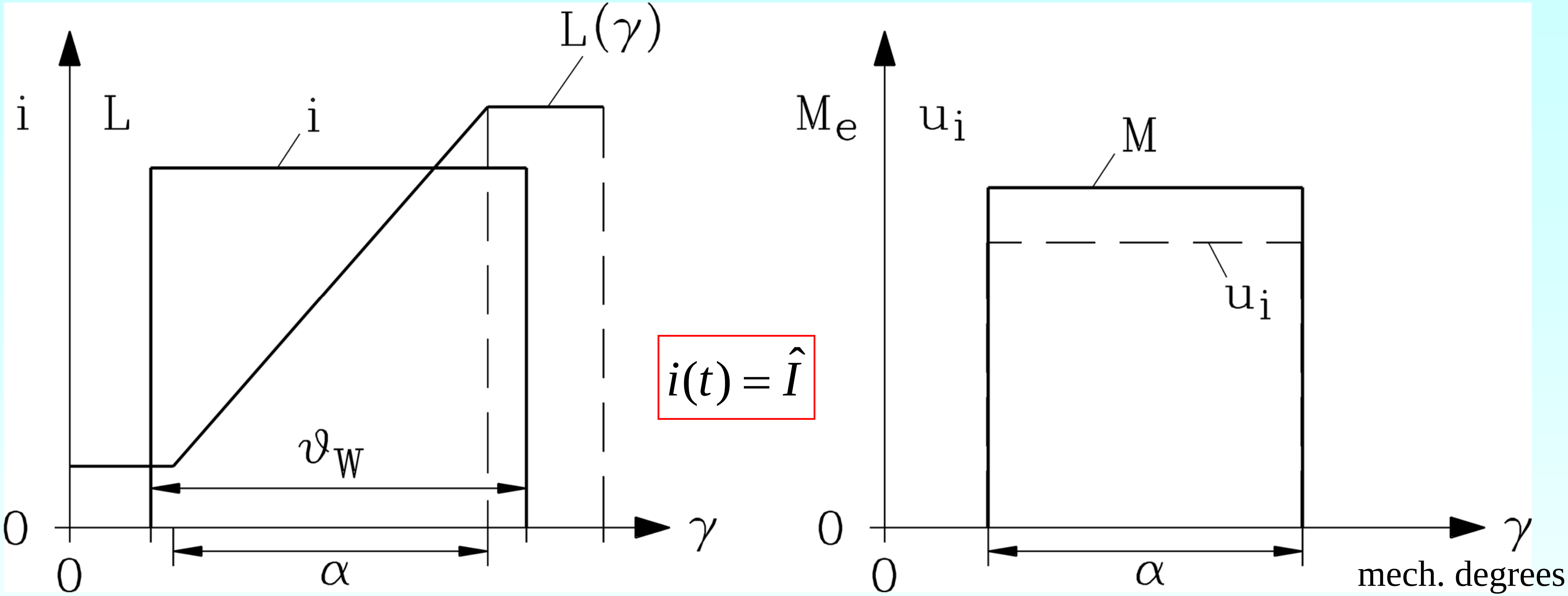
Electromagnetic torque (γ: el. degrees):

$$M_e = \frac{Q_r}{2} \cdot i^2 \cdot \frac{dL}{d\gamma}$$

One electrical period of the stator current corresponds to a rotation of the rotor by one rotor slot pitch. Hence:

$$\gamma(mech.) = \gamma(ele.) / Q_r$$

SR machine operation at ideal conditions (1)



$i(t) = \hat{I}$

- Ideally constant current per phase (=ideal inverter)

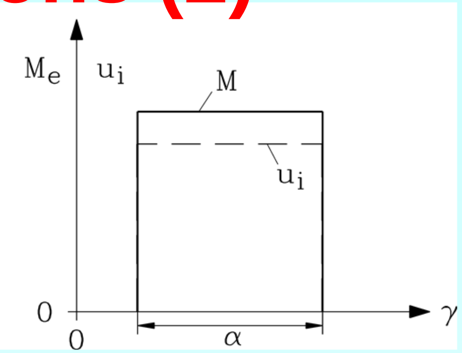
- Ideally linear rising inductance per phase (= a) no 2D fringing flux, b) no saturation)

→ Ideally constant torque, ideally constant back EMF

$$M_e = \frac{1}{2} i^2 \cdot \frac{dL}{d\gamma} = \frac{1}{2} \hat{I}^2 \cdot \frac{L_d - L_q}{\alpha}$$

$$\hat{U}_i = \hat{I} \cdot \frac{L_d - L_q}{\alpha} \cdot \Omega_m$$

SR machine operation at ideal conditions (2)



- Linear variation of phase inductance with rotor position assumed !

$L = L_s$: stator phase inductance
$$M_e = \frac{1}{2} i^2 \cdot \frac{dL_s}{d\gamma} = \frac{1}{2} \hat{I}^2 \cdot \frac{L_d - L_q}{\alpha}$$

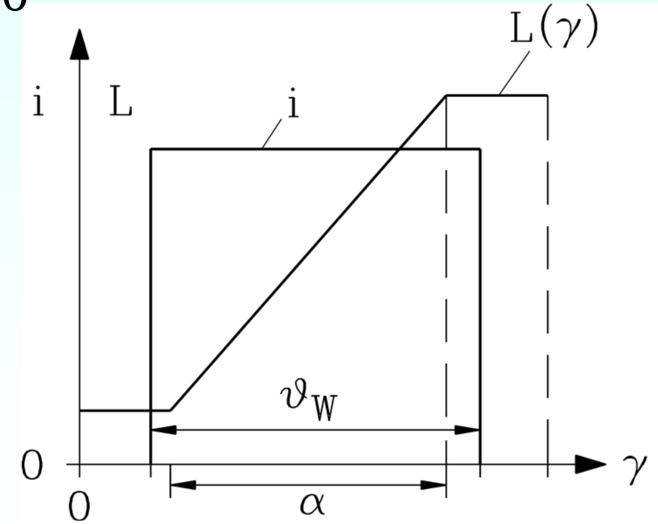
*If no saturation occurs, torque rises with the **square** of current.*

γ in mech. degrees

Note: Generator mode:

Current flow, when rotor moves from aligned to unaligned position:

negative (braking) torque
$$M_e = \frac{1}{2} i^2 \cdot \frac{dL}{d\gamma} = \frac{1}{2} \hat{I}^2 \cdot \frac{L_q - L_d}{\alpha} < 0$$

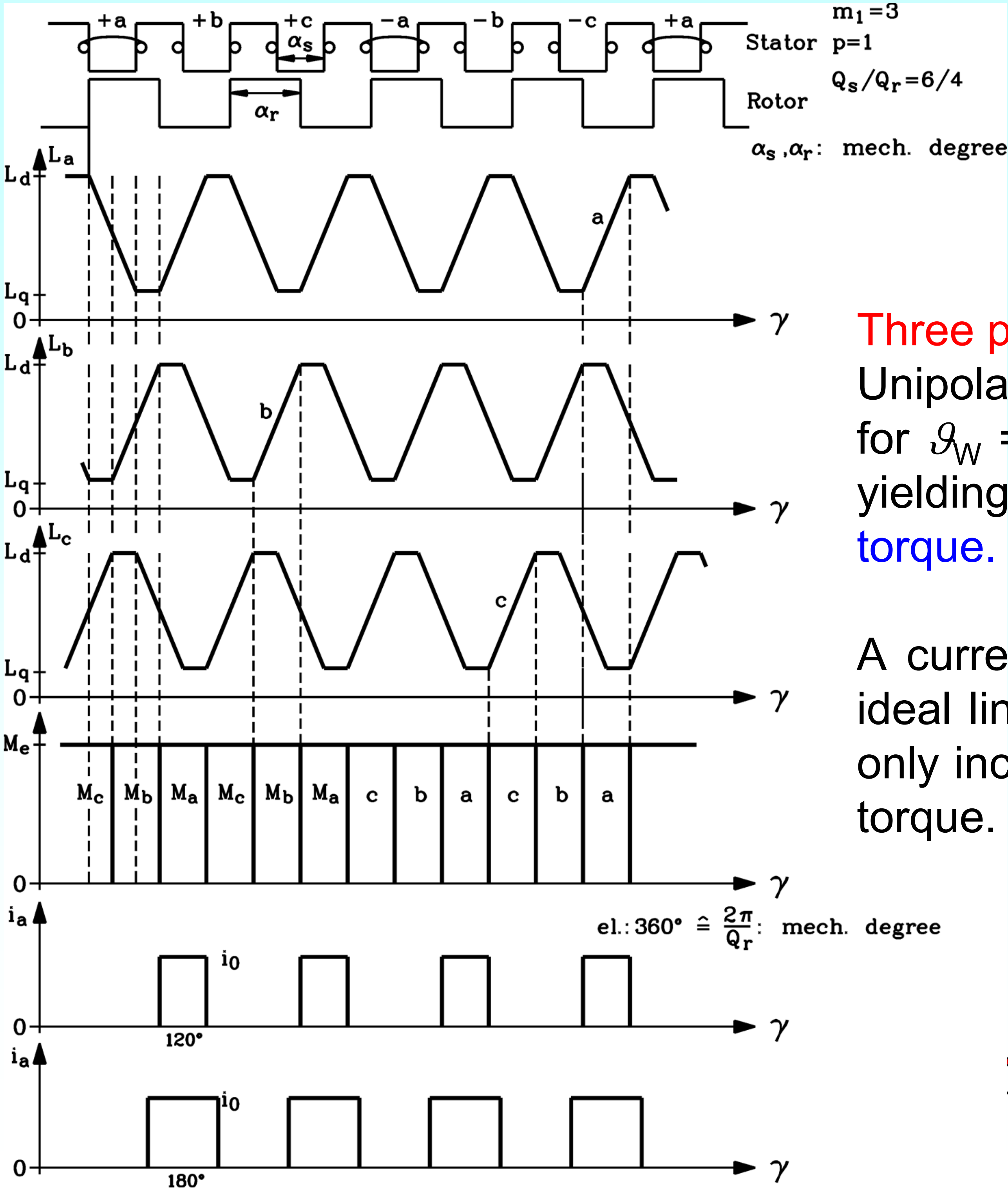


Back EMF:

$$\hat{U}_i = \hat{I} \cdot \frac{L_d - L_q}{\alpha} \cdot \Omega_m > 0, \quad P_\delta = \hat{U}_i \hat{I} / 2 > 0 \qquad \text{motor}$$

$$\hat{U}_i = \hat{I} \cdot \frac{L_q - L_d}{\alpha} \cdot \Omega_m < 0, \quad P_\delta = \hat{U}_i \hat{I} / 2 < 0 \qquad \text{generator}$$

Current angle in SR machines

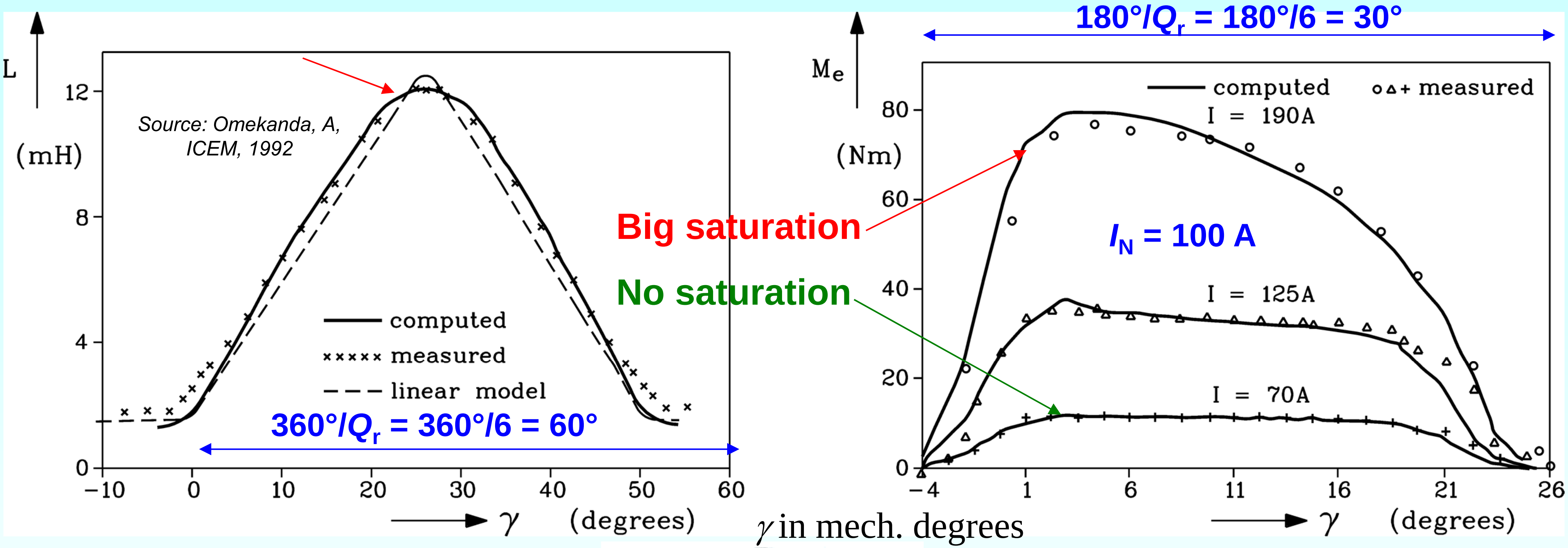


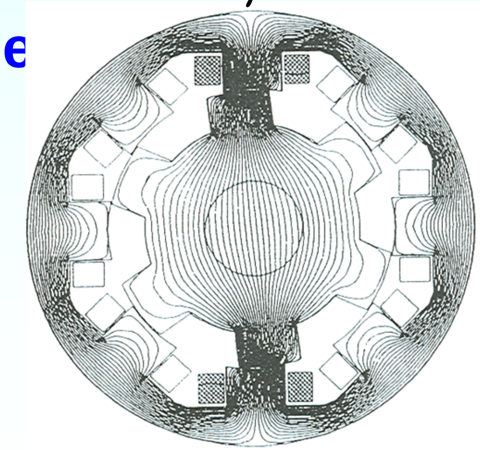
Three phase 6/4-SR machine:

Unipolar current impression is done for $\vartheta_W = \alpha = 120°$ el. for each phase, yielding a theoretically smooth torque.

A current impression of 180° at this ideal linear change of inductance will only increase resistive losses, but not torque.

Example: Numerically calculated inductance and torque per phase





Inductance per phase

- Real inductance does not rise exactly linear with rotor position

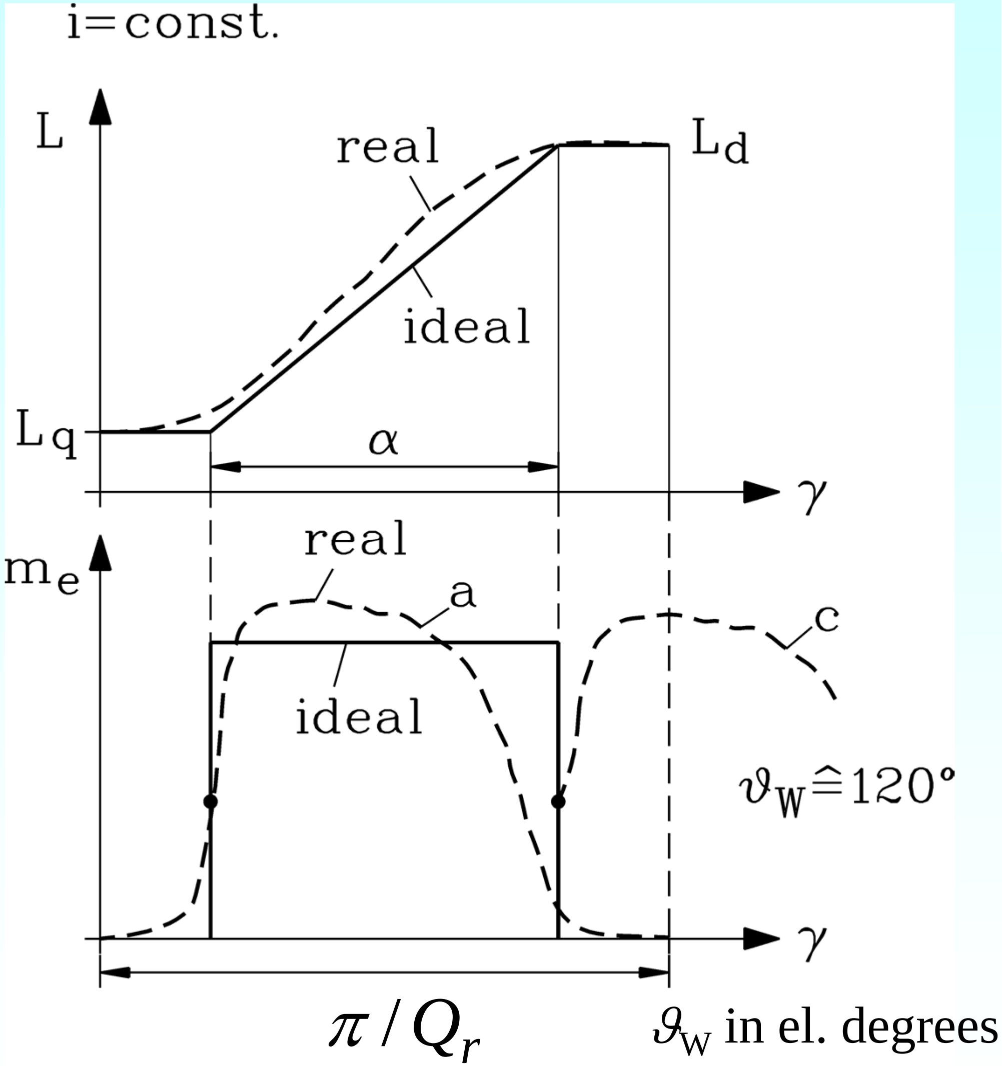
$Q_s = 8$, $Q_r = 6$, $2p = 2$, $m = 4$

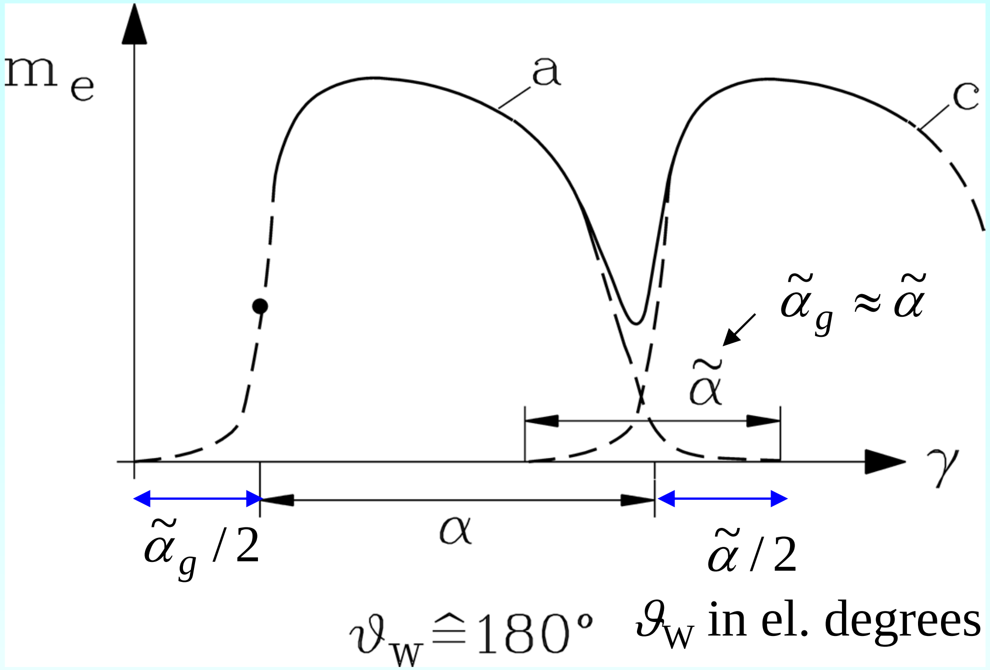
Torque per phase

- Real torque is not ideally constant, although current is ideally constant.
- Saturation deviates torque further.

Real change of inductance with moving rotor

$$M_e(\gamma) = (1/2) \cdot i^2 \cdot dL / d\gamma$$

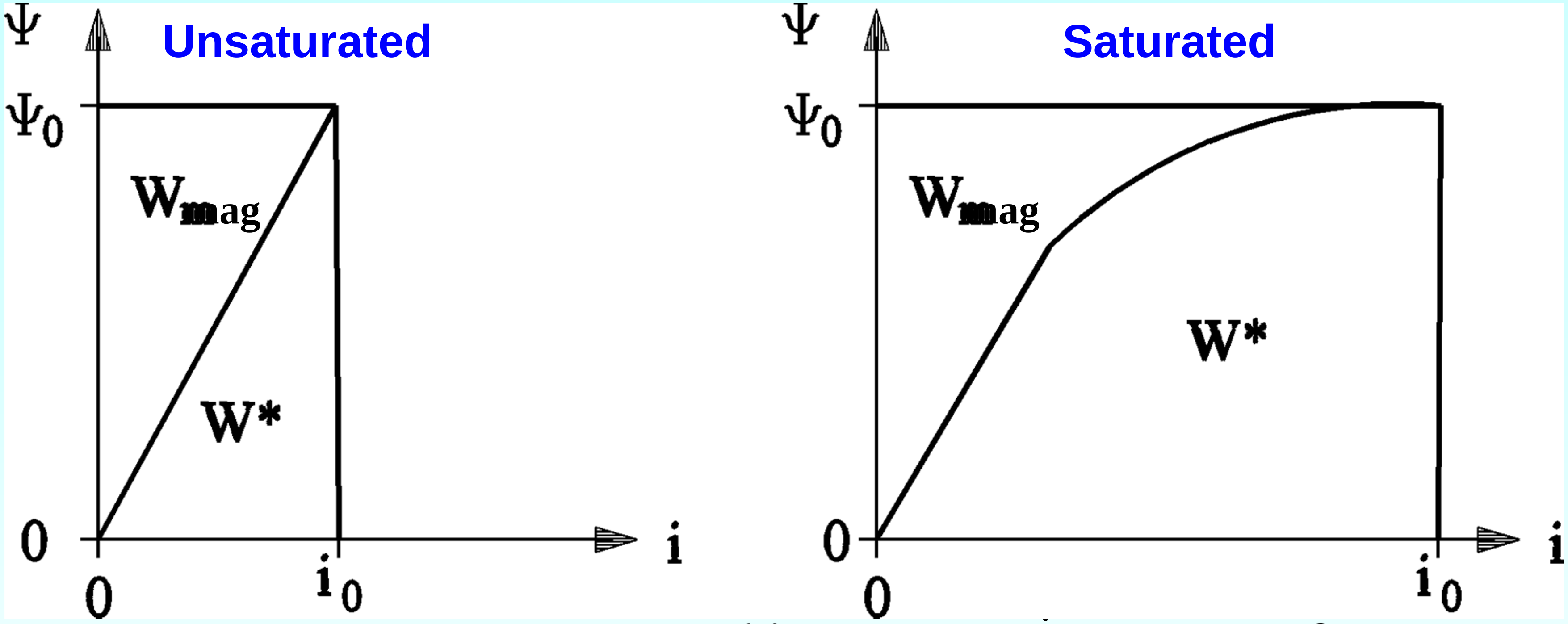




- Real: Non-linear change of inductance: Torque ripple occurs !

- If current angle is increased from 120°el. to 180°el., the torque ripple is reduced and average torque is raised.

Saturation in SR machines

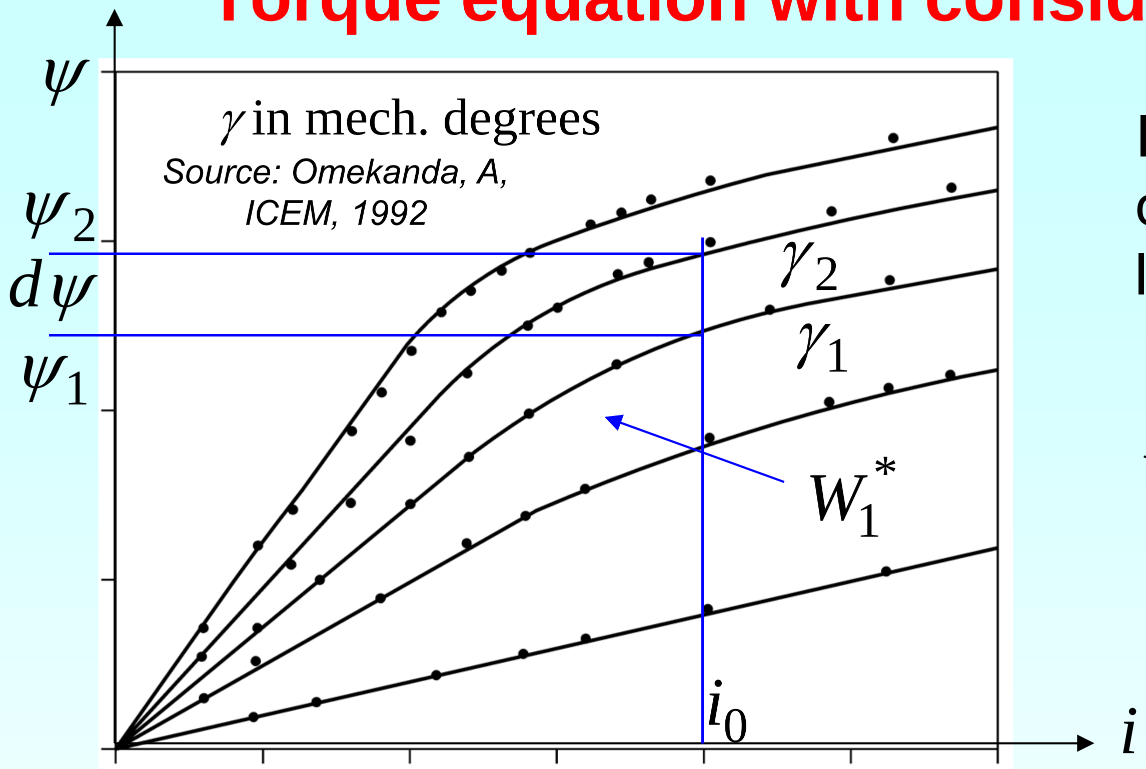


Magnetic energy: unsaturated $W_{mag} = \int_0^{\psi} i \cdot d\psi = L \int_0^{i} i \cdot di = L \frac{i^2}{2}$

Magnetic co-energy: $W^* = \psi \cdot i - W_{mag}$

In saturated machine magnetic co-energy is bigger than magnetic energy !
Electromagnetic torque is proportional to co-energy, so high saturation is aimed !

Torque equation with consideration of iron saturation



If rotor moves by increment angle $d\gamma$ (at constant current) form *q* to *d* axis, flux linkage increases by $d\psi$.

$$W_1^* = \psi_1 \cdot i_0 - W_{mag,1}$$

$$W_2^* = \psi_2 \cdot i_0 - W_{mag,2}$$

$$dW^* = W_2^* - W_1^* =$$

$$= (\psi_2 - \psi_1) \cdot i_0 - (W_{mag,2} - W_{mag,1})$$

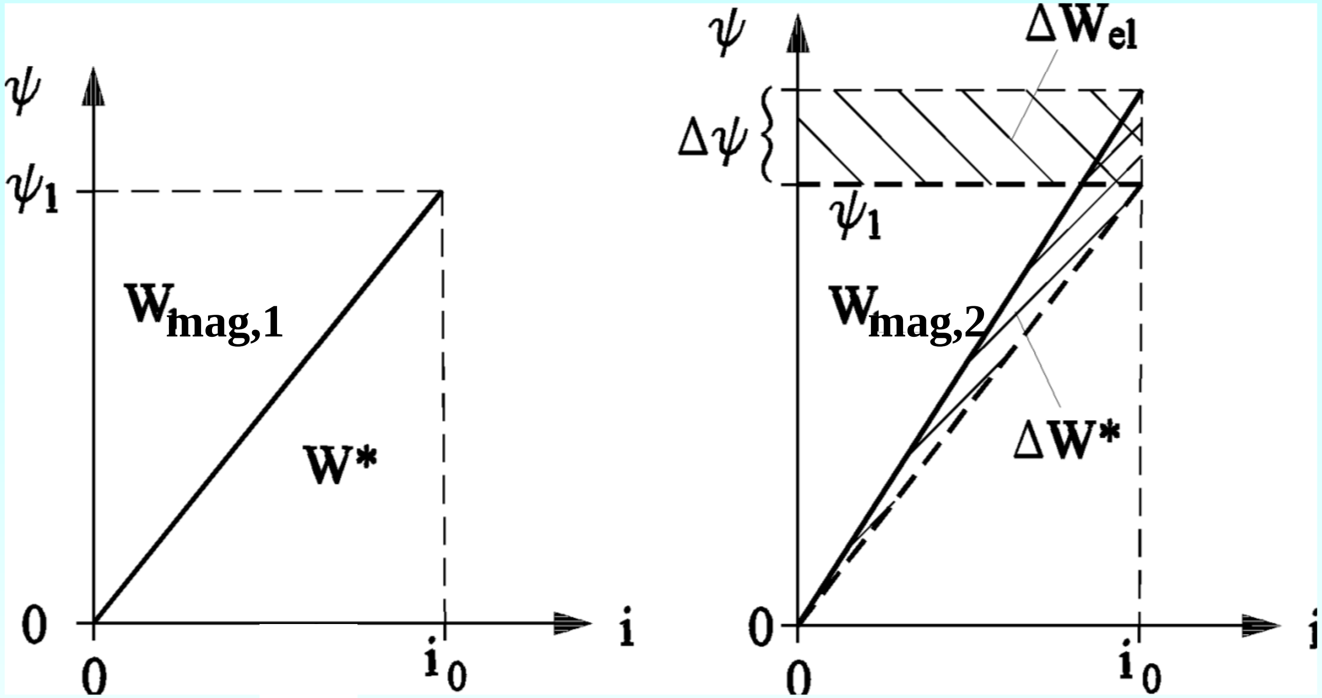
Increase of magnetic energy and co-energy leads to energy balance per phase:

$$dW^* = d\psi \cdot i_0 - dW_{mag}$$

$$u = R \cdot i_0 + \frac{d\psi}{dt} \quad \Rightarrow \quad dW_e = u \cdot i_0 \cdot dt = R \cdot i_0^2 \cdot dt + i_0 \cdot d\psi = R \cdot i_0^2 \cdot dt + dW_{mag} + dA_m$$

$$dA_m = M_e \cdot d\gamma = M_e \cdot \Omega_m \cdot dt \quad \Rightarrow \quad dW^* = dA_m \quad \Rightarrow \quad \boxed{M_e(\gamma, i) = \frac{dW^*}{d\gamma}}$$

Magnetic energy and co-energy in linear material



If rotor moves by increment angle $\Delta\gamma$ (at constant current) form *q* to *d* axis, flux linkage increases by $\Delta\psi$.

γ in mech. degrees

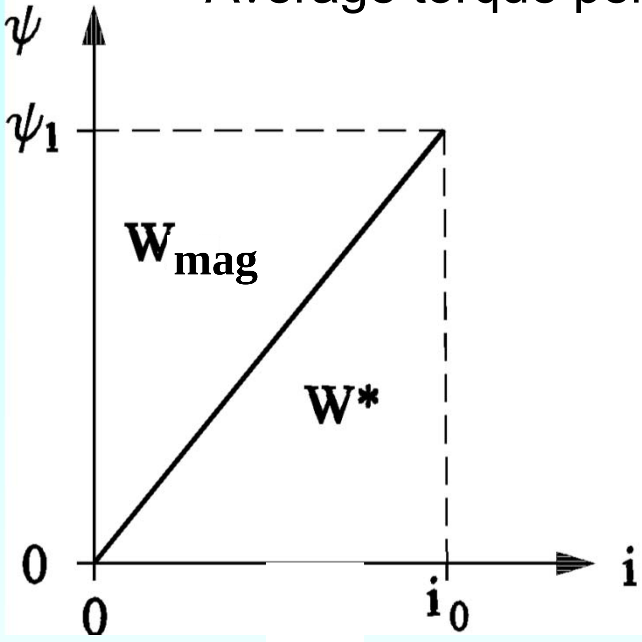
Increase of magnetic energy and co-energy leads to energy balance per phase:

$$W_{mag,2} = W_{mag,1} + dW_{mag} = W_{mag,1} + i_0 \cdot d\psi - dW^*$$

$$u = R \cdot i_0 + \frac{d\psi}{dt} \quad \Rightarrow \quad dW_e = u \cdot i_0 \cdot dt = R \cdot i_o^2 \cdot dt + i_0 \cdot d\psi = R \cdot i_0^2 \cdot dt + dW_{mag} + dA_m$$

$$dA_m = M_e \cdot d\gamma = M_e \cdot \Omega_m \cdot dt \quad \Rightarrow \quad dW^* = dA_m \quad \Rightarrow \quad \boxed{M_e(\gamma, i) = \frac{dW^*}{d\gamma}}$$

Example: Torque calculation for linear iron



Average torque per phase for rotor movement from *q*- to *d*-axis at phase current *i*:

a) Torque calculation from co-energy:

$$M_e(\gamma,i)=\frac{dW^*}{d\gamma} \qquad \Delta W^*_{q\to d}=\frac{L_d}{2}i^2-\frac{L_q}{2}i^2$$

$$\Delta\gamma_{q\to d}=\pi/Q_r$$

γ: mech. degrees

$$M_e(\gamma,i)=\frac{\Delta W^*}{\Delta\gamma}=\left(\frac{L_d}{2}-\frac{L_q}{2}\right)\cdot i^2\cdot\frac{Q_r}{\pi}$$

b) Torque calculation change of inductance:

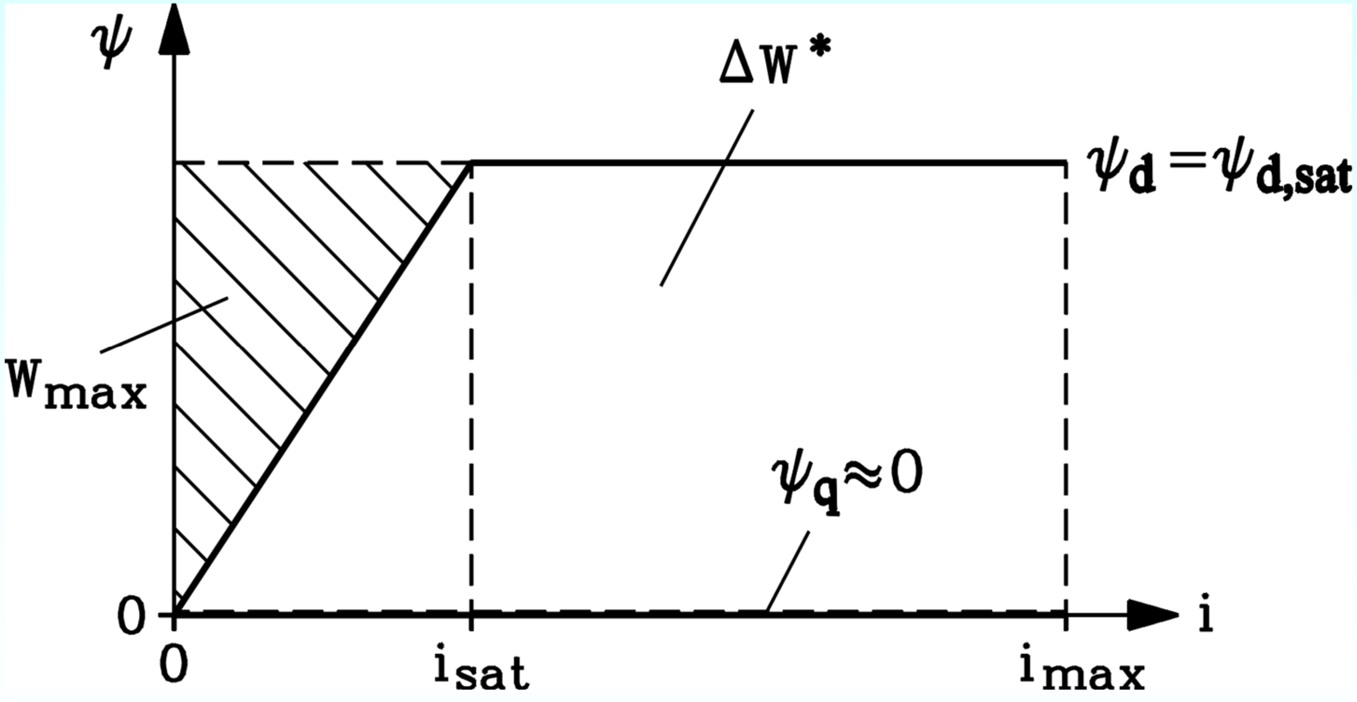
$$M_e=\frac{1}{2}i^2\cdot\frac{dL}{d\gamma}=\frac{1}{2}i^2\cdot\frac{L_d-L_q}{\pi/Q_r}$$

Facit: For linear iron methods a) and b) deliver identical results. For saturated iron method a) must be used.

High utilization of SR machine needs high saturation

Torque calculation is done from map of $\psi(i,\gamma)$-curves, evaluating for given current the change of co-energy with change of rotor angle γ.

SR machines shall be operated highly saturated in order to limit inverter rating by limiting switched magnetic energy.



Torque is proportional to change of co-energy between *d*- and *q*-position ΔW^*:

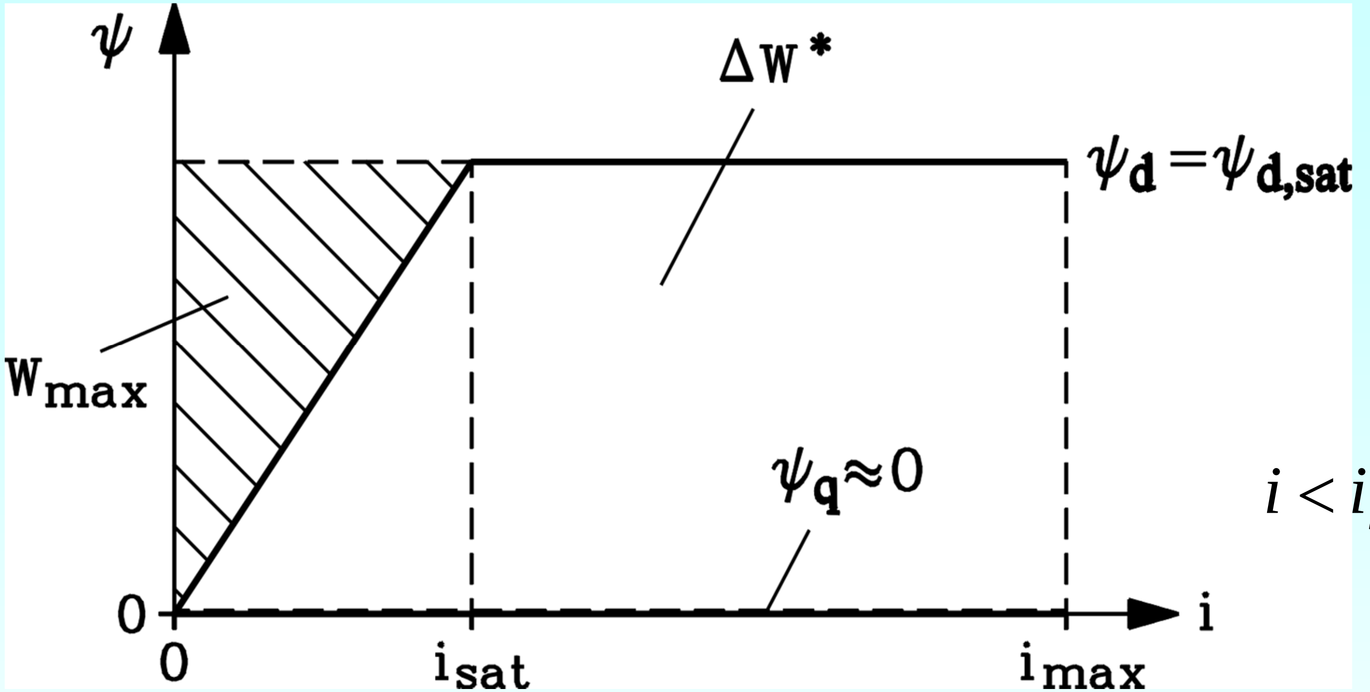
a) Unsaturated case $i < i_{sat}$

Torque is proportional i^2

b) Saturated case $i > i_{sat}$

Torque tends to be proportional nearly *i*

Torque-current characteristic



$$W_{\max} = \psi_{d,sat} \cdot i_{sat} / 2$$

$$\Delta\gamma_{q\to d} = \pi / Q_r$$

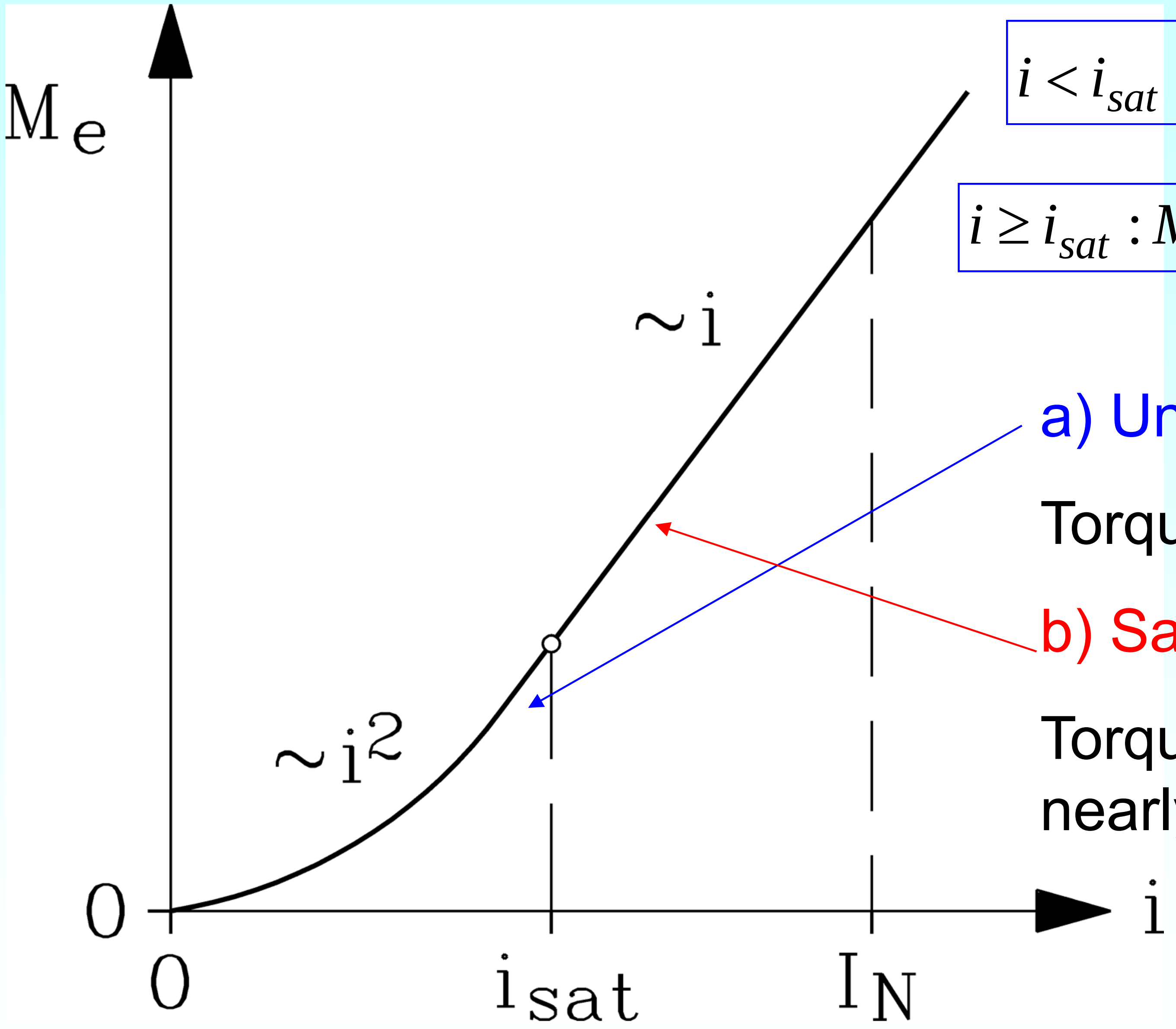
$$i < i_{sat} : \Delta W^*_{q\to d} = W_{\max} \cdot (i / i_{sat})^2$$

$$i < i_{sat} : M_e = \Delta W^*_{q\to d} / \Delta\gamma_{q\to d} = W_{\max} \cdot (i / i_{sat})^2 \cdot Q_r / \pi$$

$$i \ge i_{sat} : \Delta W^*_{q\to d} = W_{\max} + \psi_{d,sat} \cdot (i - i_{sat}) = W_{\max} + 2W_{\max} \cdot (i / i_{sat} - 1)$$

$$i \ge i_{sat} : M_e = \Delta W^*_{q\to d} / \Delta\gamma_{q\to d} = W_{\max} \cdot (2i / i_{sat} - 1) \cdot Q_r / \pi$$

Torque-current curve of switched reluctance machine



$$i < i_{sat} : M_e = W_{\max} \cdot (i / i_{sat})^2 \cdot Q_r / \pi$$

$$i \geq i_{sat} : M_e = W_{\max} \cdot (2i / i_{sat} - 1) \cdot Q_r / \pi$$

a) Unsaturated case $i < i_{sat}$

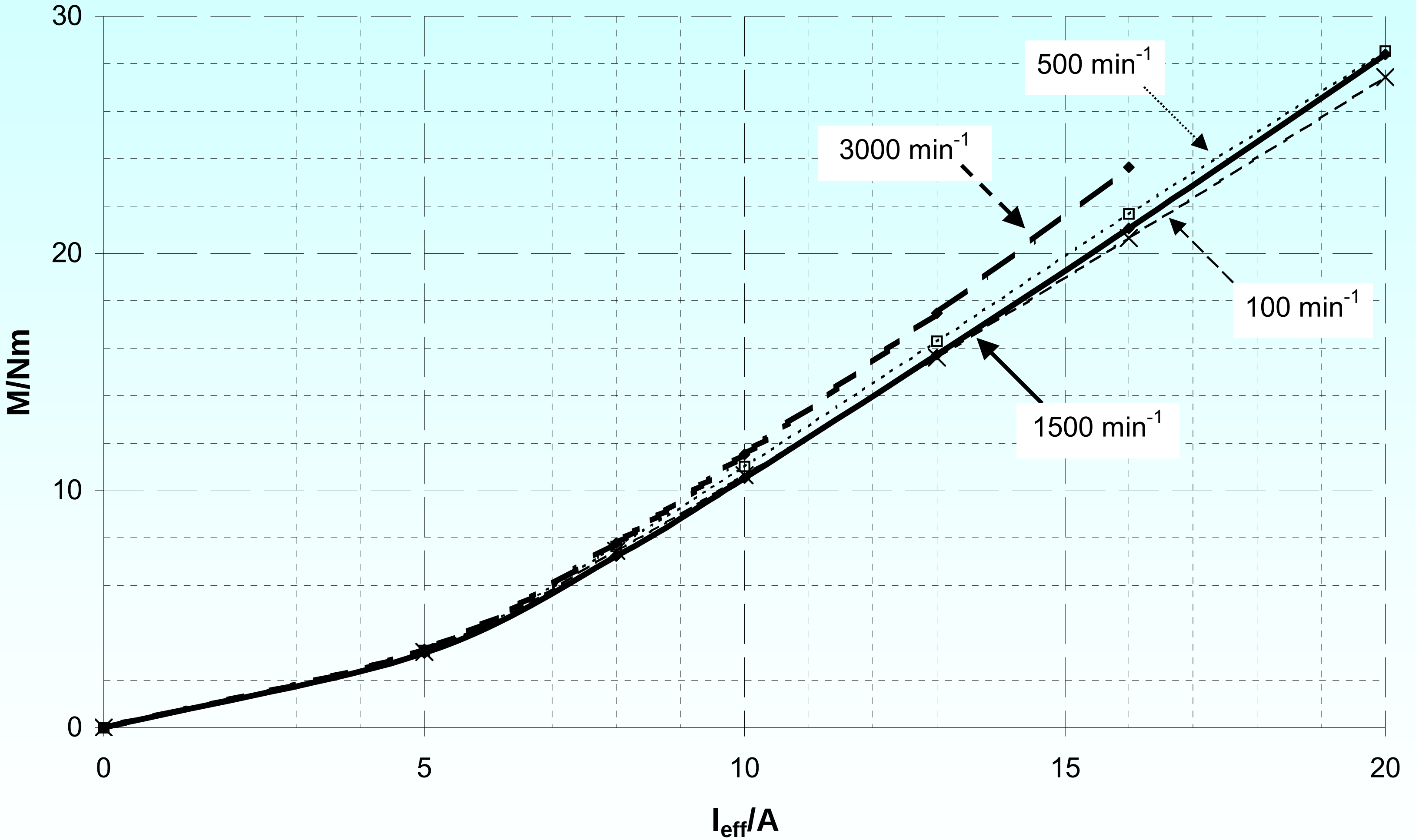
Torque is proportional i^2

b) Saturated case $i \geq i_{sat}$

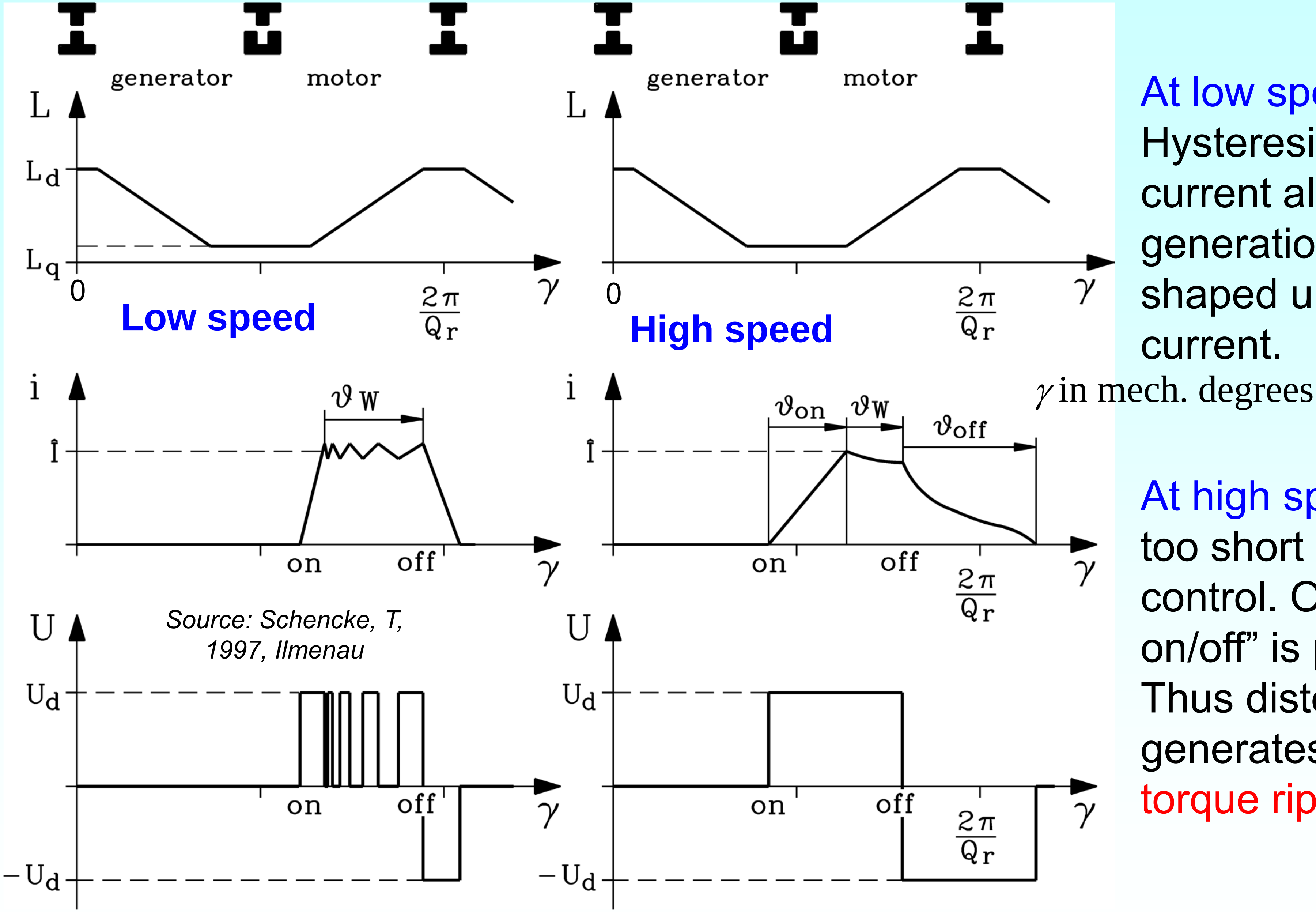
Torque tends to be proportional nearly *i*

Measured torque-current curve of a 1.2 kW SRD

4-pole, 3-phase SRD: Rated data: 1.2 kW, 1500 … 6000/min, total mass 32 kg, rotor inertia 3.9 g·m^2, stator/rotor teeth: 12/8, Company SICME/Italy



Real shape of unipolar current

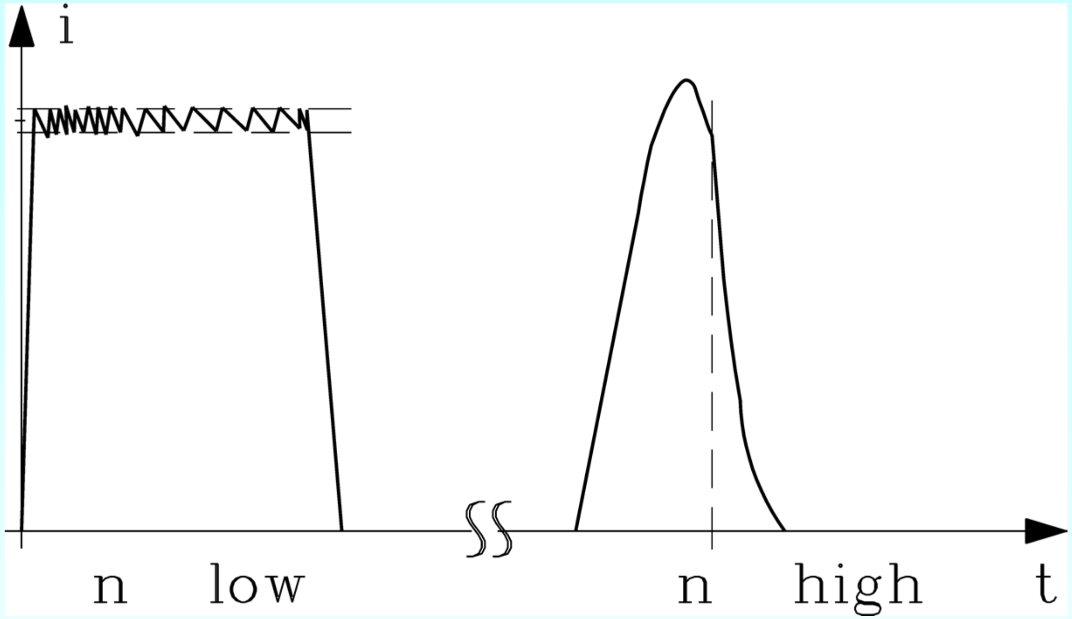


Source: Schencke, T, 1997, Ilmenau

At low speed: Hysteresis control of current allows generation of block shaped unipolar current.

At high speed: Time is too short for hysteresis control. Only ”voltage on/off” is possible. Thus distorted current generates increased torque ripple.

Real shape of uni-polar current



At low speed: Hysteresis control of current allows generating rather block shaped unipolar current.

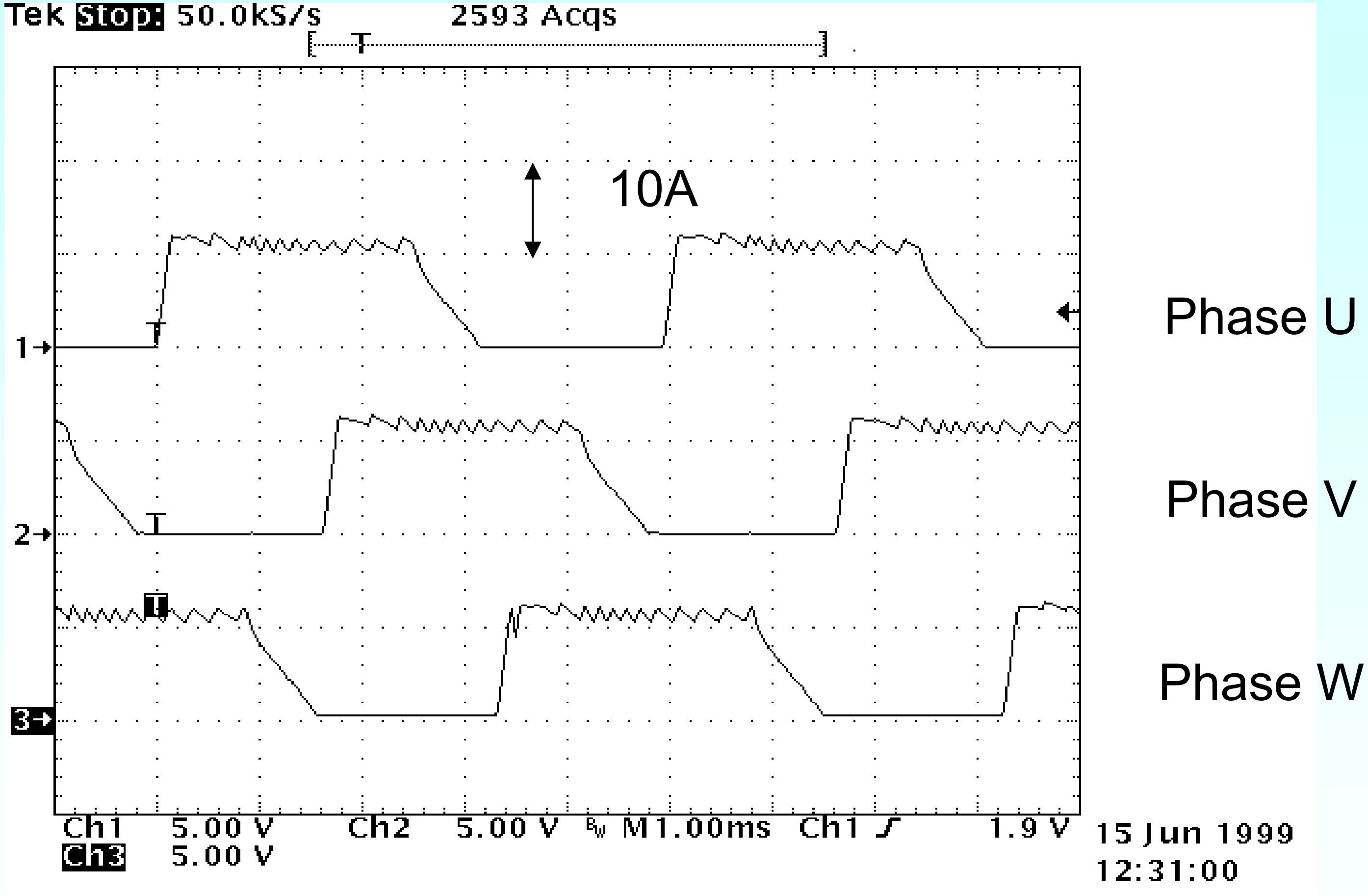
At high speed: Time is too short for hysteresis control. Only ”voltage on/off” is possible. Thus distorted current generates increased torque ripple.

Real SR machines show considerable torque ripple: at low speed due to non-linear variation of inductance, at high speed: increased ripple due to distorted current.

Frequency of torque ripple: $f_{puls} = n \cdot Q_r \cdot m$ e.g. 3000/min, Q_r = 8, m = 3: 1.2 kHz

Measured uni-polar current signal at n_N = 1500/min

4-pole, 3-phase SRD: Rated data: 1.2 kW, 1500 … 6000/min, total mass 32 kg, rotor inertia 3.9 g·m^2, stator/rotor teeth: 12/8, Company SICME/Italy



n=1500min^{-1} I_{eff}=8A

Currents are nearly block-shaped

Current angle nearly 180°el

r.m.s. current at 180°el:

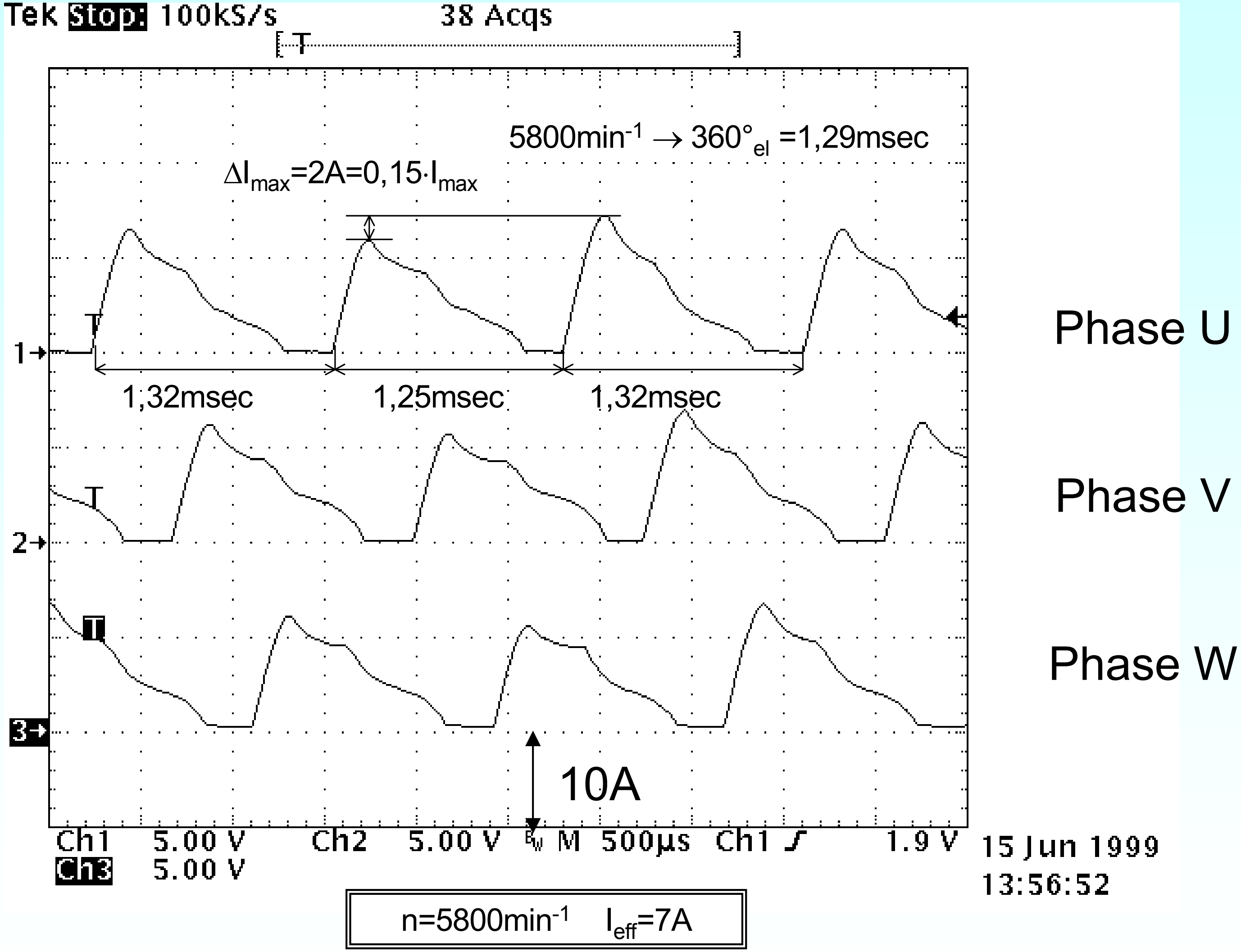
$$I_{rms} = \sqrt{\frac{1}{T}\int_0^T i(t)^2 dt} =$$

$$= \sqrt{\frac{1}{T}\hat{I}^2\frac{T}{2}} = \frac{\hat{I}}{\sqrt{2}} = 0.71\hat{I}$$

$$I_{rms} = 0.71 \cdot 12 = 8.5A$$

Measured uni-polar current signal at n_{max} = 5800/min

4-pole, 3-phase SRD: Rated data: 1.2 kW, 1500 … 6000/min, total mass 32 kg, rotor inertia 3.9 g·m², stator/rotor teeth: 12/8, Company SICME/Italy



Current wave-form deviates strongly from the ideal block shape

SR Drive operation – torque-speed characteristic

a) Current limit: Inverter current limit usually 200% rated motor current to allow short time overload

b) Voltage limit: DC link block voltage is maximum inverter voltage: $R_s \cong 0$:

$$u = U_d = R \cdot \hat{I} + L \cdot \frac{d\hat{I}}{dt} + \hat{U}_i \quad \Rightarrow \quad U_d = \hat{U}_i = \hat{I} \cdot \frac{dL}{d\gamma} \cdot \Omega_m$$

Block current: $\frac{d\hat{I}}{dt} = 0$

$$\hat{I} = \frac{U_d}{dL_s / d\gamma} \cdot \frac{1}{\Omega_m} \cong \frac{U_d}{(L_d - L_q)/\alpha} \cdot \frac{1}{\Omega_m}$$

$$M_e \cong \frac{1}{2 \cdot (L_d - L_q)/\alpha} \cdot \left(\frac{U_d}{\Omega_m} \right)^2$$

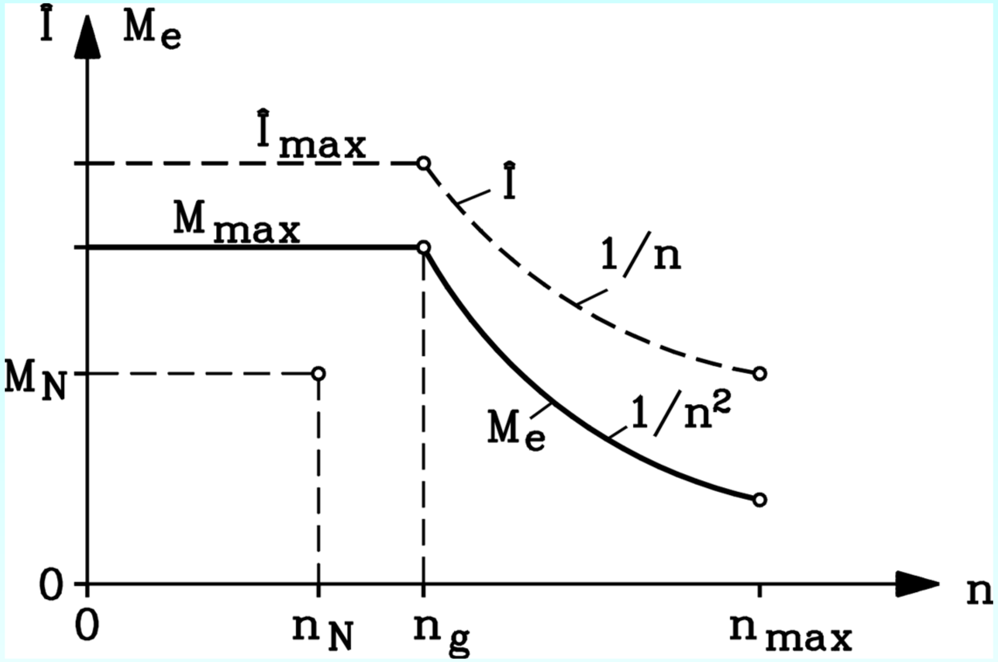
Possible current flow rises with inverse of decreasing speed, until it reaches the inverter current limit at speed:

$$n_g = \frac{1}{2\pi} \cdot \frac{U_d}{\hat{I}_{max} \cdot \left((L_d - L_q)/\alpha \right)}$$

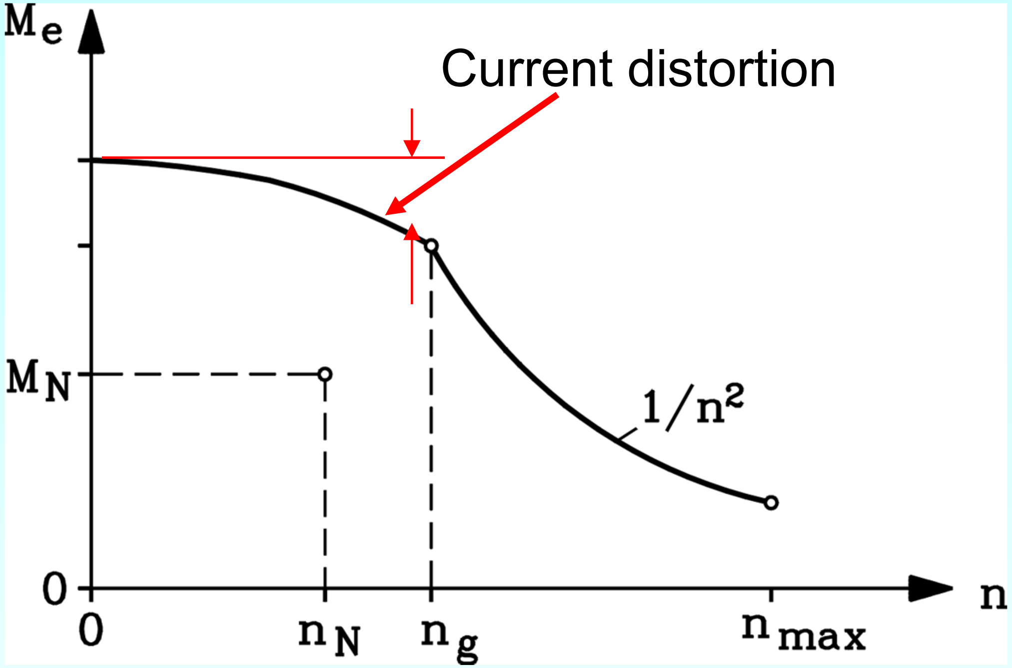
α in mech. degrees

At the voltage limit the maximum possible torque of SR drives decreases with the square of rising speed.

Torque-speed characteristic of SR machine



a) for ideal block-shaped current,



b) considering real current shape which is distorted with rising speed

Inverter current control:

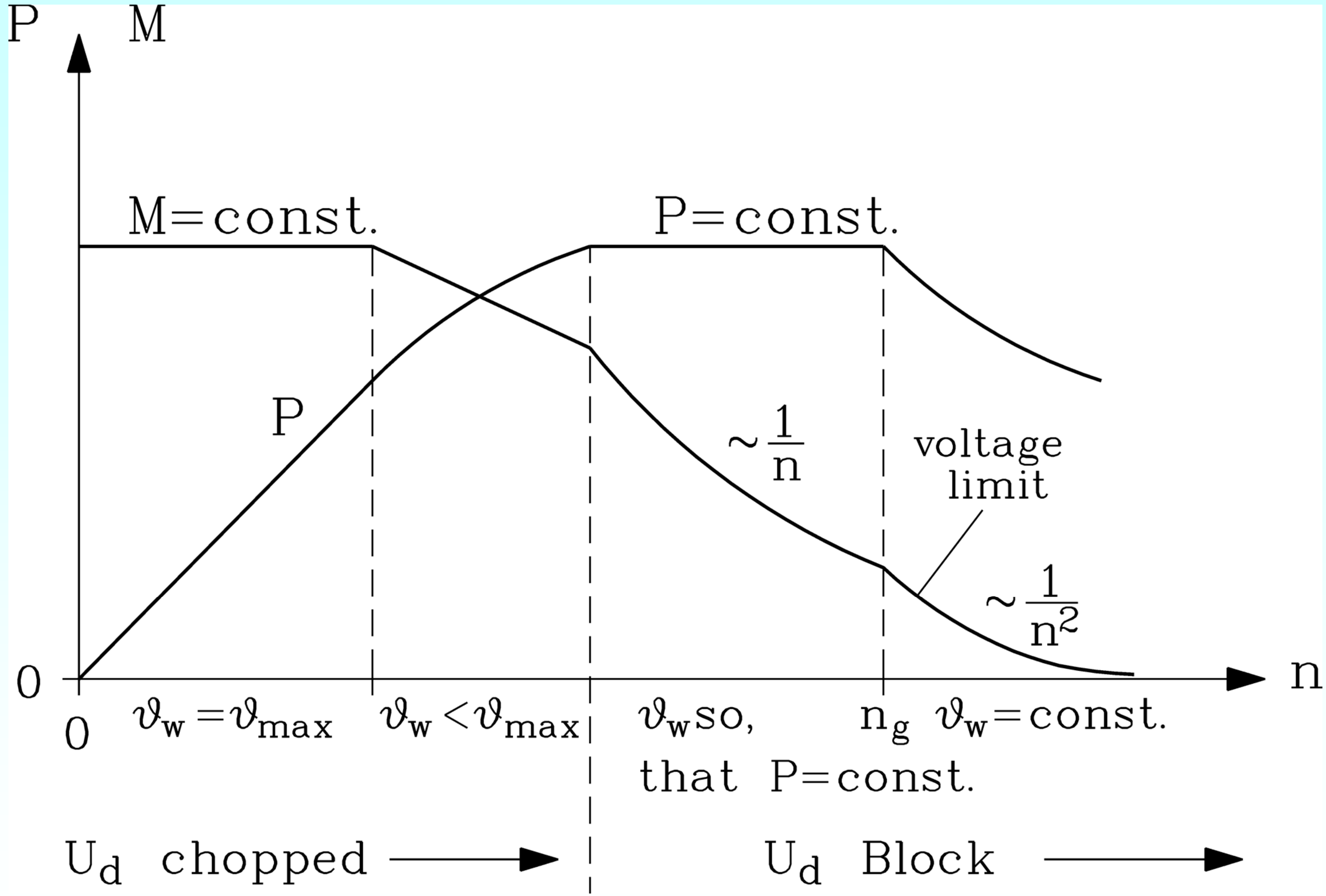
At low speed: **Block current** by hysteresis control with constant current angle

Increased speed: Current impulse duration T_W has to decrease

At high speed: Only voltage "switch on/off" possible so, that average torque decreases with $1/n$ (**constant power operation**).

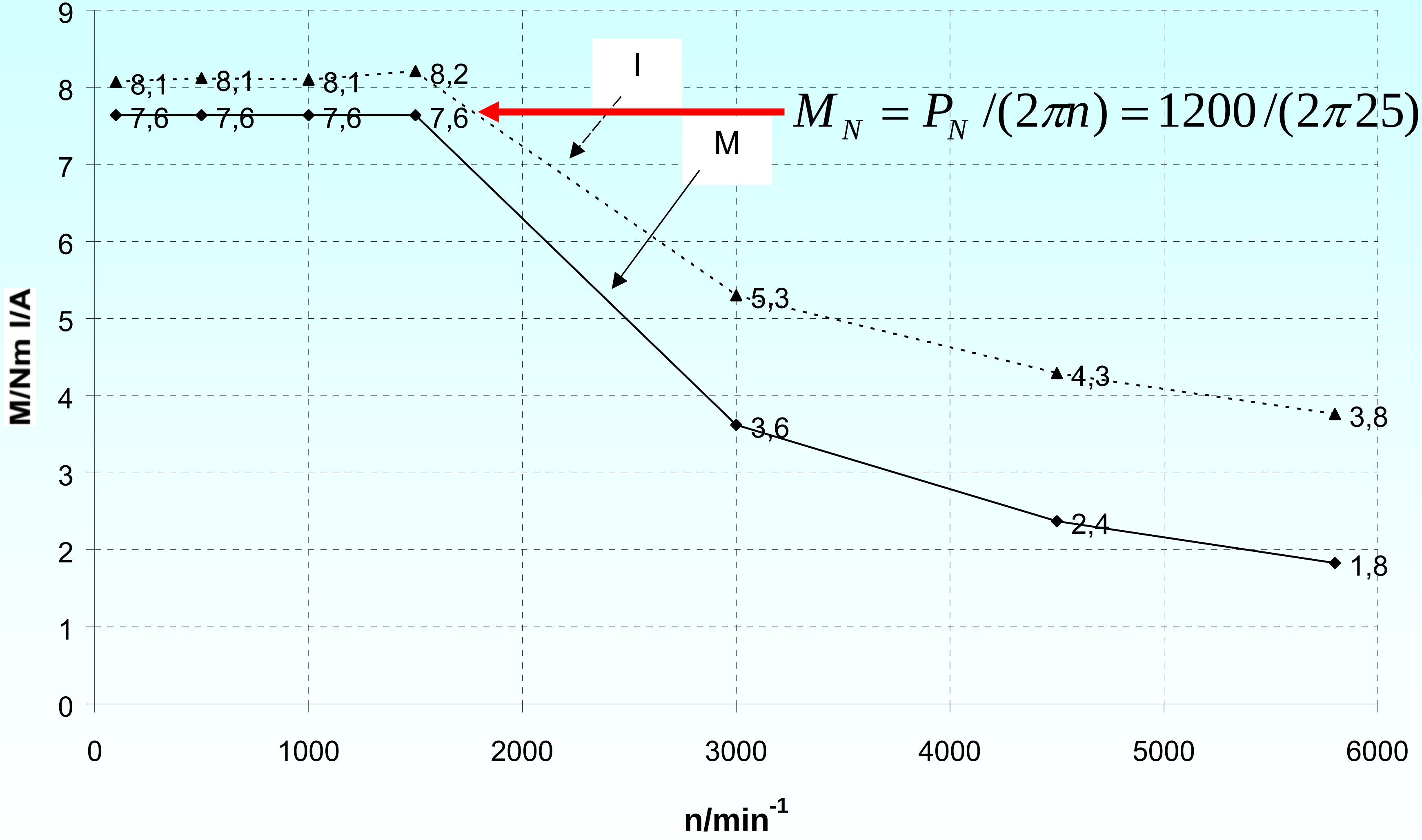
Voltage limit: No adjusting of current angle possible: torque decreases with $1/n^2$.

Maximum SR torque & power, depending on speed



Measured maximum SR torque & r.m.s. current over speed

4-pole, 3-phase SRD: Rated data: 1.2 kW, 1500 … 6000/min, total mass 32 kg, rotor inertia 3.9 g·m^2, stator/rotor teeth: 12/8, Company SICME/Italy

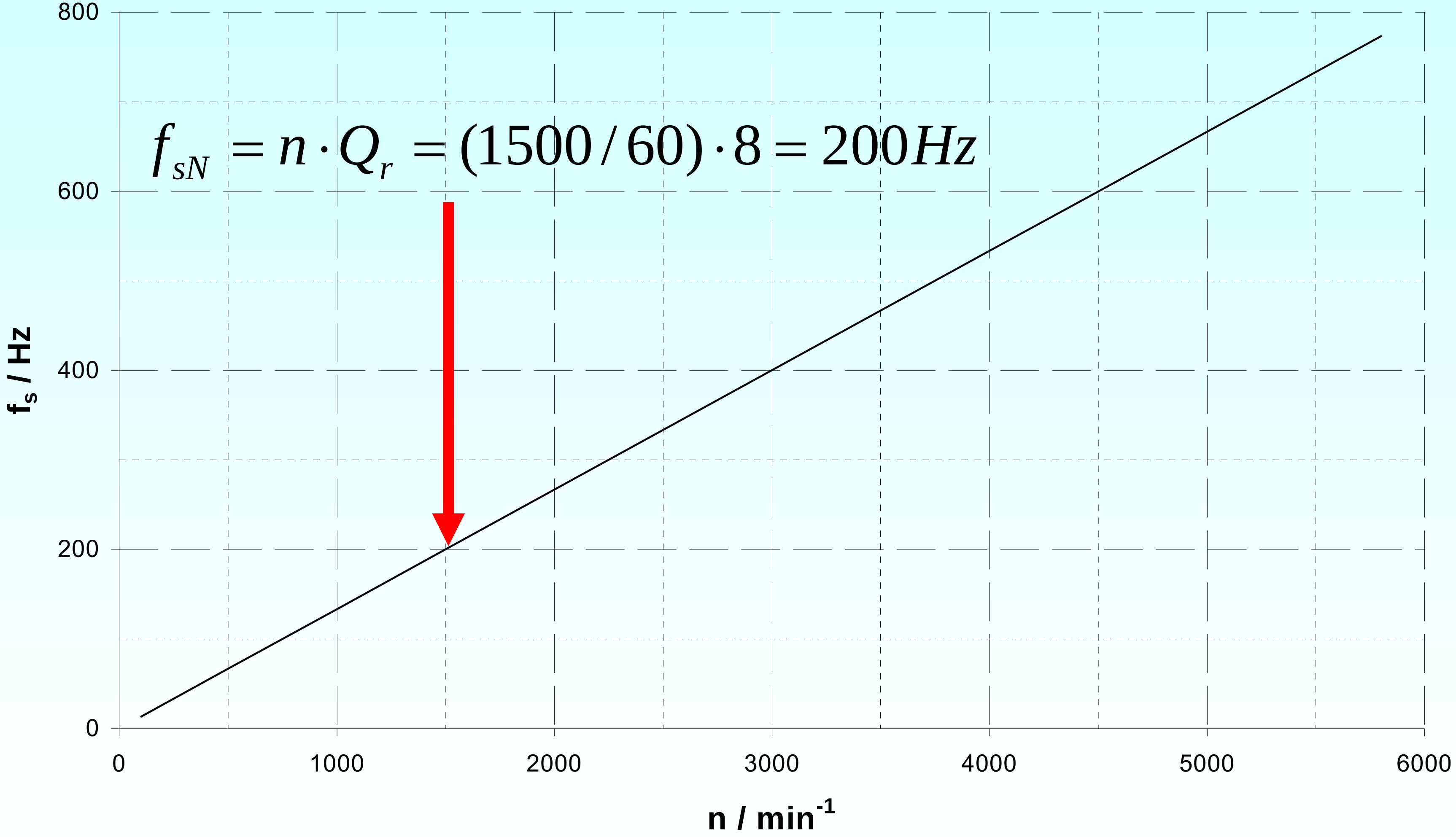


$$M_N = P_N/(2\pi n) = 1200/(2\pi 25) = 7.65 Nm$$

Stator frequency per phase over speed

4-pole, 3-phase SRD: Rated data: 1.2 kW, 1500 … 6000/min, stator/rotor teeth: 12/8
Company SICME/Italy

$$f_s = n \cdot Q_r$$

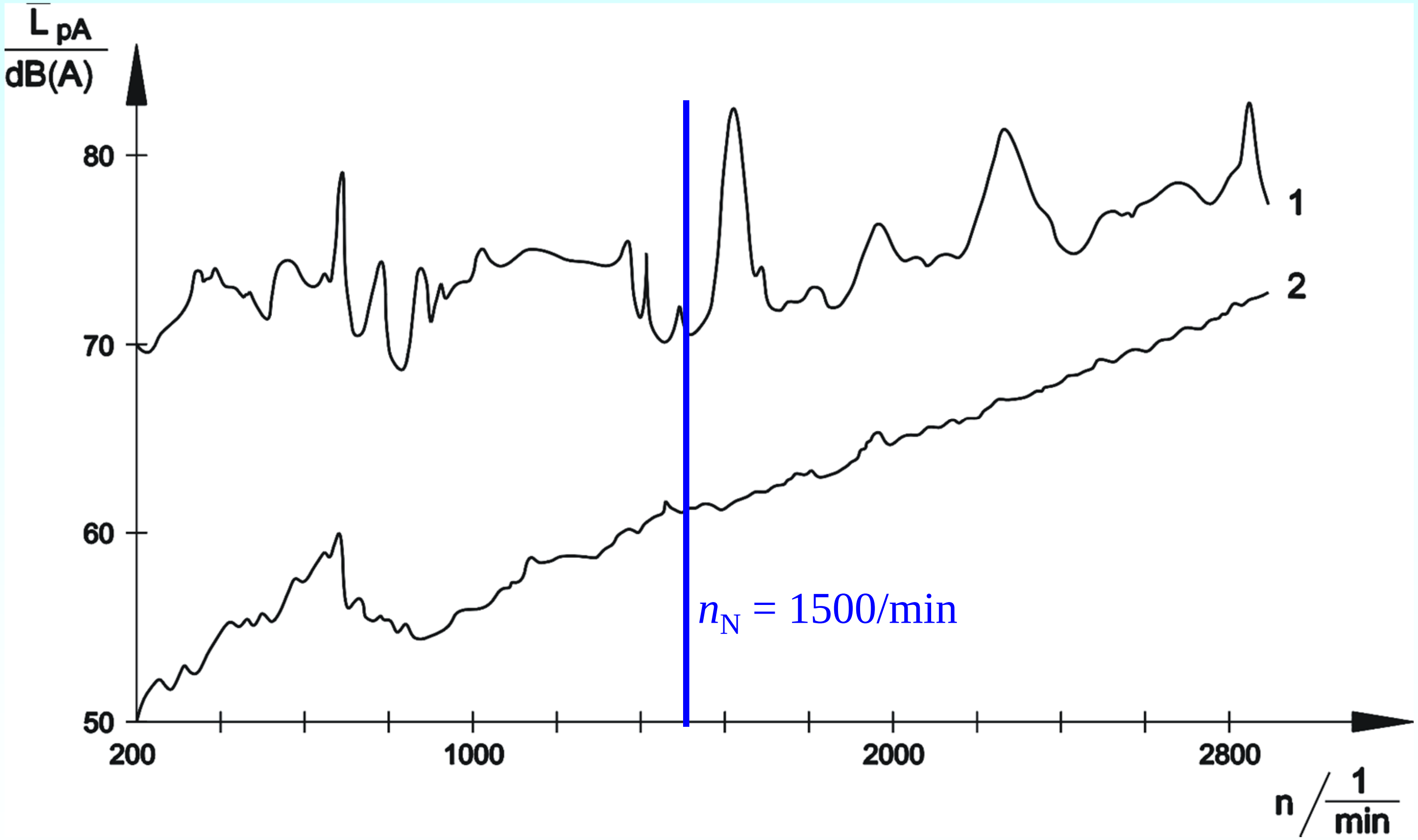


Magnetically excited acoustic noise

Pulsating radial magnetic pull with frequency: $f_{puls} = n \cdot Q_r \cdot m$

Pull causes radial vibrations of stator yoke and housing ⇒ acoustic sound.

If frequency coincides with eigen-frequency of stator yoke: resonance ! As stator yoke is very thin, motor ”rings like a bell”.



Measured sound pressure level:
7.5 kW, $2p = 4$,
$n_N = 1500$/min
12/8 SR machine,
Operation at
1: rated current
2: no-load current.
Exciting frequency varies up to 1.2 kHz !

Comparison of inverter fed induction and SR motor

Same rated power & speed, identical cooling = totally enclosed, fan on shaft

Data: 7.5 kW, base/top speed 1500/min / 3000/min, Th. Cl. F, $m = 3$, $2p = 4$

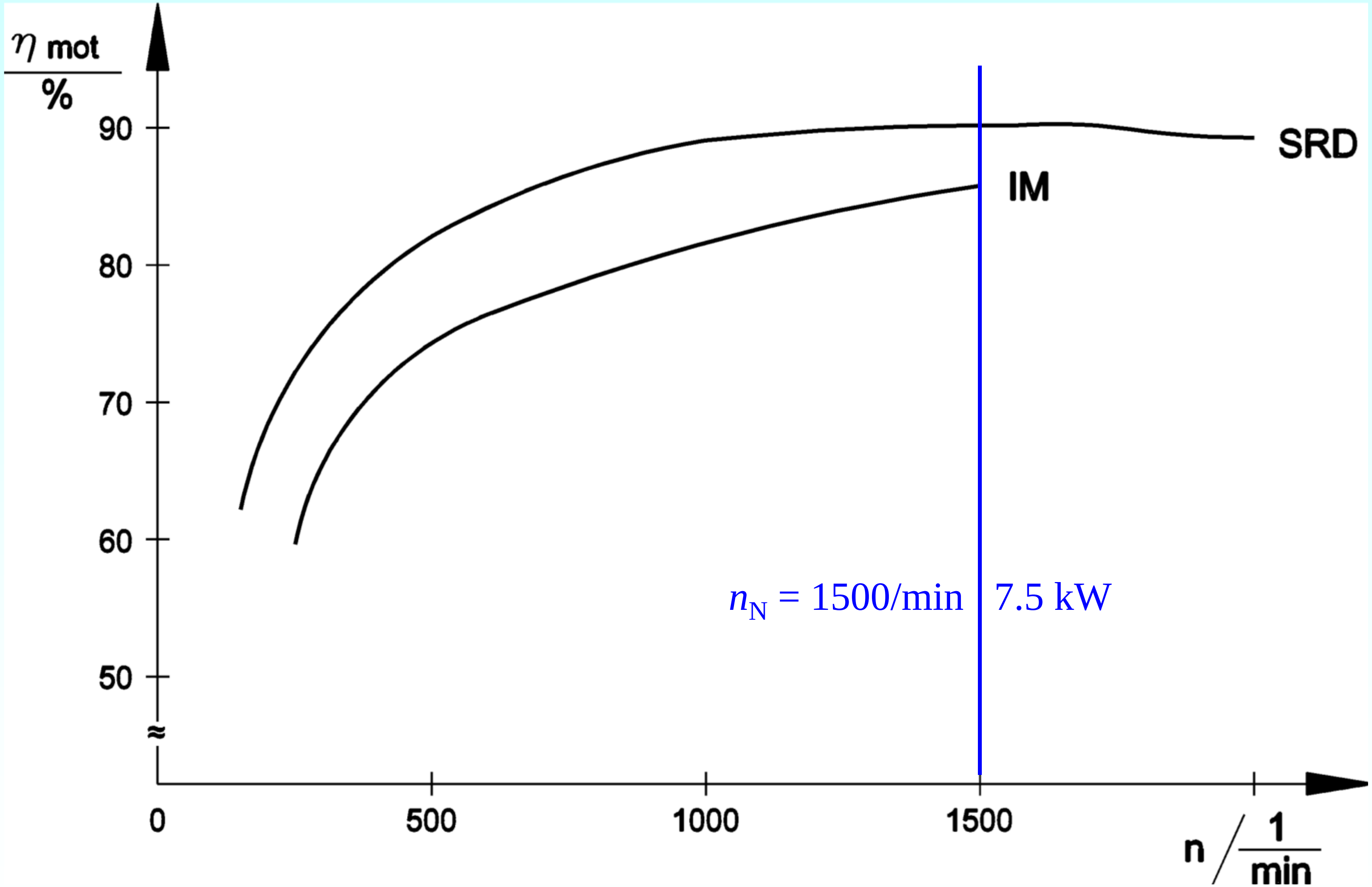
Thermal load run: 1500/min, 54 Nm and $U_d = 540$ V: Result:

	Switched Reluctance Machine	*Induction Machine*
Input / Output power P_{in} / P_{out}	9440 W/ 8480 W	9950 W/ 8480 W
Phase current I (rms)/ $\hat{I}$ (peak)	13.3 A/ 27.5 A	17.45 A/ 30 A
Stator frequency f_s	200 Hz	52 Hz ($U_{s,k=1}$ = 225.5V)
Armature temperature rise	110 K	101 K
Iron losses / friction&windage losses	200 W/ 165 W	265 W/ 55 W
Stator copper losses/cage losses	595 W/ 0 W	650 W/ 350 W
Additional losses	0 W	150 W
Stator current density J_s	5.25 A/mm^2	8.23 A/mm^2
Current loading $A = 2mN_sI_s/(d_{si}\pi)$	513 A/cm	305 A/cm
Motor efficiency η_{mot}	**89.8 %**	**85.2 %**
Inverter efficiency η_{inv}	96.6 %	97.0%
Drive efficiency η	**86.7 %**	**82.6 %**

Comparison of measured motor efficiency at 54 Nm

12/8 SR machine (SRD) / inverter-fed standard induction machine (IM)

Four-pole, 3-phase: at 54 Nm, 100 K armature temperature rise



Applications of SR drives

Example:

Starter-generator for military aircraft jet (*US Air Force*, manufacturer GE)

- Rated power 250 kW, rated speed 13 500/min, rated torque 177 Nm, rated current 750 A, DC link voltage 270 V
- Maximum speed 22200/min, over-speed 26000/min, overall system efficiency: 90%
- Three phase four pole 12/8 SR machine !

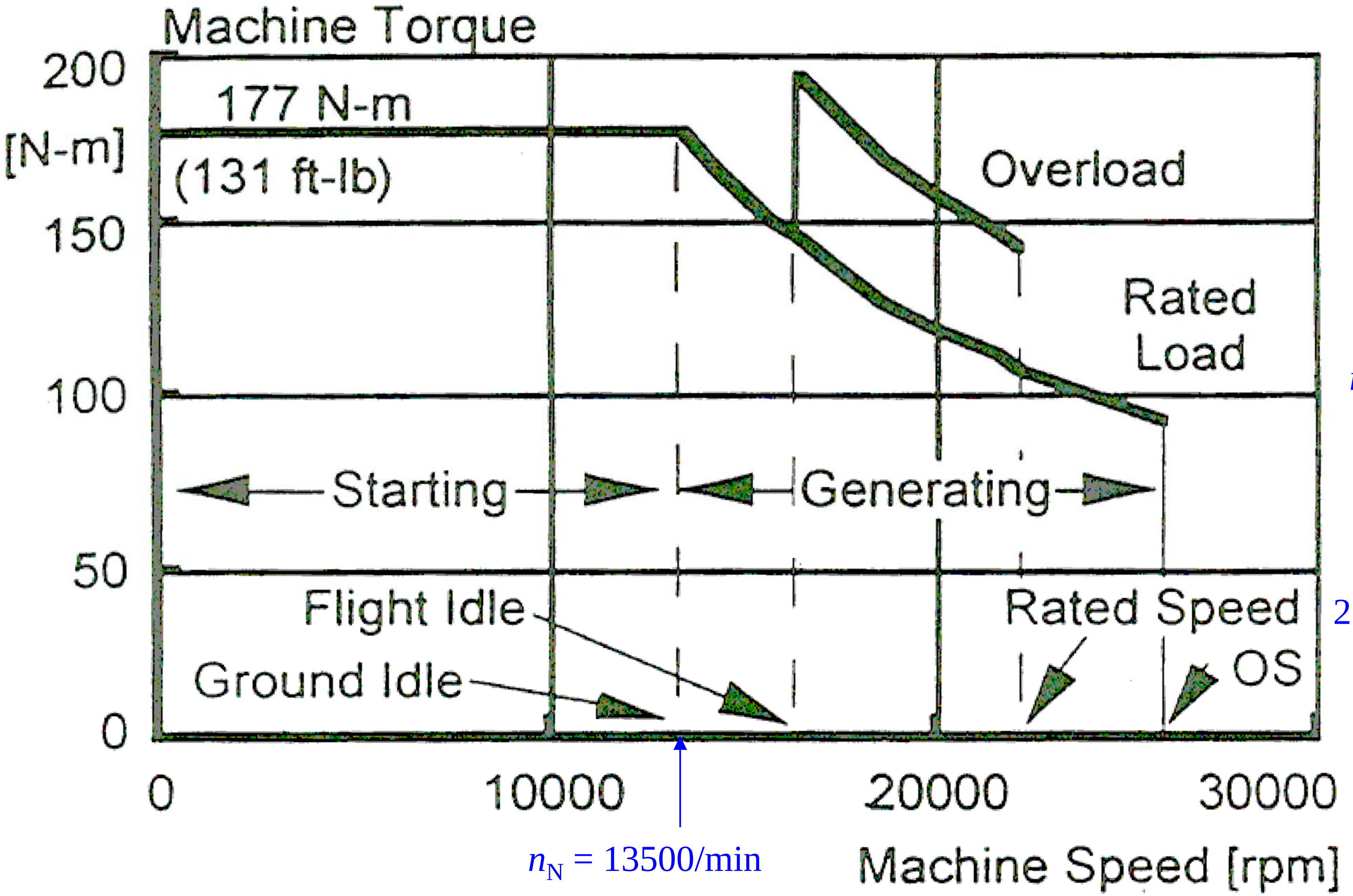
Reliability: Two independent three phase systems: each 125 kW power. In case of failure motor is ”fail-silent” = no current = no force = no induced voltage, so risk of fire due to short circuit is minimized.

Small motor size: Motor is *intensively cooled by oil and high speed.* Motor mass is only 70 kg, yielding ”power weight” of P/m = 3.6 kW/kg.

Low speed range 0 ... 13500/min: SR machine starts compressor of air craft engine with constant torque 177 Nm.

High speed range 13500 ... 26000/min: SR machine is generator at 250 kW.

Torque-speed curve of aircraft starter generator



OS: over-speed

n_{OS} = 26000/min

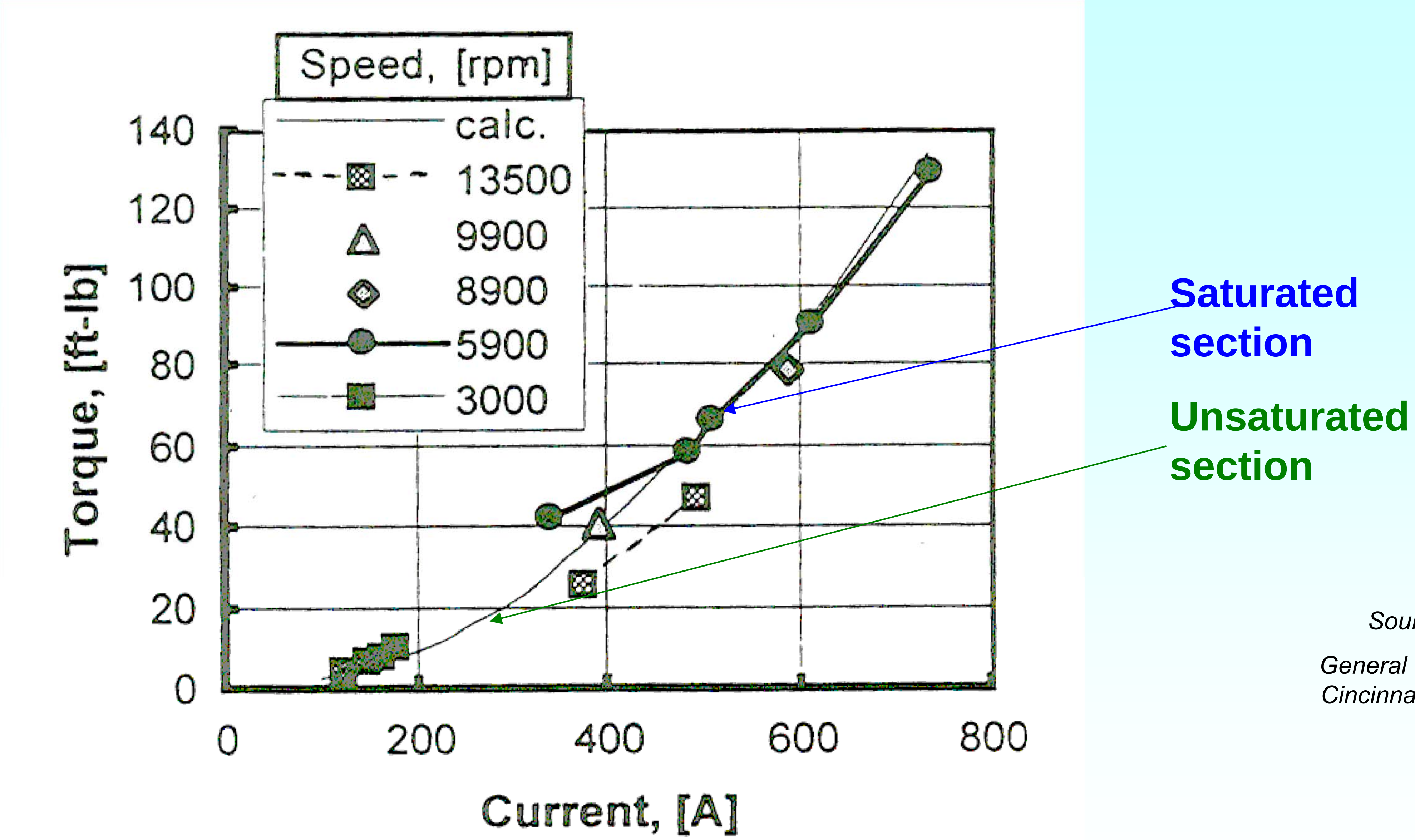
22200/min

n_N = 13500/min

Source:

General Electric, Cincinnatti, USA

Torque-current curve of aircraft starter generator



Source:

General Electric, Cincinnati, USA

Surface cooled switched reluctance machine

Three phases

Four poles

$Q_s = 12$, $Q_r = 8$

Cooling fins on housing

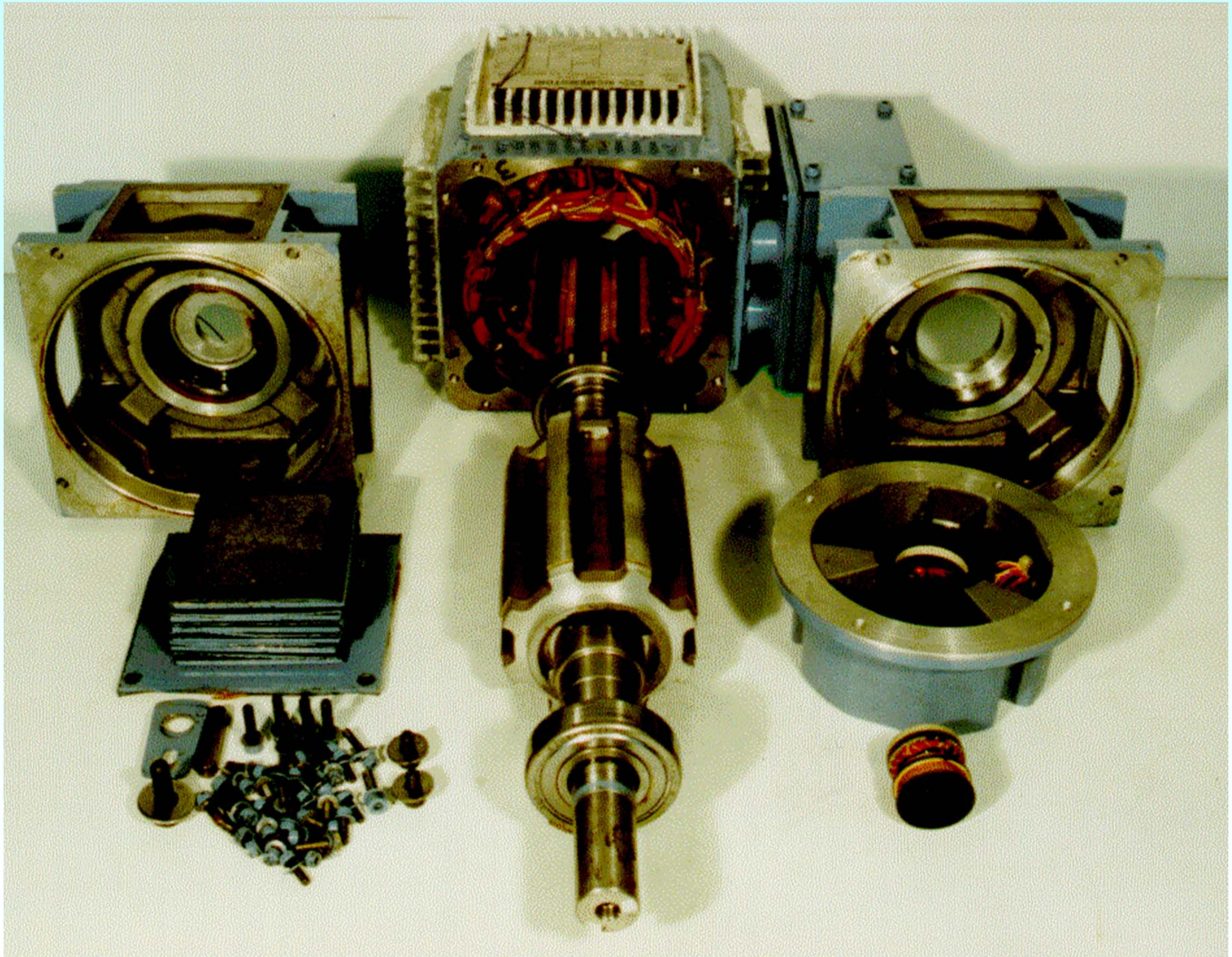
Resolver for position encoding

Rated speed: 1500/min

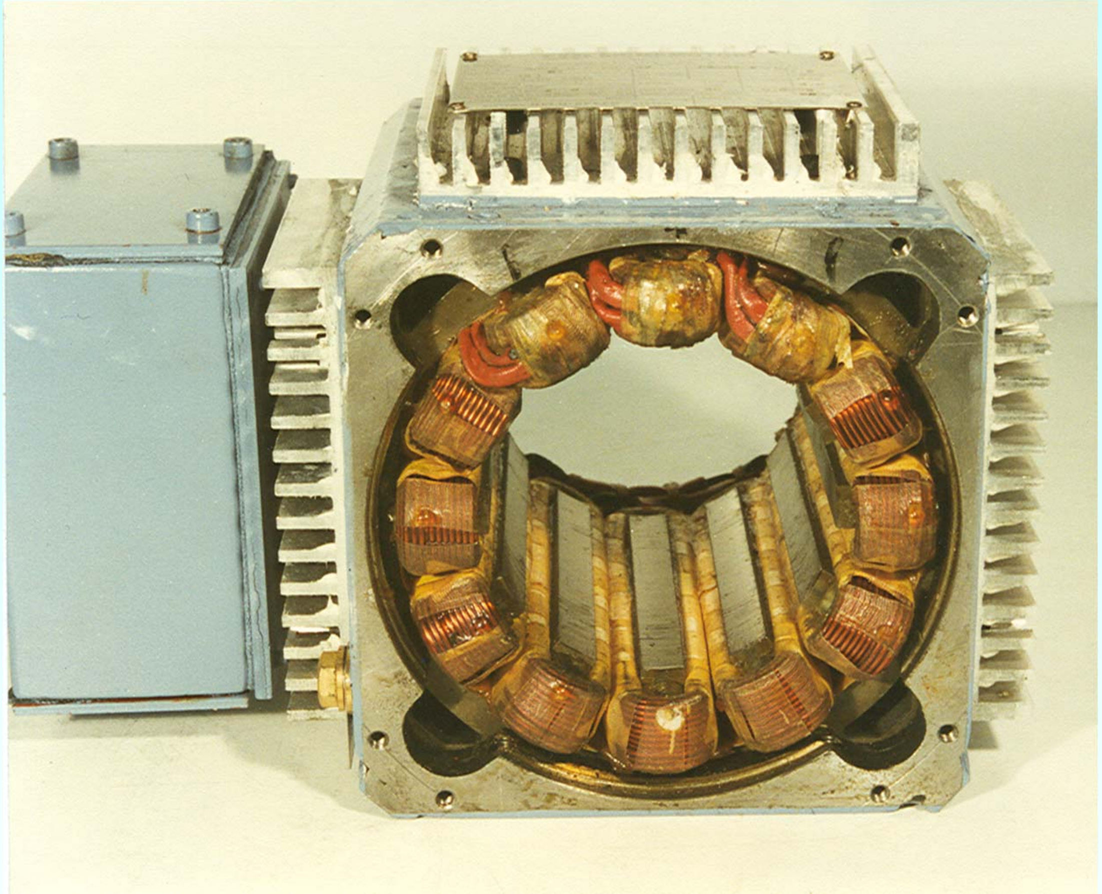
Maximum speed: 6000/min

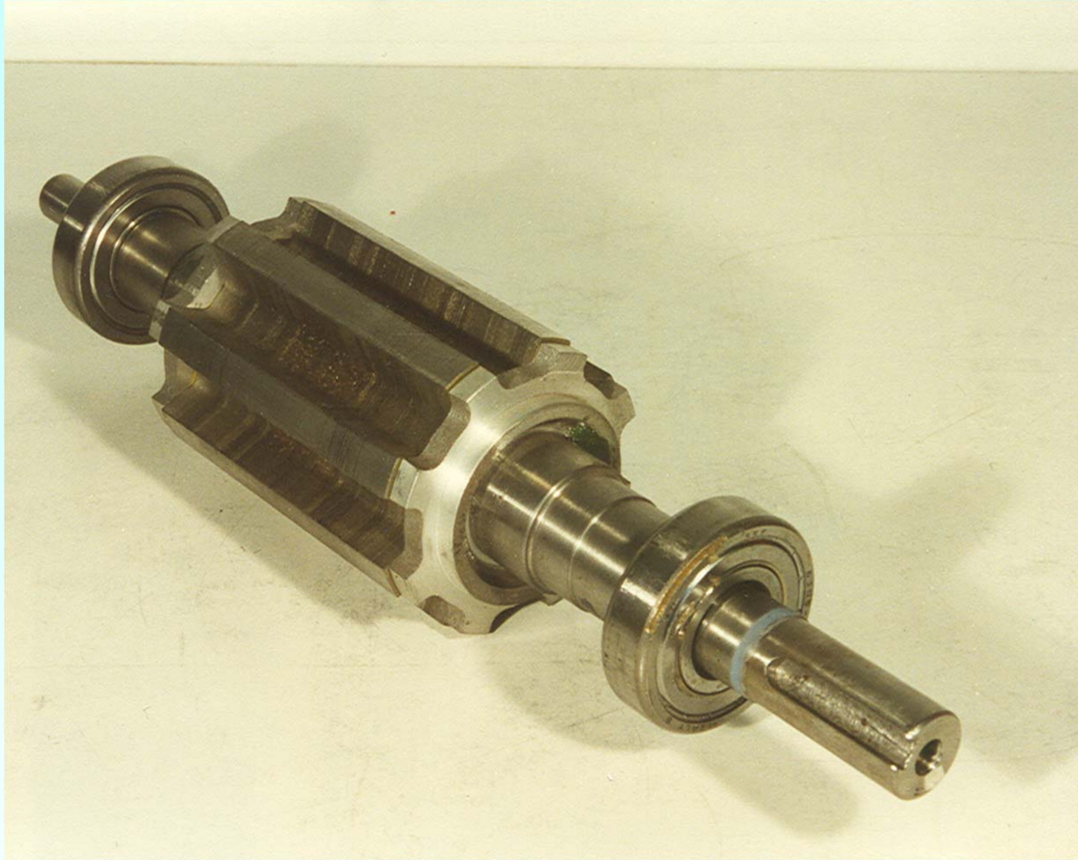
Source:

SICME, Italy



Stator and rotor of switched reluctance machine





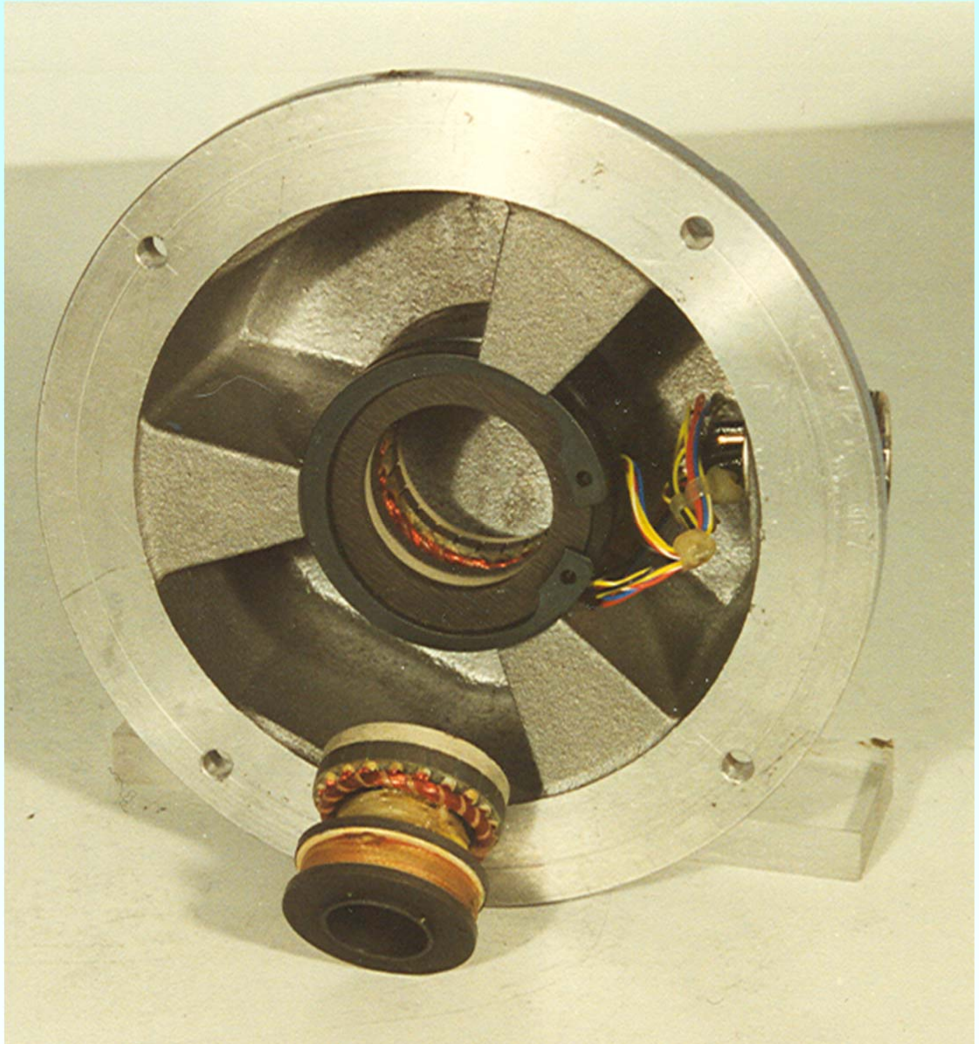
Three phases, four poles, $Q_s = 12$, $Q_r = 8$

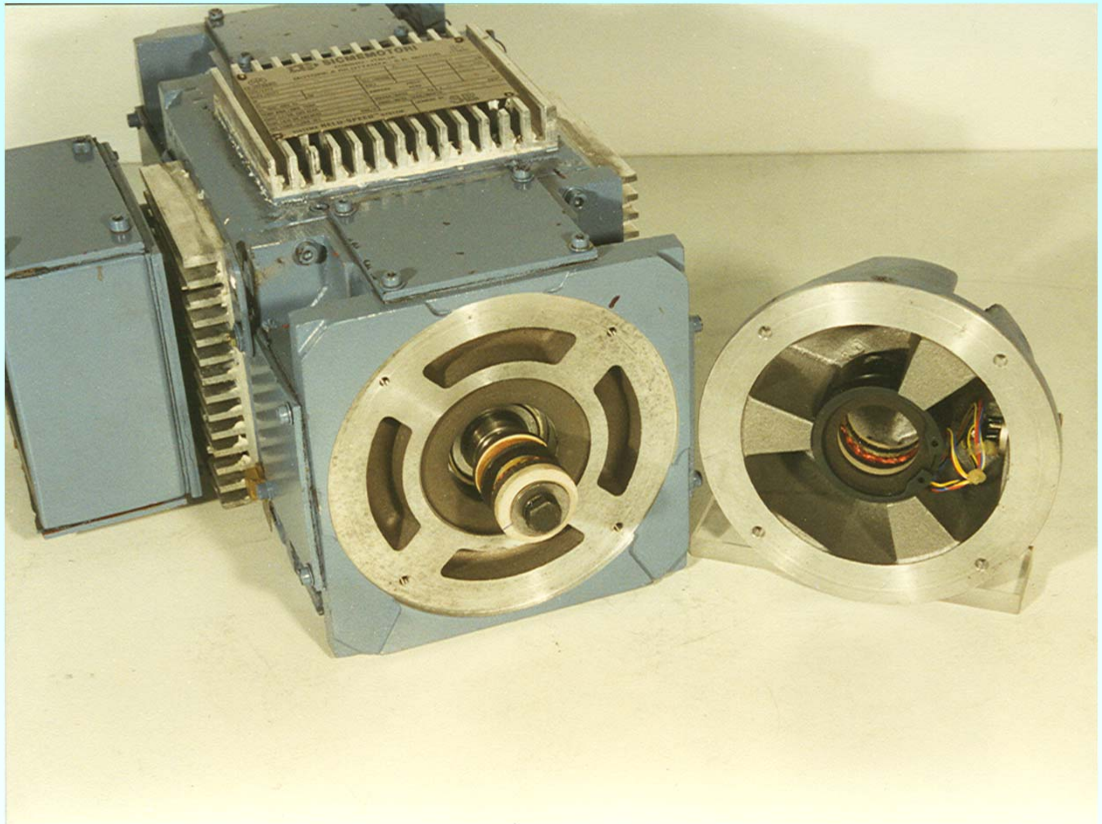
Rated speed: 1500/min, maximum speed: 6000/min

Source:

SICME, Italy

Resolver for switched reluctance machine



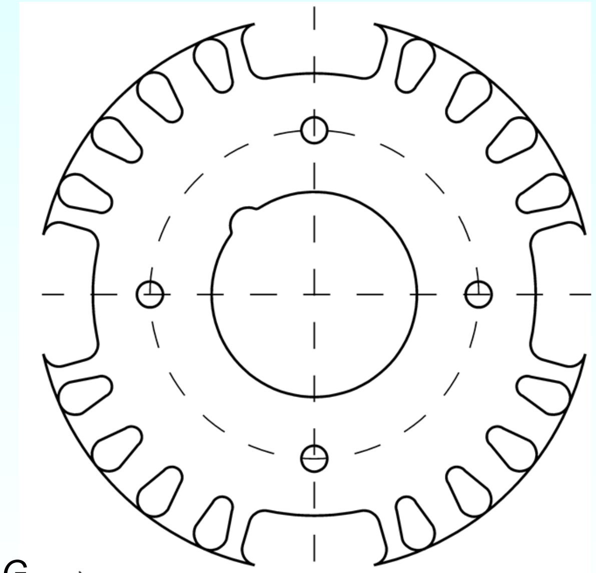


Source:

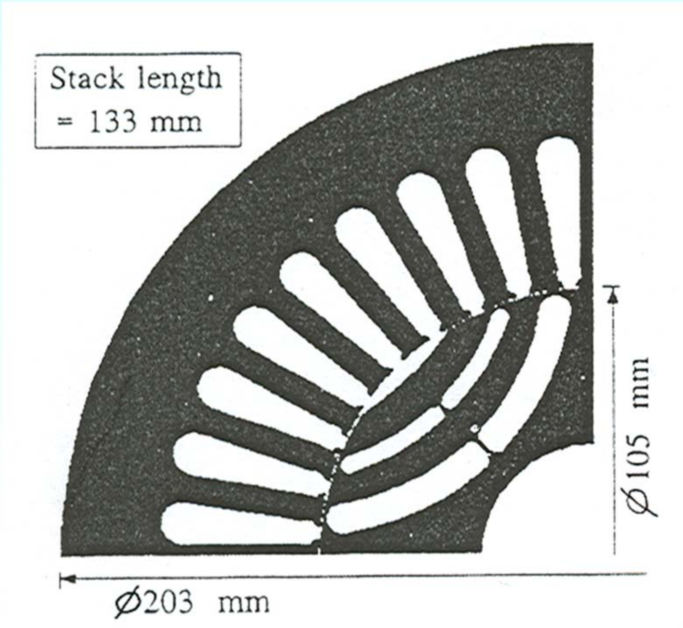
SICME, Italy

2. Reluctance machines

2.2 Synchronous reluctance machines

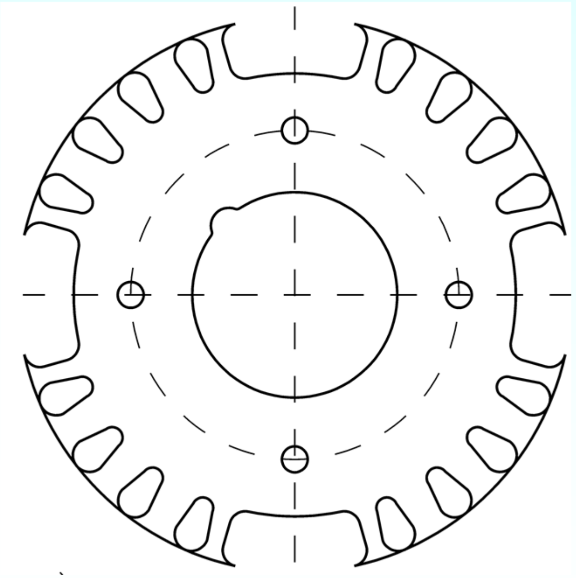


Source: Siemens AG. Germany



Source: M. Kamper, WCRR Conf, 1997

2.2.1 Line-starting synchronous reluctance machines

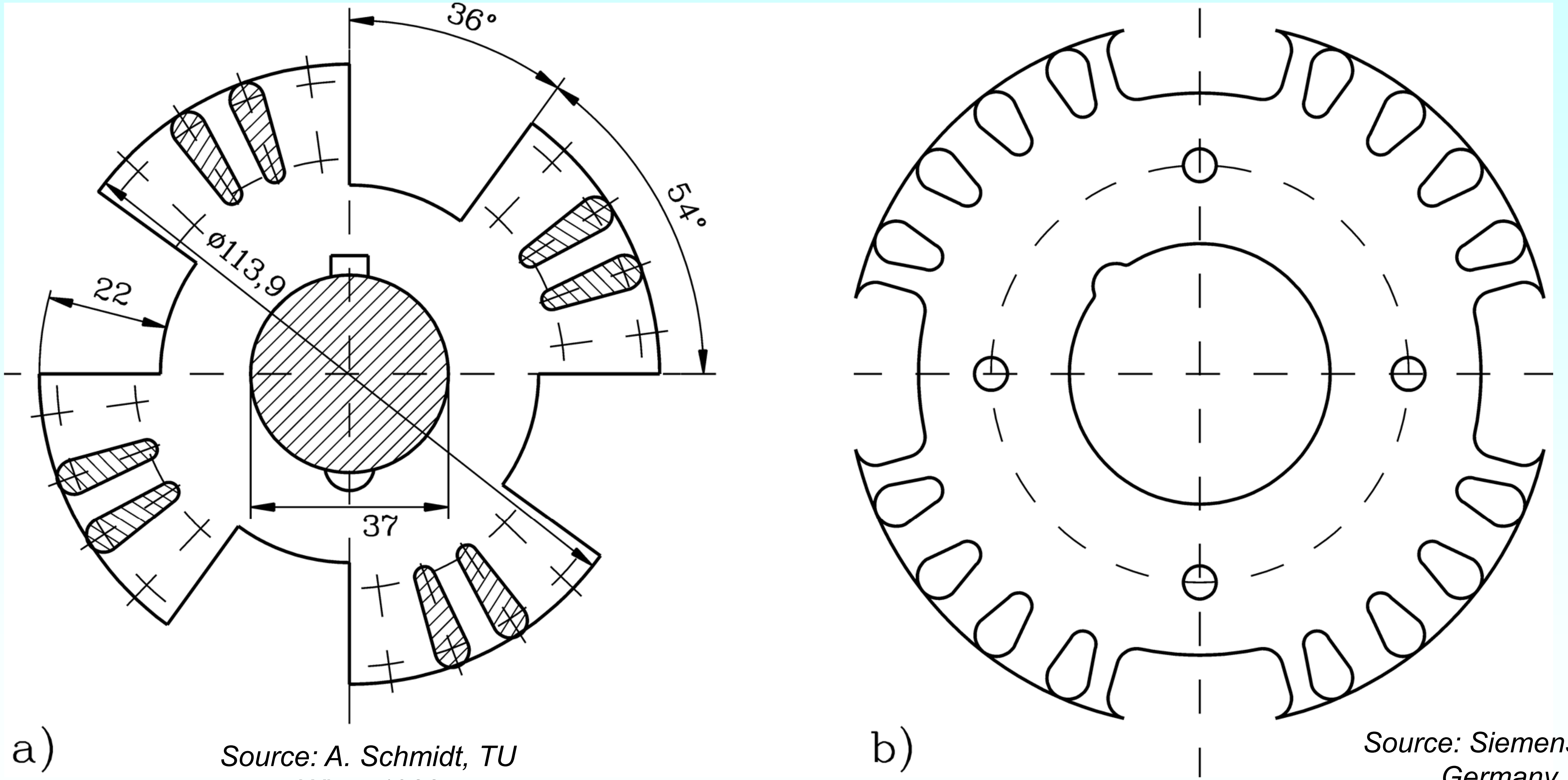


Source: Siemens AG. Germany

4-pole rotors of synchronous reluctance machines

a) 2.2 kW, shaft height 112 mm

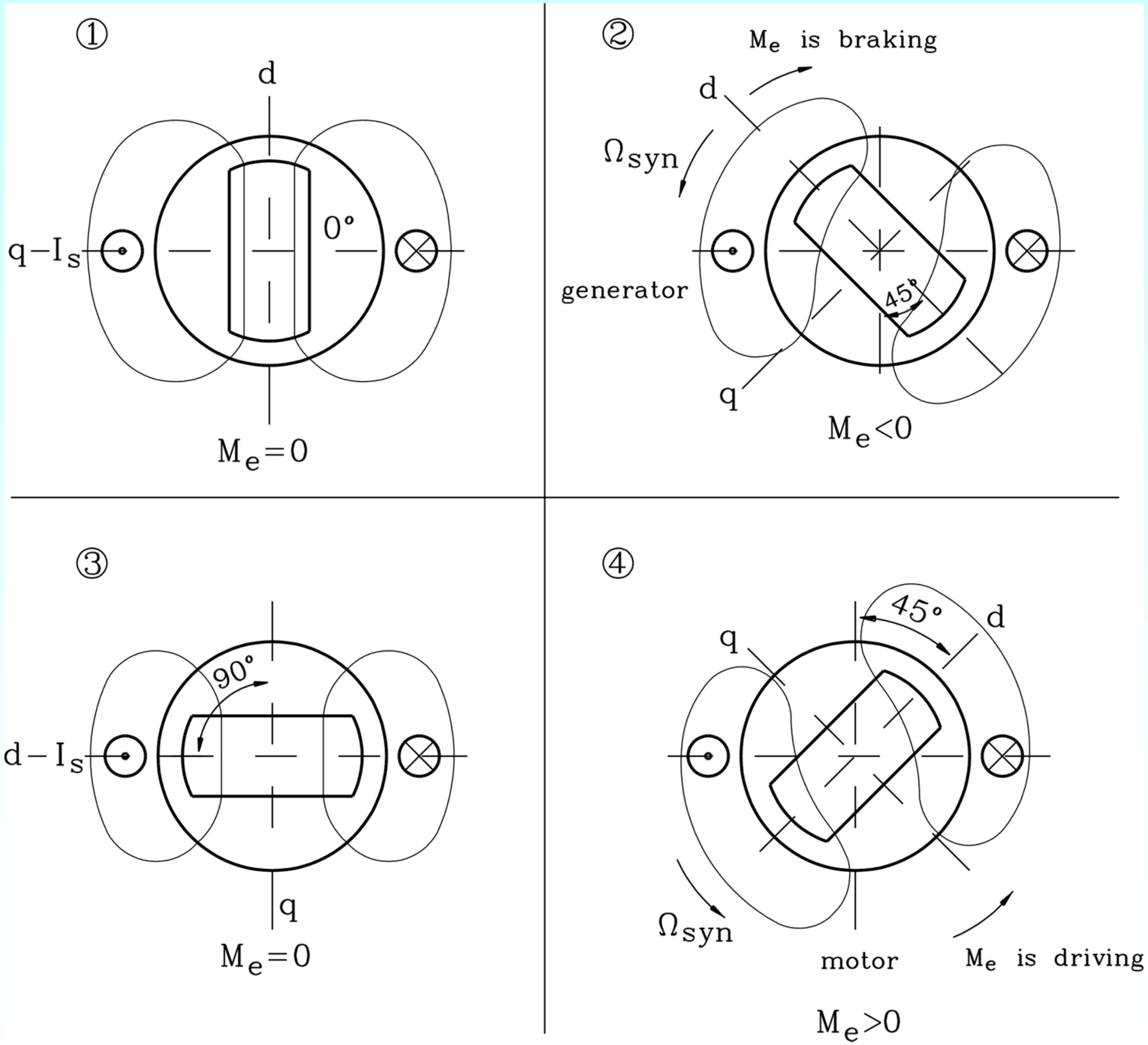
b) 550 W, shaft height 80 mm



Source: A. Schmidt, TU Wien, 1988

Source: Siemens AG. Germany

Basic function of synchronous reluctance machine



Stator three phase winding operated at AC voltage system to generate rotating stator field with stator frequency f_s.

Rotor has variable air-gap:

small (d-axis): inductance L_d

big (q-axis): inductance L_q

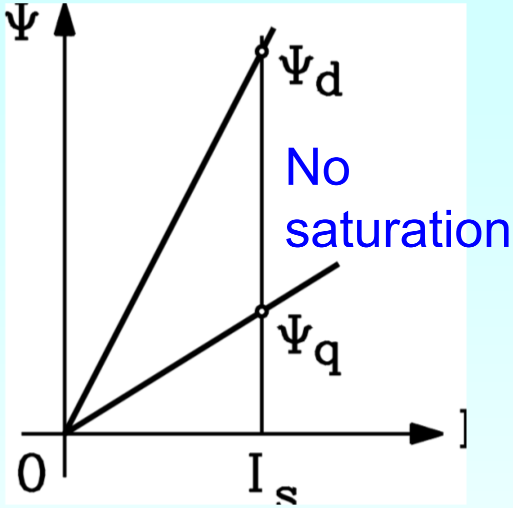
Air gap field tries to align rotor by tangential magnetic pull = reluctance torque.

Rotor rotates synchronously with stator field: $n = f_s/p$.

Pull-out: at load angle 45°

Air gap flux linkage in *d*- and *q*-axis

$$\underline{\Psi}_{hd} = L_{hd} \cdot \underline{I}_d \cdot \sqrt{2} \qquad \underline{\Psi}_{hq} = L_{hq} \cdot \underline{I}_q \cdot \sqrt{2} \qquad \Rightarrow \qquad \underline{\Psi}_h = \underline{\Psi}_{hd} + \underline{\Psi}_{hq}$$



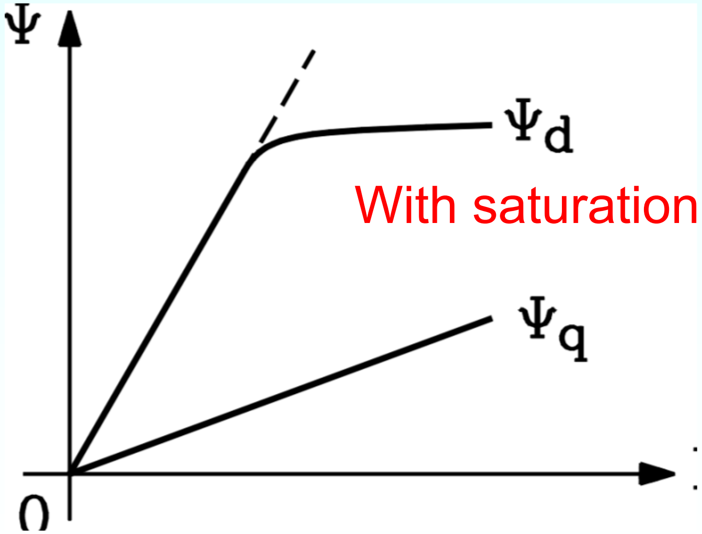
At $R_s = 0$: $\underline{I}_s = I_d + jI_q = \underline{I}_d + \underline{I}_q$

$$\underline{U}_s = jX_d \underline{I}_d + jX_q \underline{I}_q = jX_d I_d - X_q I_q$$

Power balance:

$$P_e = m \cdot U_s \cdot I_s \cdot \cos\varphi = m \cdot \left(U_{s,\mathrm{Re}} \cdot I_{s,\mathrm{Re}} + U_{s,\mathrm{Im}} \cdot I_{s,\mathrm{Im}}\right) =$$

$$= m \cdot \left(-X_q I_d I_q + X_d I_d I_q\right) = \Omega_m M_e$$



Torque equation:

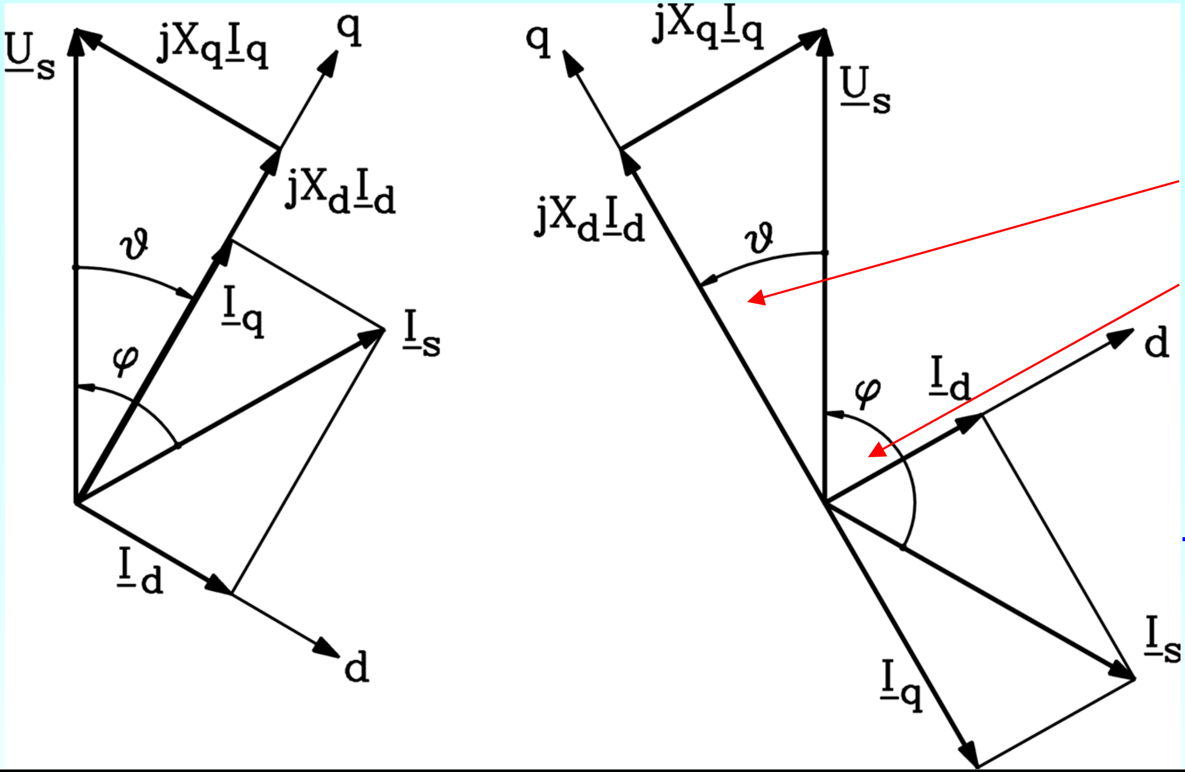
$$M_e = \frac{p \cdot m}{\omega_s} \cdot \left(X_d - X_q\right) \cdot I_d I_q$$

Big difference between d- and q-axis inductance is needed : typically $L_d/L_q \sim 5$.

I_d :"magnetizing" current:"main" flux d-axis

I_q: torque-delivering current

Synchronous reluctance motor / generator (R_s = 0)



Load angle

Phase angle

Machine is always
inductive consumer !

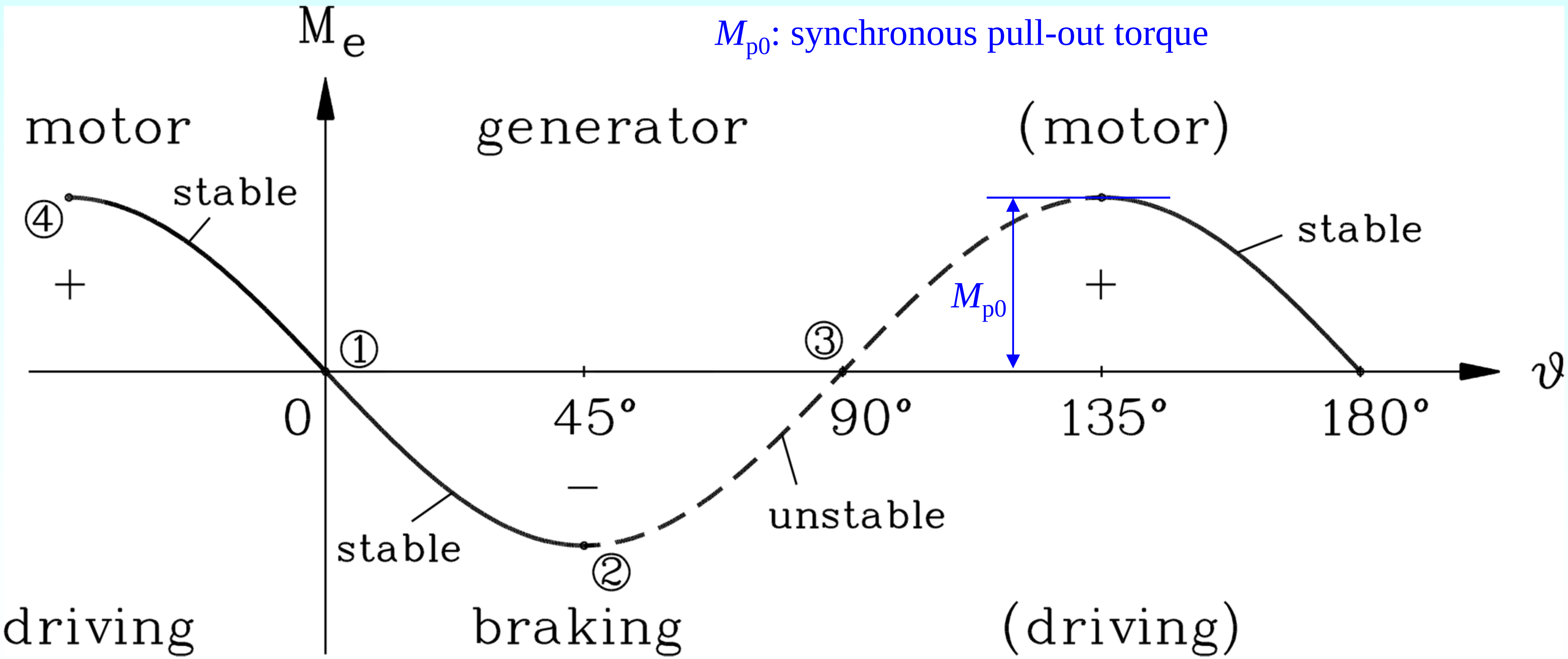
	Motor	Generator
Load angle ϑ	< 0	> 0
Phase shift φ	0 ... 90°	90° ... 180°
d-current	> 0	> 0
q-current	> 0	< 0
Electric power	> 0	< 0

Operation at constant stator voltage amplitude

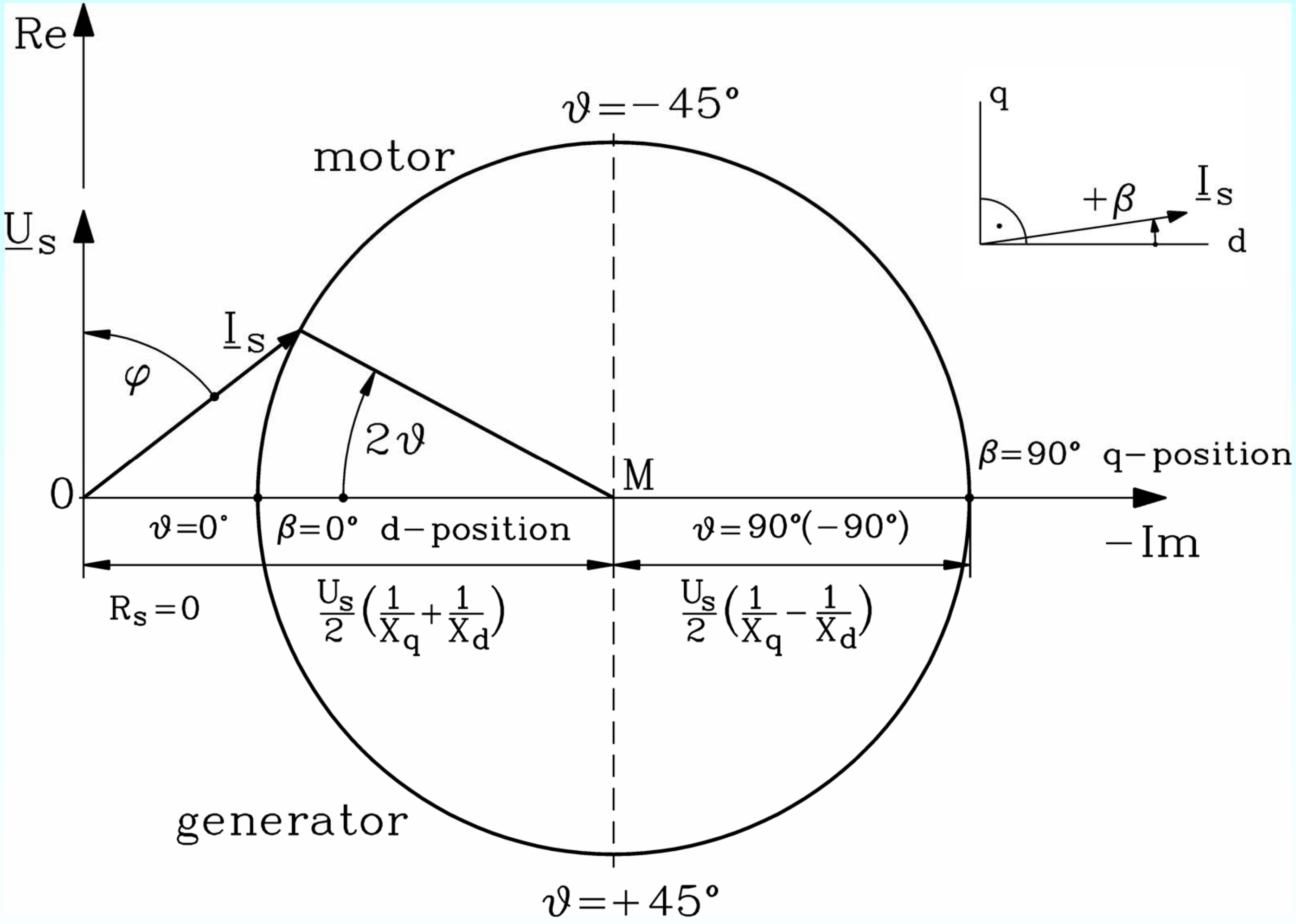
For $R_s = 0$: With $U_s \cos\vartheta = I_d X_d$, $-U_s \sin\vartheta = I_q X_q$ we get:

Torque, depending on voltage: $$M_e = -\frac{p \cdot m}{\omega_s} \cdot \frac{U_s^2}{2} \cdot \left(\frac{1}{X_q} - \frac{1}{X_d} \right) \cdot \sin(2\vartheta)$$

M_{p0}: synchronous pull-out torque



Current root locus at constant voltage ($R_s = 0$)



$$M_e \sim U_s I_s \cos\varphi = -U_s \cdot \frac{U_s}{2} \cdot \left(\frac{1}{X_q} - \frac{1}{X_d}\right) \cdot \sin\vartheta$$

Circle diagram of reluctance machine („reluctance circle“)

Minimum current at no-load (d-current) $I_{s0} = U_s/X_d$

At +/-45° load angle: Maximum torque

Increase of current beyond 45°, but UNSTABLE operation.

Maximum current at load angle 90°: $I_{s,max} = U_s/X_q$. Periodicity with 90°.

Current always lagging = machine is always inductive consumer !

Phasor diagram including stator resistive voltage drop

- Phasor diagram for synchronous reluctance machine for motor operation.

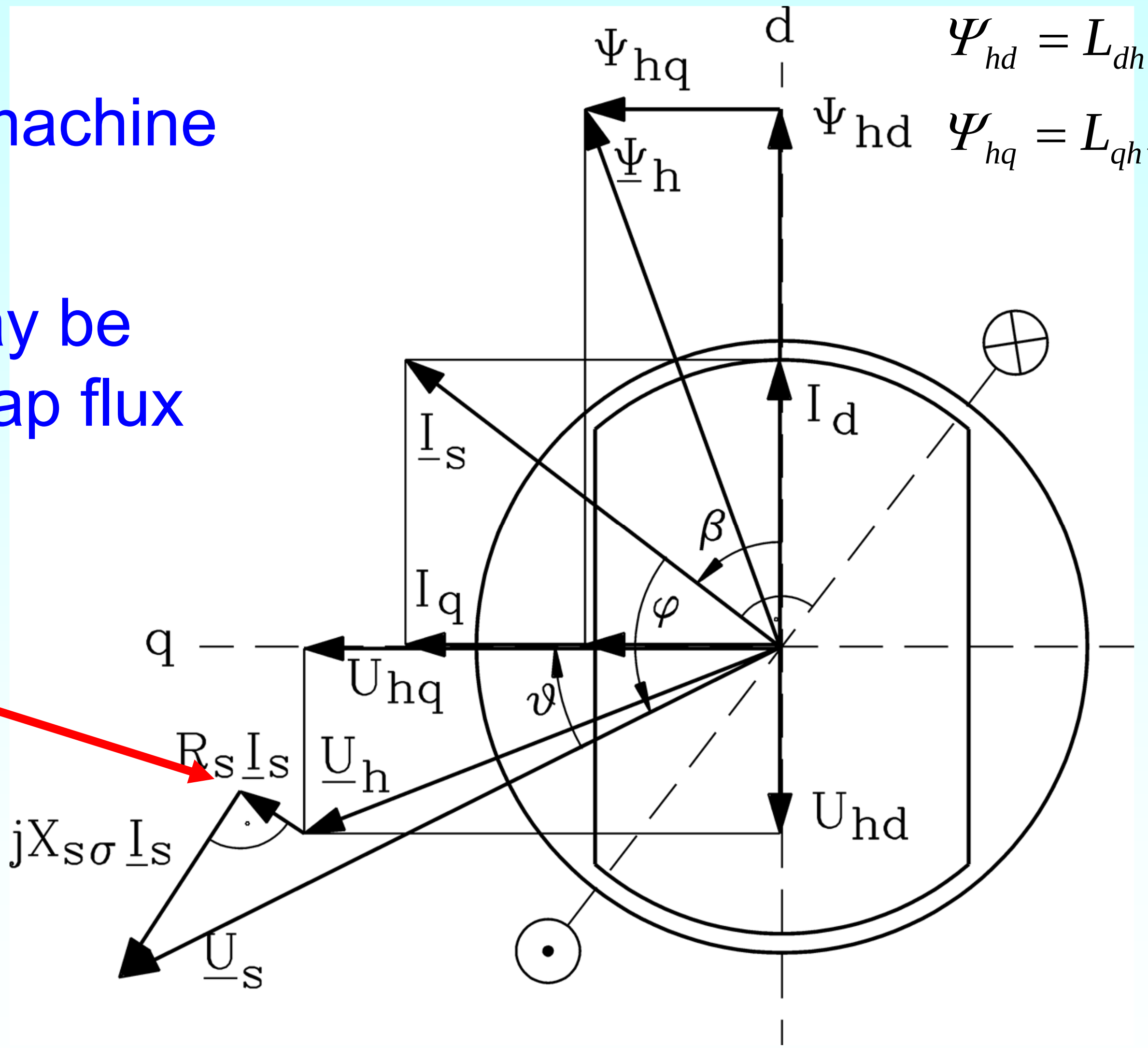
- Flux linkage phasors may be taken as direction of air gap flux components.

Influence of stator resistance especially for these rather small machines considerable !

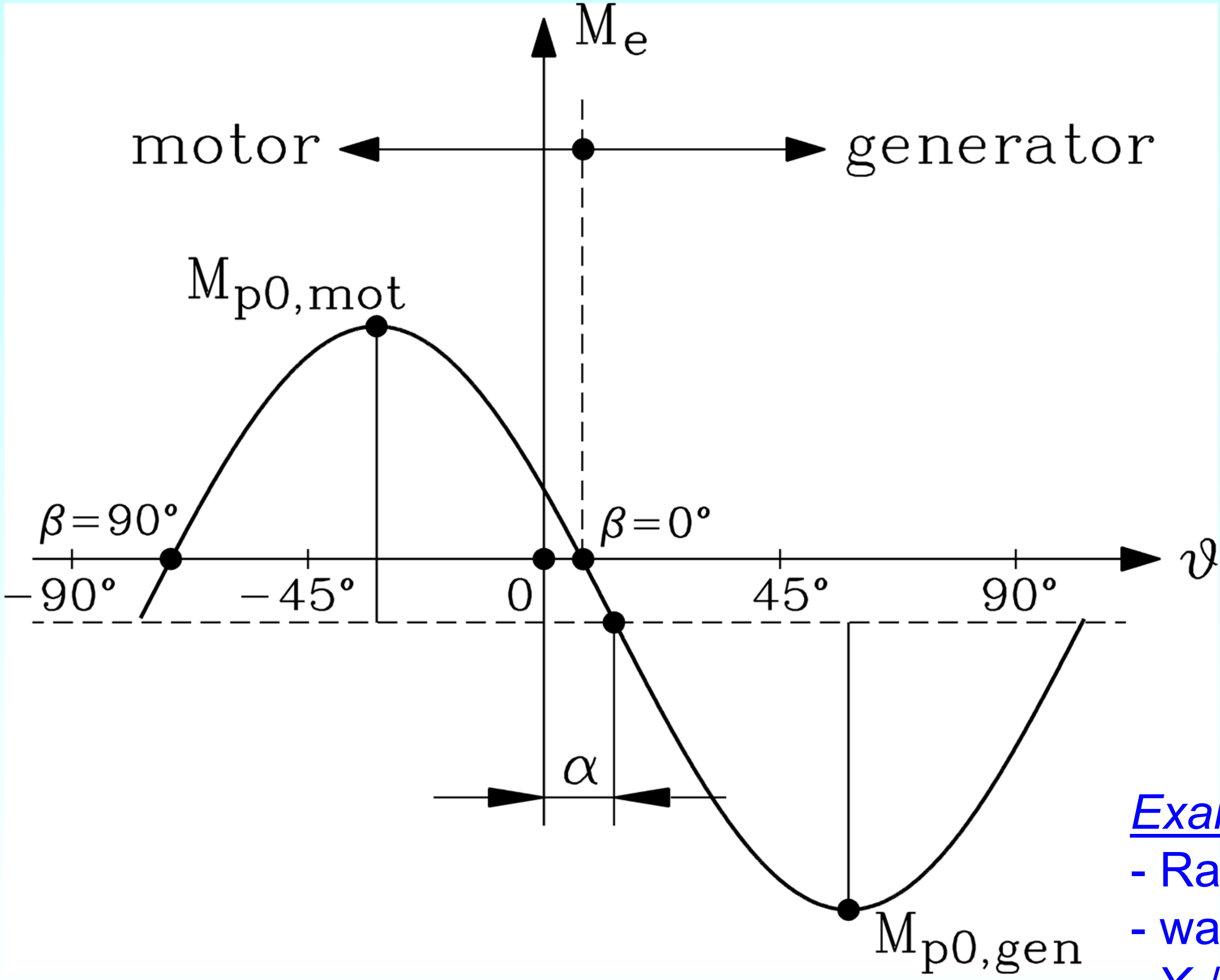
$$X_d = X_{dh} + X_{s\sigma} \qquad X_q = X_{qh} + X_{s\sigma}$$

$$\Psi_{hd} = L_{dh} I_d \sqrt{2}$$

$$\Psi_{hq} = L_{qh} I_q \sqrt{2}$$



Torque over load angle for $R_s > 0$



- Torque curve shifted by angle α
- Motor pull out torque reduced
- Generator pull out torque increased

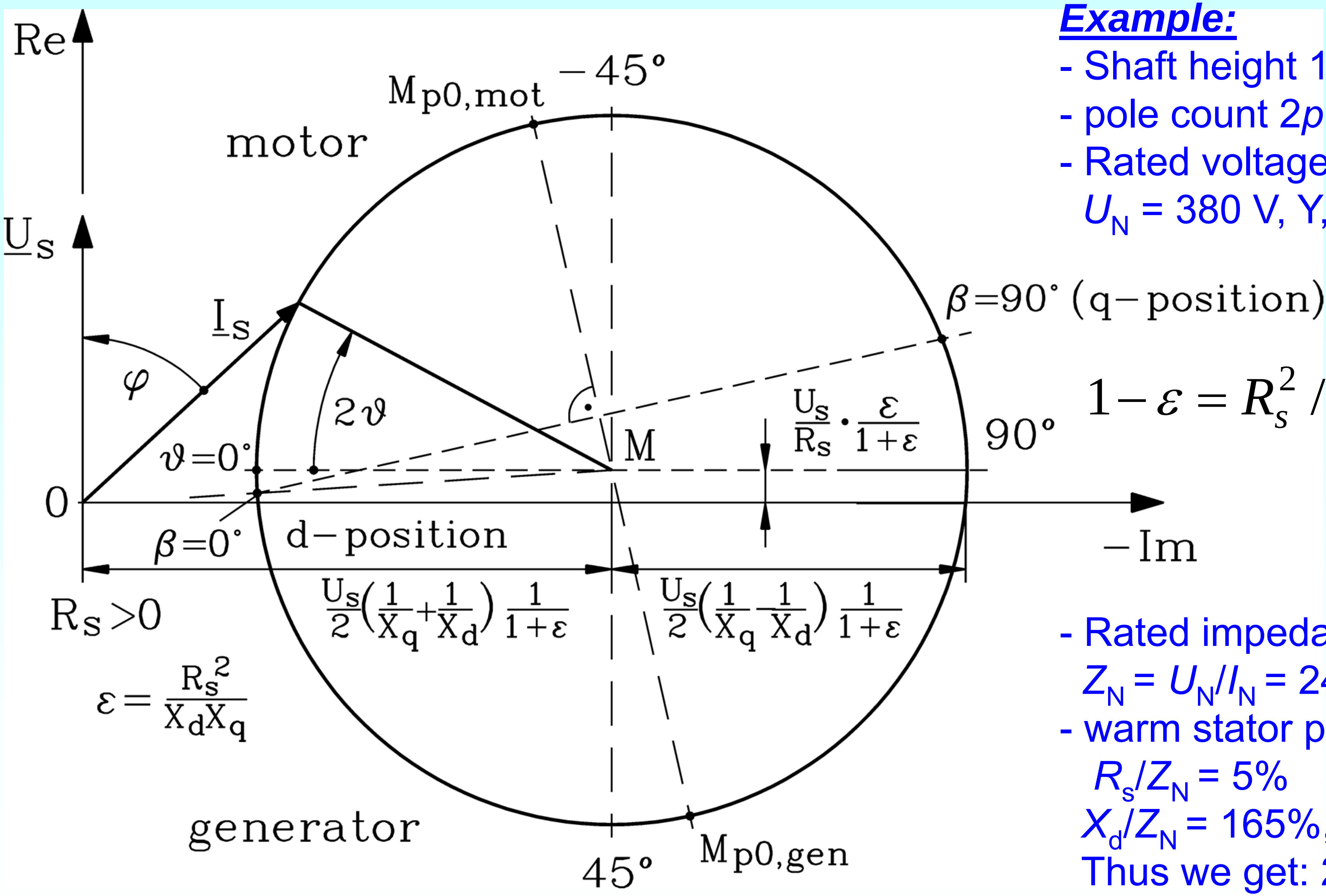
$$2\alpha = \arctan\left(\frac{R_s(X_d + X_q)}{X_d X_q - R_s^2}\right) > 0$$

Example: 2.2 kW, 380 V, 50 Hz, $2p = 4$:
- Rated impedance: $Z_N = U_N / I_N = 24.4\ \Omega$
- warm stator phase resistance: $R_s / Z_N = 5\%$

$X_d / Z_N = 165\%$, $X_q / Z_N = 33\%$

Thus we get: $2\alpha = 10.3°$

Current root locus at constant voltage ($R_s > 0$)



Example:
- Shaft height 112 mm
- pole count $2p = 4$
- Rated voltage and current: $U_N = 380$ V, Y, $I_N = 9$ A, 50 Hz

$$1-\varepsilon = R_s^2/(X_d X_q) = 0.995$$

- Rated impedance: $Z_N = U_N/I_N = 24.4\ \Omega$
- warm stator phase resistance: $R_s/Z_N = 5\%$

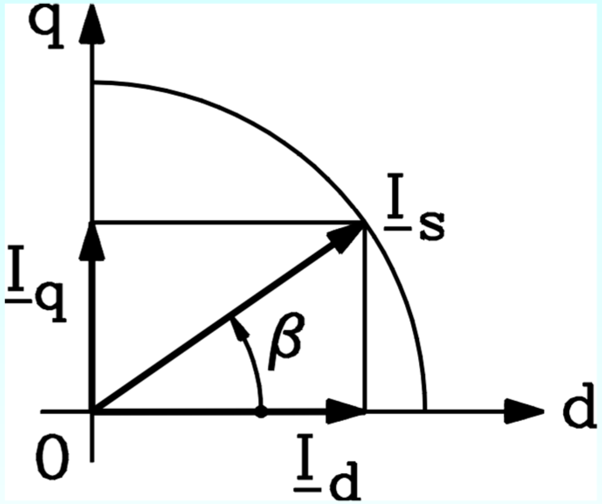
$X_d/Z_N = 165\%$, $X_q/Z_N = 33\%$

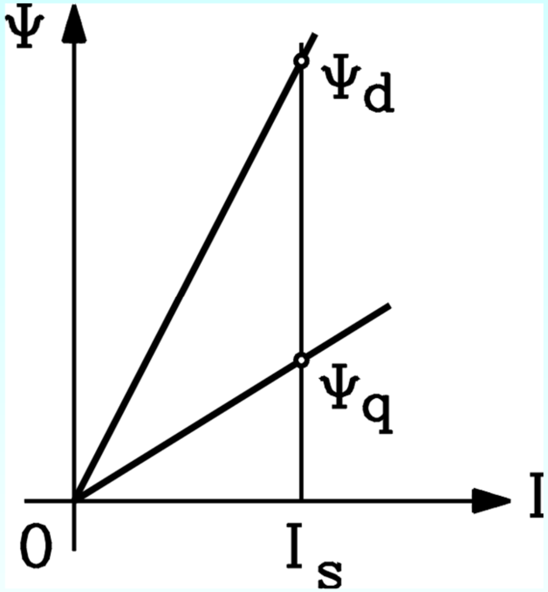
Thus we get: $2\alpha = 10.3°$

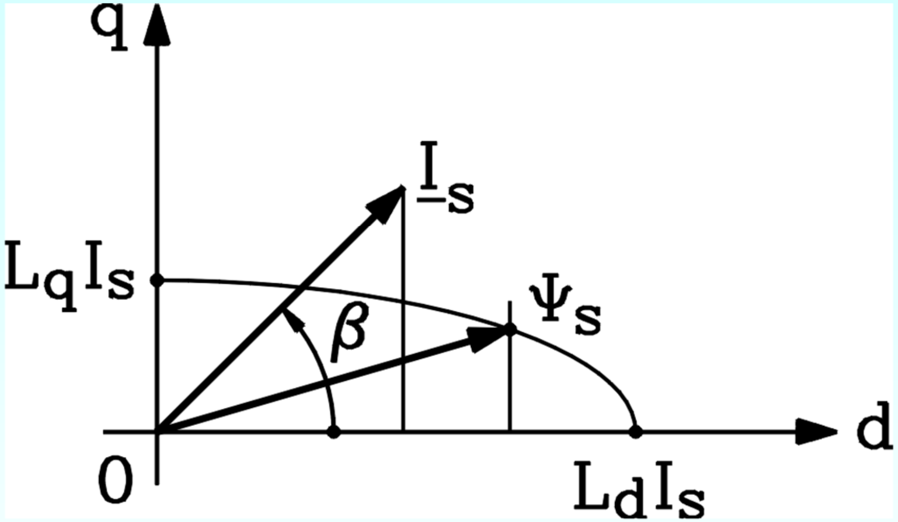
Influence of saliency at current control

No saturation:

Inverter current control: If current phasor is shifted by angle β from d-axis with constant amplitude: current locus is circle, BUT flux linkage locus $\Psi_s(\beta)$ is ELLIPSE.

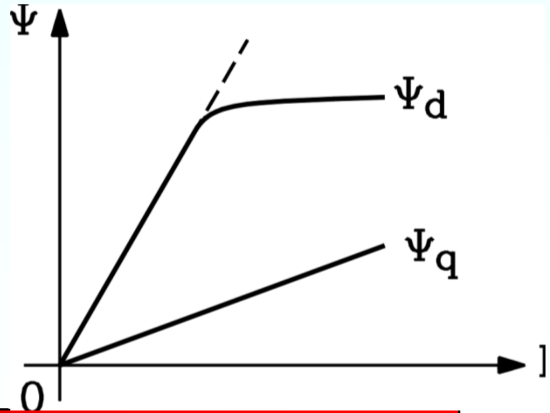




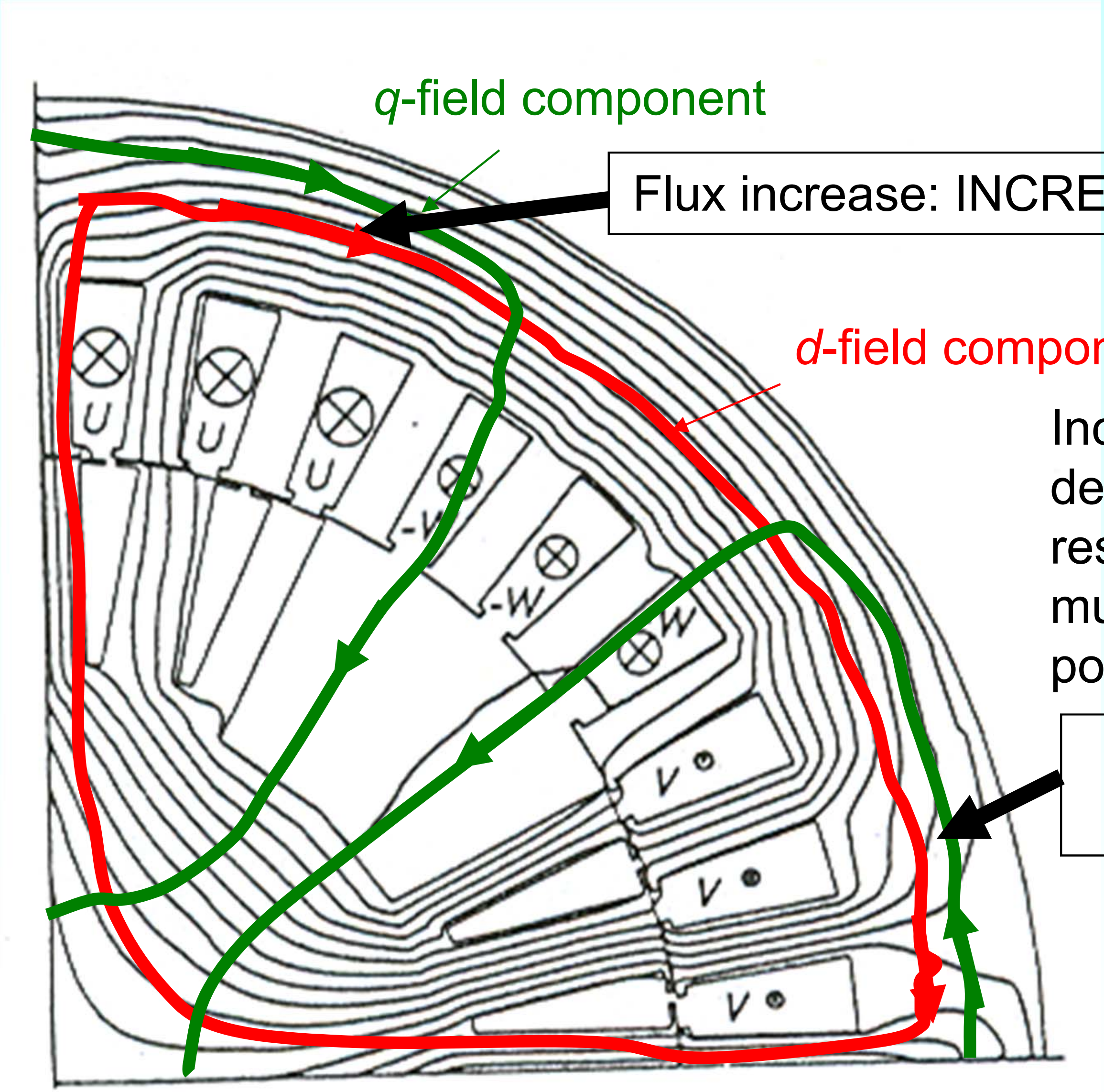


With saturation (mainly in d-axis):

Flux linkage locus $\Psi_s(\beta)$ is no longer an ELLIPSE, but has to be calculated step-by-step with numerical field analysis.



Increased saturation due to "cross-coupling" between *d*- and *q*-axis magnetic field



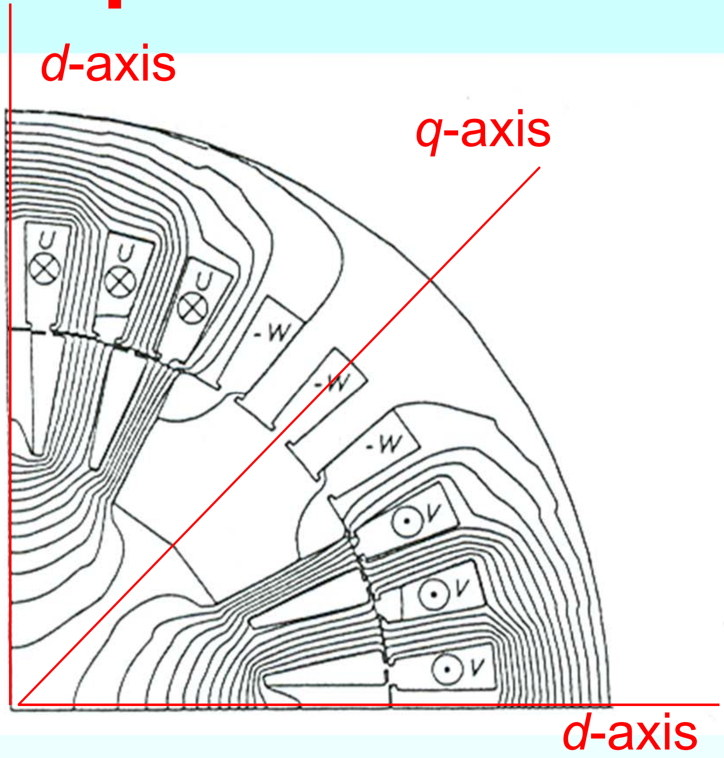
<u>*Example:*</u> $\beta = 45°: I_d = I_q$

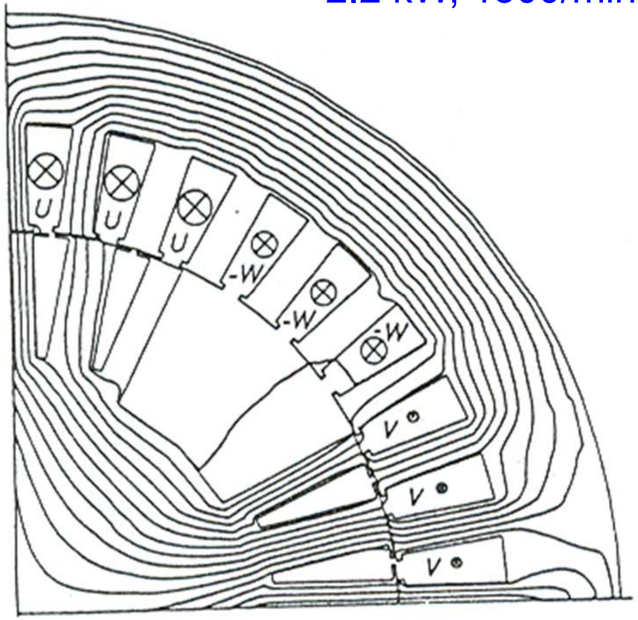
Increased saturation stronger than decreased saturation, which leads to a resultant flux reduction (FLUX LOSS). It must be calculated by <u>intermediate</u> rotor positions between *d*- and *q*-axis.

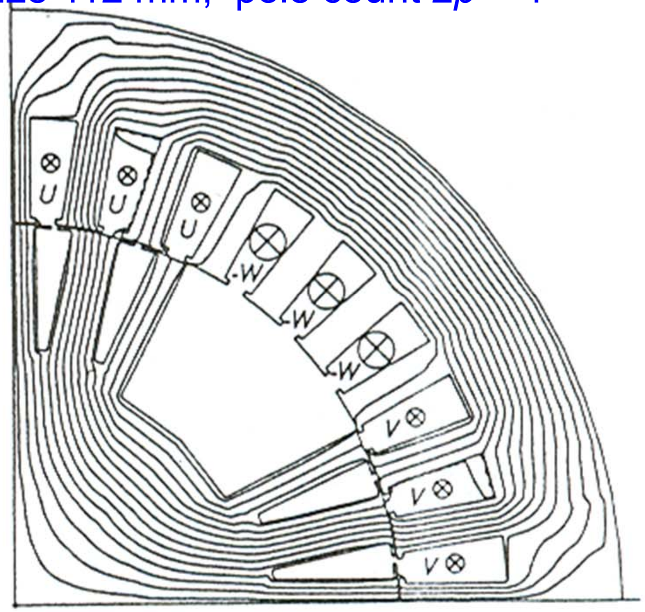
Influence of *d*-field on *q*-field and vice versa is called "magnetic coupling" of *d*- and *q*-axis!

4-pole machine: Numerically calculated flux lines

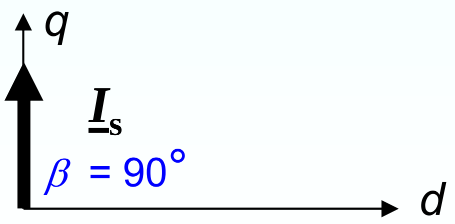
Example: Rated voltage and current: U_N = 380 V, Y, I_N = 9 A, 50 Hz
2.2 kW, 1500/min, frame size 112 mm, pole count $2p$ = 4

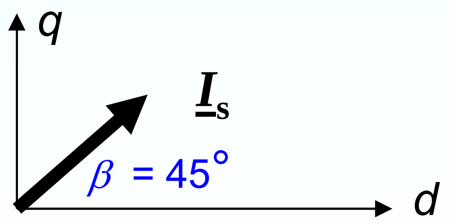


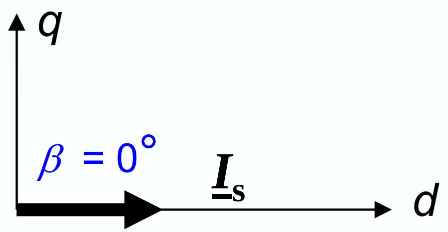




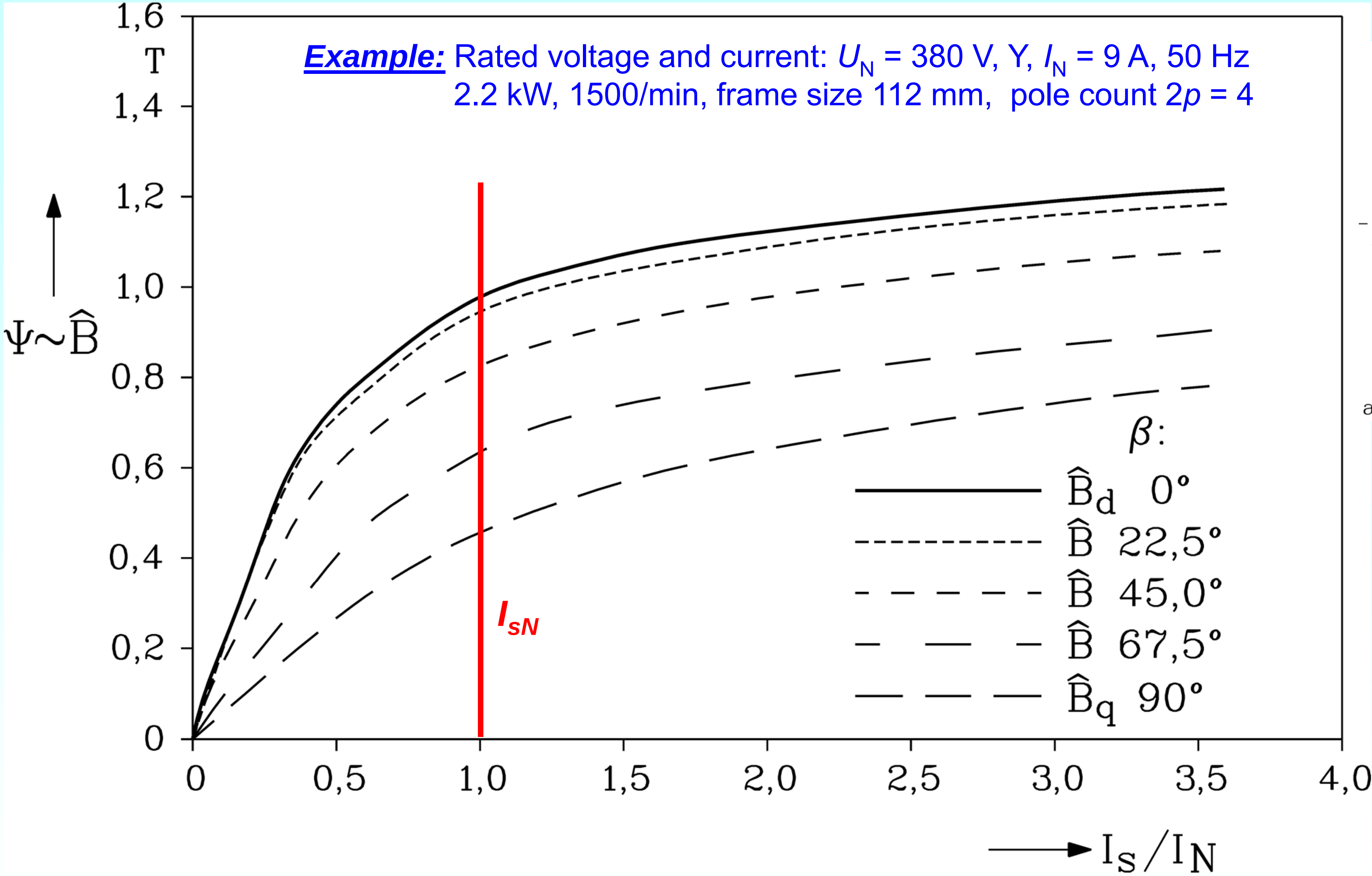
Rotor in *q*-position	Rotor half between *q*- and *d*-position	Rotor in *d*-position
Current angle: β = 90°	β = 45°	β = 0°

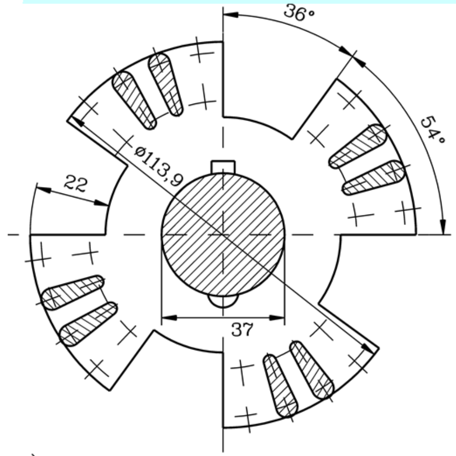






Numerically calculated flux linkage characteristics

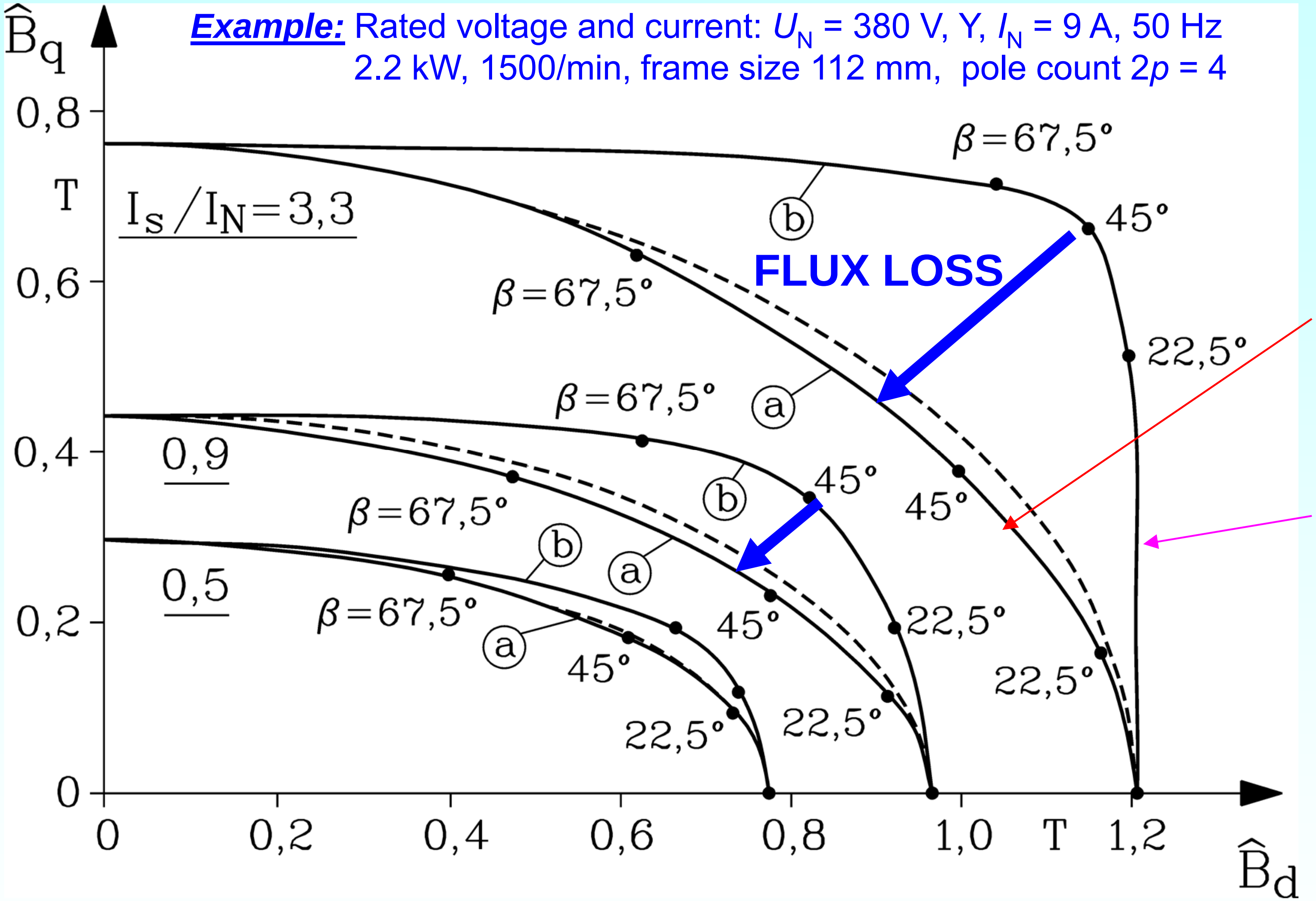




a)

Numerically calculated flux linkage characteristics at different current angle β

Locus of air gap flux density amplitude

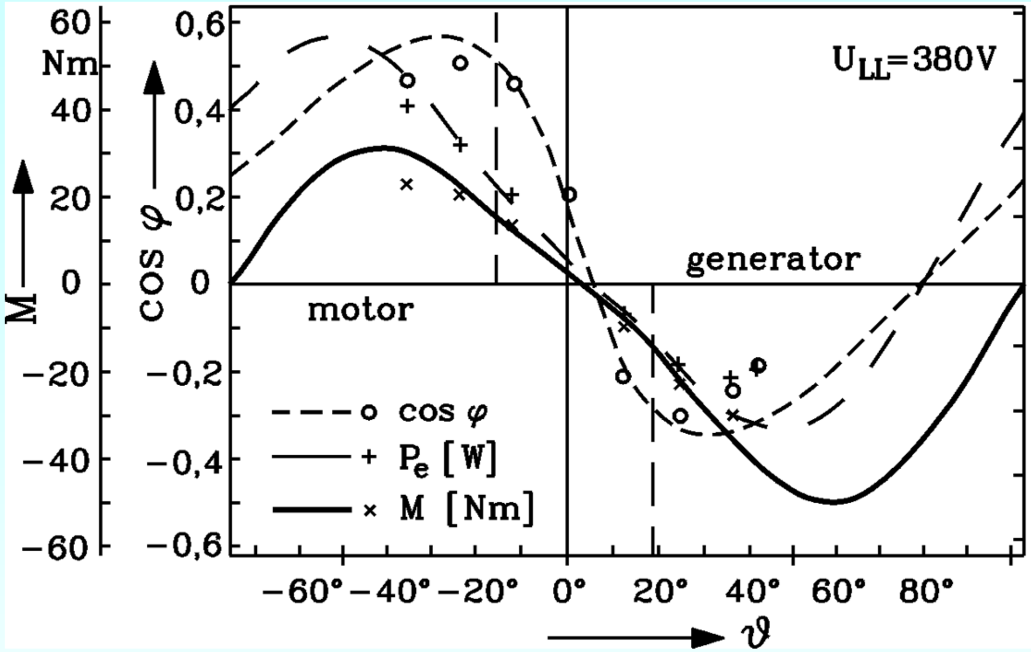


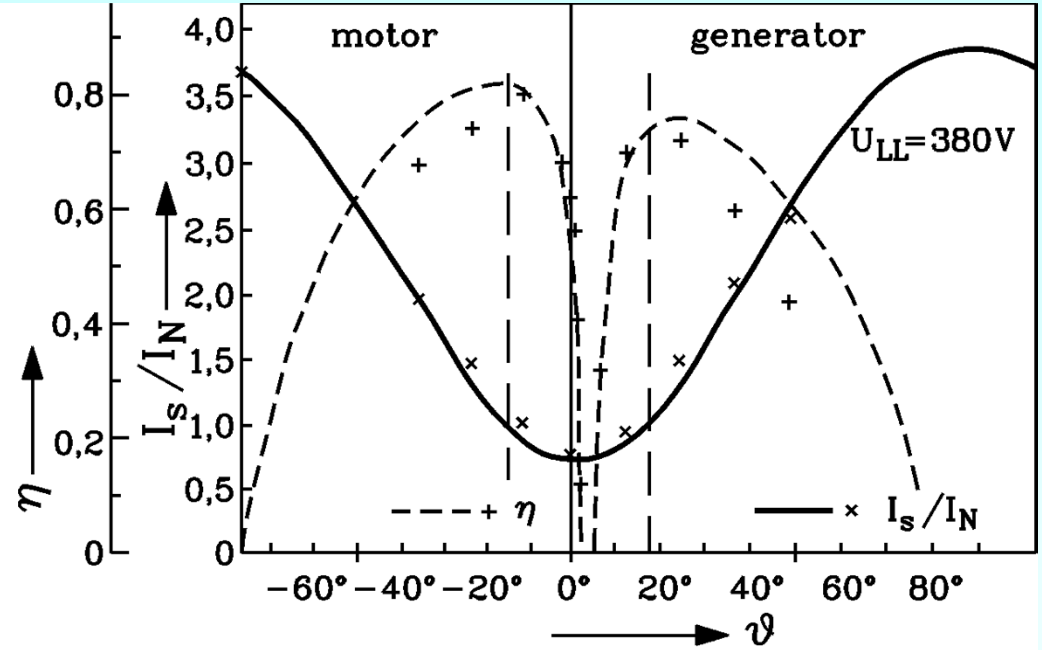
(dotted line -----: approximation ellipses)

- Different stator current: 50%, 90%, 330% of rated current
- Different current angles β
- Curves (a): flux linkage characteristic with “magnetic coupling
- Curves (b): No magnetic coupling between *d*- and *q*-axis considered

Facit: Method b) yields wrong results except for d- and q-axis.

Measured and calculated torque, power and current





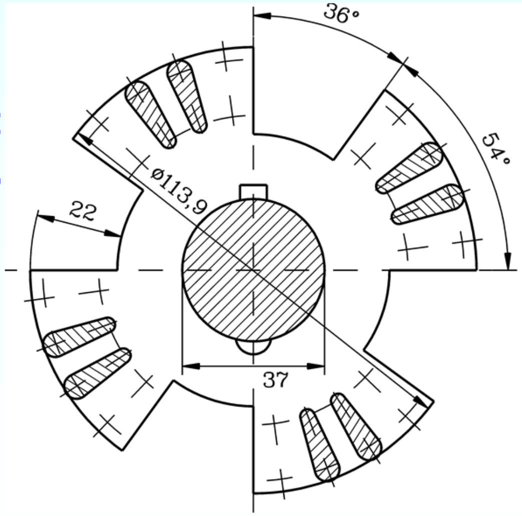
Four pole synchronous reluctance machine:

(1) Measured values: points

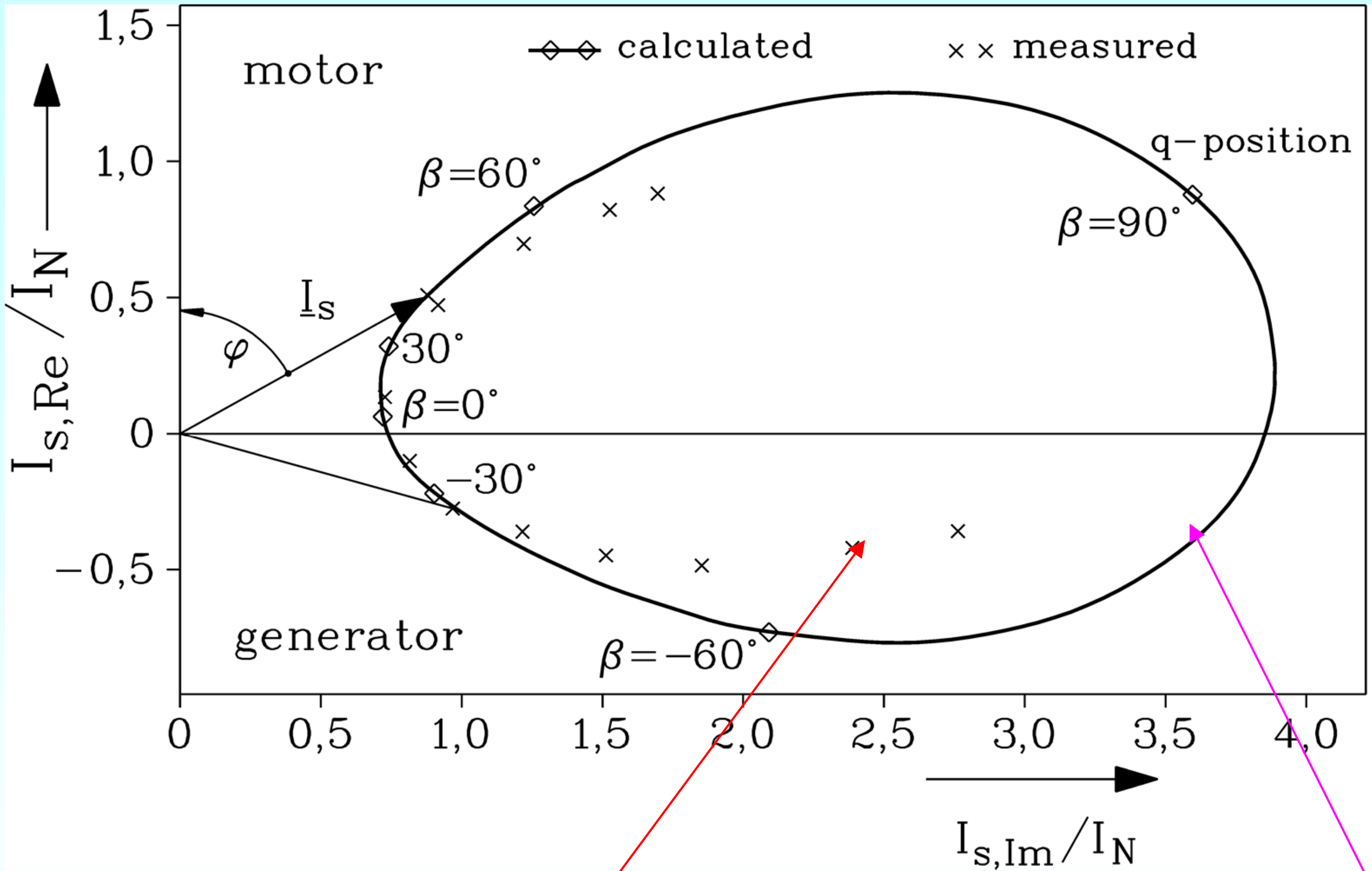
(2) Calculated: with consideration of "magnetic coupling" of *d*- and *q*-axis

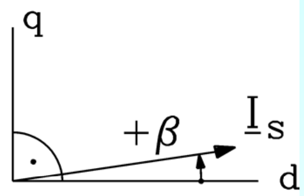
Torque, electrical power, power factor, current, efficiency

Example: Rated voltage and current: U_N = 380 V, Y, I_N = 9 A, 50 Hz, 2.2 kW, 1500/min, frame size 112 mm, pole count $2p$ = 4



Current root locus of saturated machine





Example: Rated voltage and current: U_N = 380 V, Y, I_N = 9 A, 50 Hz, 2.2 kW, 1500/min, frame size 112 mm, pole count $2p$ = 4

Comparison of measured (points) and calculated locus of stator phasor current; four pole synchronous reluctance machine

Calculation of saturated reluctance machines

- *Saturation and two-dimensional flux density distribution has to be taken into account for reliable calculation results*

- *Numerical field calculation is needed for calculating reluctance machines.*

- *Due to magnetic "cross coupling of d- and q-axis" by common flux path in the stator yoke, which adds to total saturation, it is necessary to calculate the total flux linkage for each current phasor.*

- *Considering d- and q-flux independently (= neglecting "magnetic coupling") is yielding too big flux for positions between d- and q-axis.*

Comparison of power-to-weight ratio of motors

Steady state torque per volume by 30% to 50% lower for synchronous reluctance machines, when compared with induction machines.

380 V Y, 50 Hz	*Induction motor*	*Reluctance motor*
Output power P_m / Rated current I_N	4 kW / 8.7 A	2.2 kW / 9.3 A
Power factor $\cos\varphi$	0.83	0.46
Efficiency η	84 %	78 %
Rotational speed n_N	1447 /min	1500 /min
$P_m/S = \cos\varphi \cdot \eta$	0.7	0.36

TOO high magnetizing current!

4-pole machines, identical stator and cooling

shaft height 112 mm, 36 stator slots

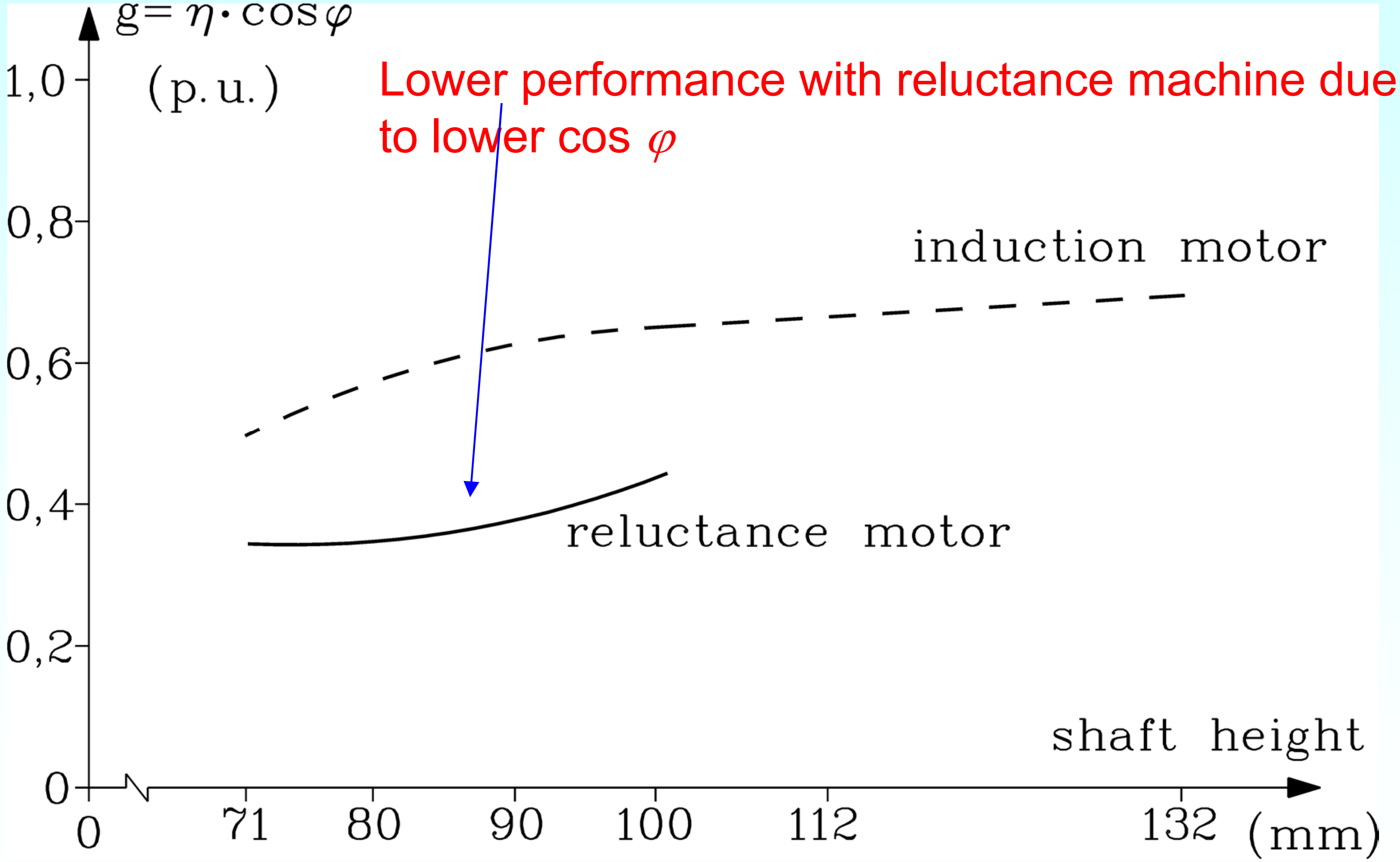
totally enclosed, fan cooled (TEFC), 380 V Y, 9 A, 50 Hz

For increased power output special rotor design (expensive) is necessary !

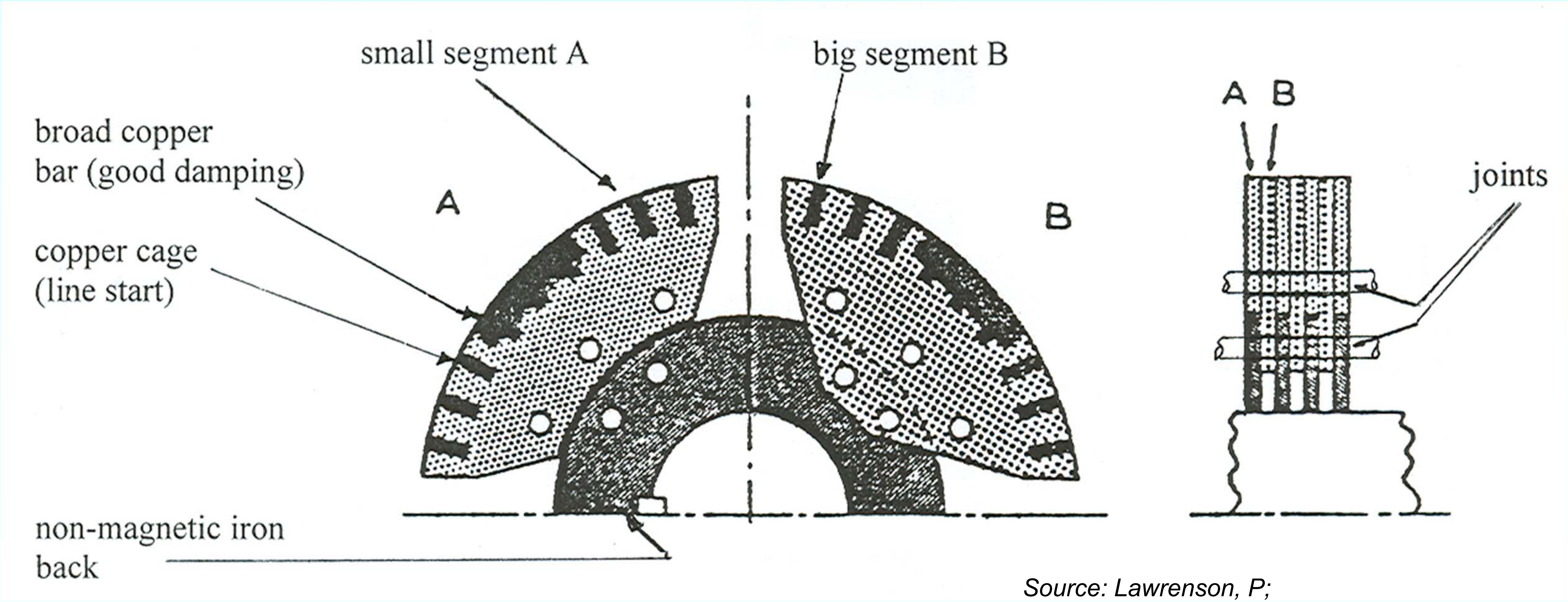
Product of rated efficiency and power factor *g*

Comparison of 4-pole machines:

Line-operated synchronous reluctance machine vs. induction motor



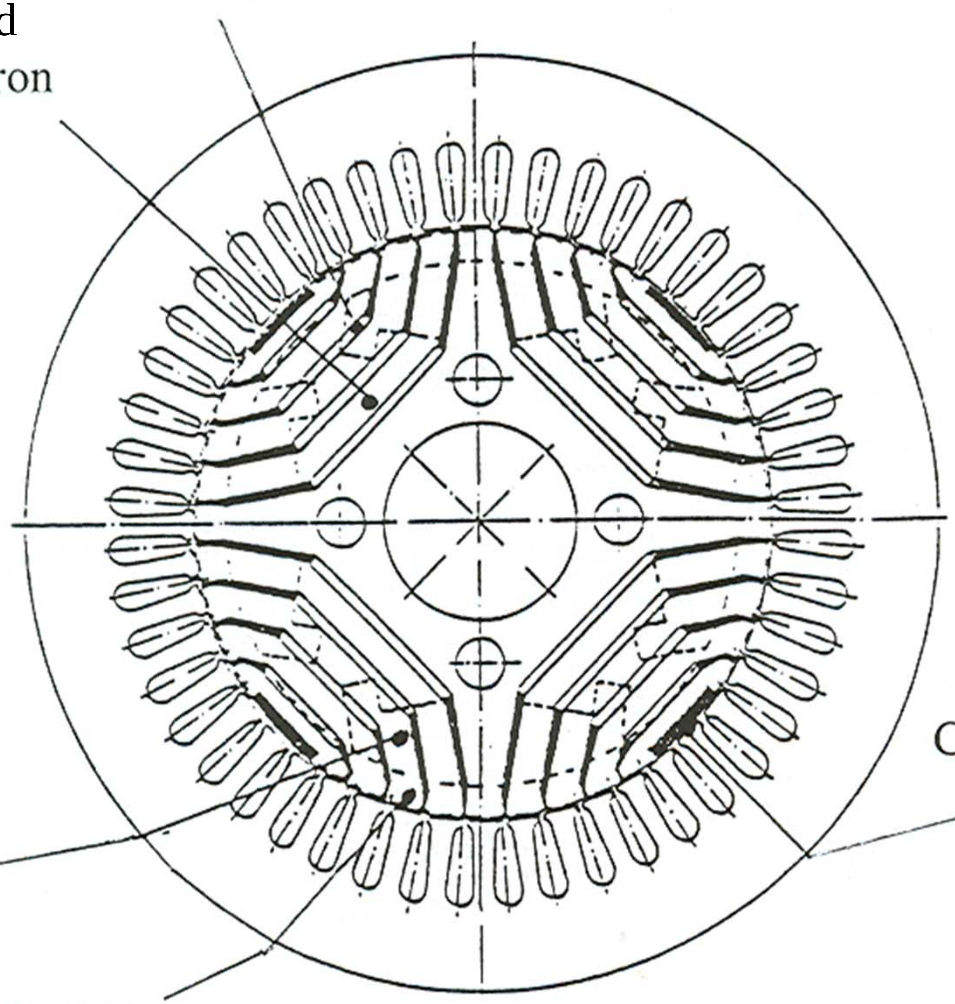
Special segmented sheet rotor design for increased ratio X_d/X_q



Source: Lawrenson, P; Gupta, S, IEE, 1967

- X_d/X_q can be increased up to 10 !
- Rotor construction is very expensive, so it is not used in industry !

Segmented reluctance rotor for increased X_d/X_q



Source: Taegen, F; 1990, Archiv f. Elektrotechnik

- Design gives big ratio X_d/X_q of about 10 !
- But:

a) Expensive rotor design

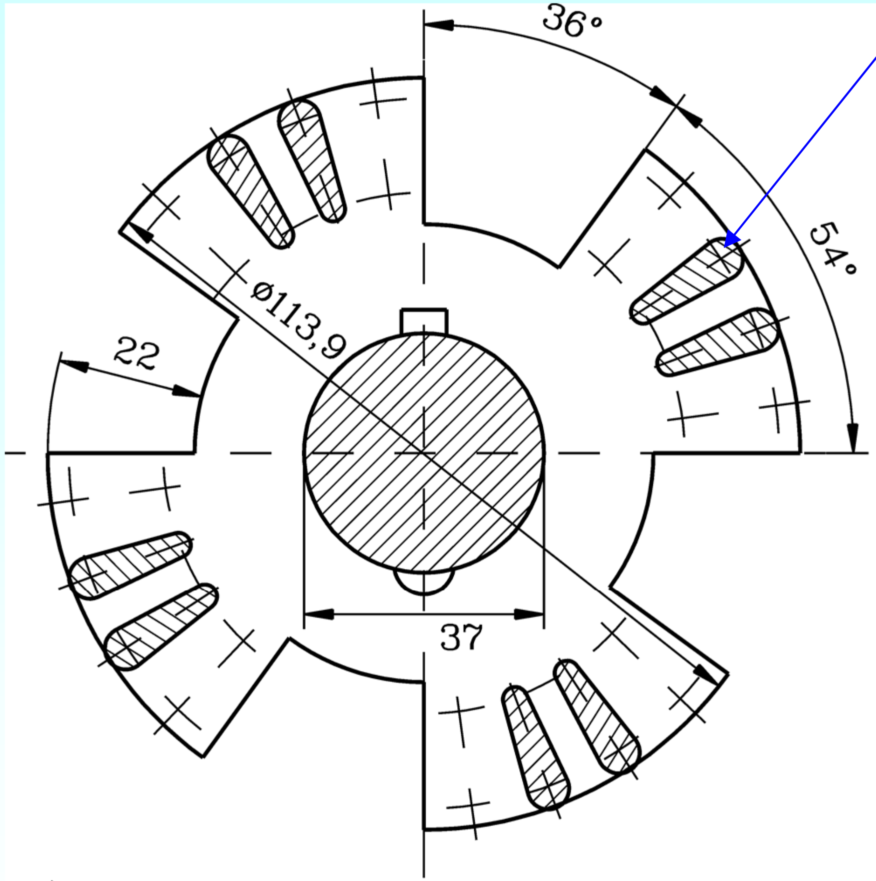
b) „Slotting" due to axially laminated rotor gives rise to air gap flux density ripple, which causes magnetically excited noise.

Facit:

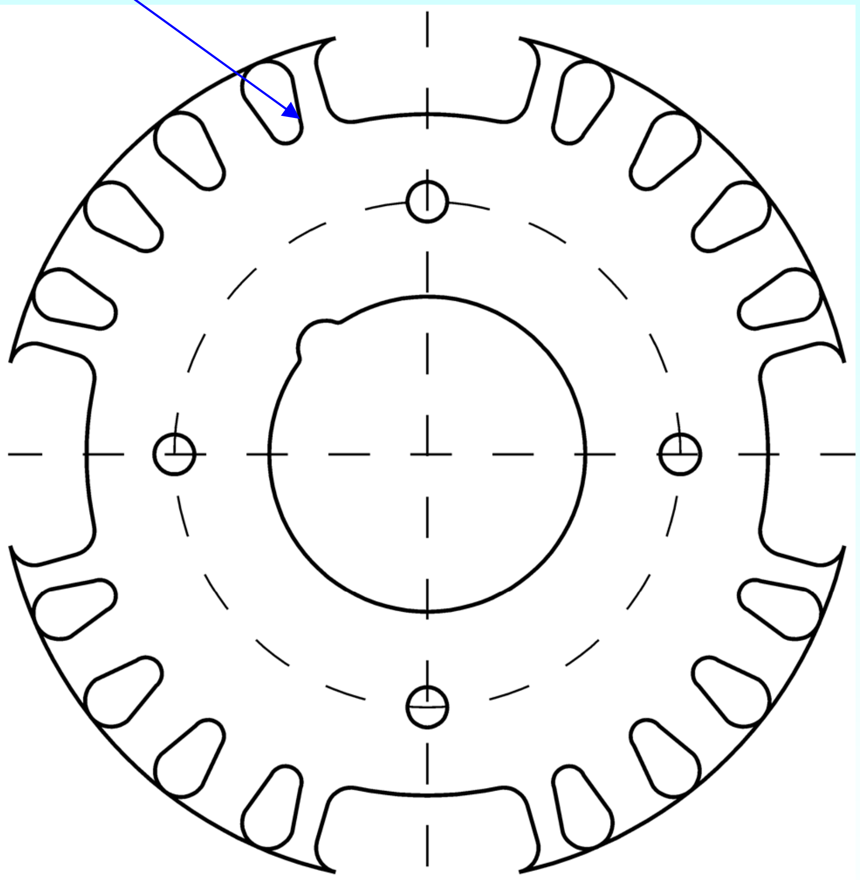
This rotor design is not used in industry.

Starting cage for synchronous reluctance machines

Die-cast **aluminum cage** for asynchronous starting



Source: A. Schmidt, TU Wien, 1988



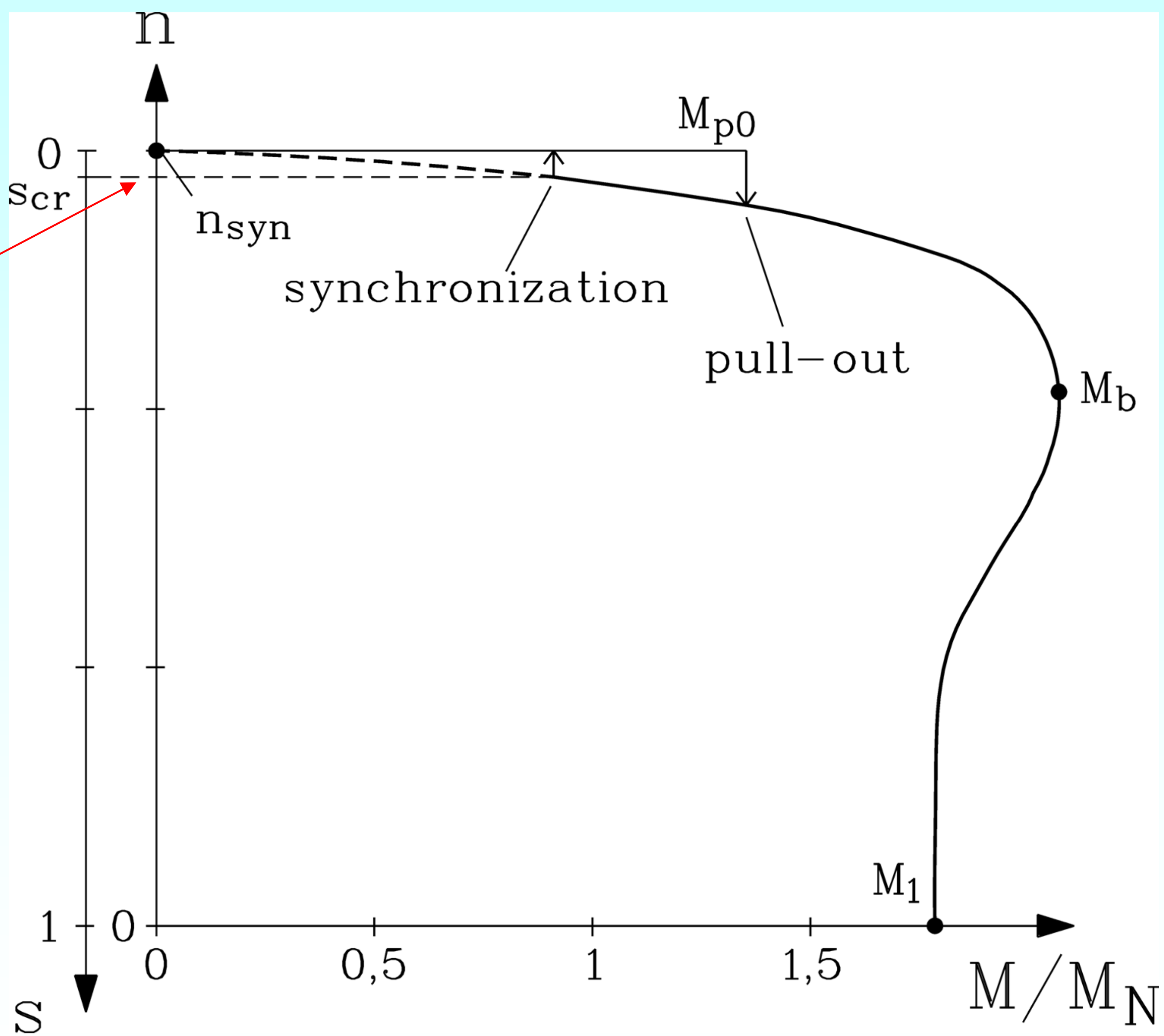
Source: Siemens AG. Germany

Asynchronous starting and synchronization (pull-in)

- Minimum slip (below critical slip s_{cr}) necessary for pull-in

- Asynchronous torque at this slip lower than synchronous pull-out torque

- Critical slip depends on rotor cage data and rotor inertia !

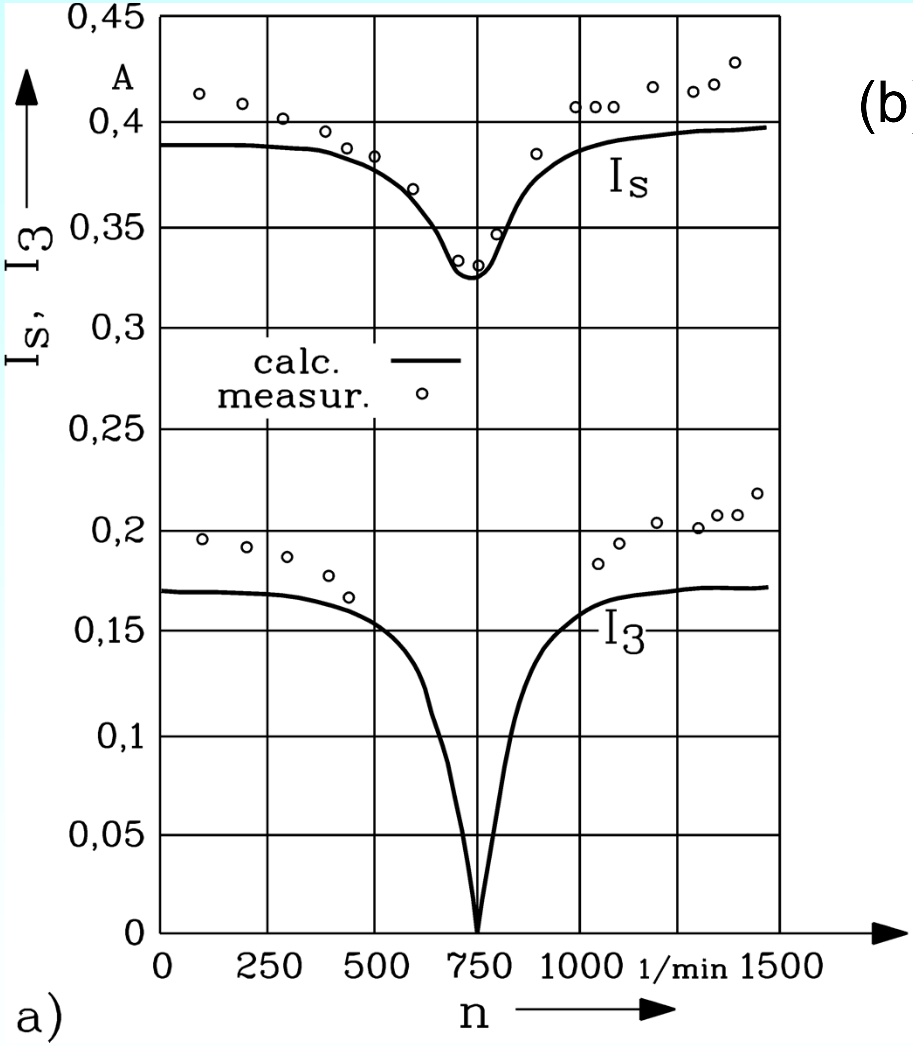


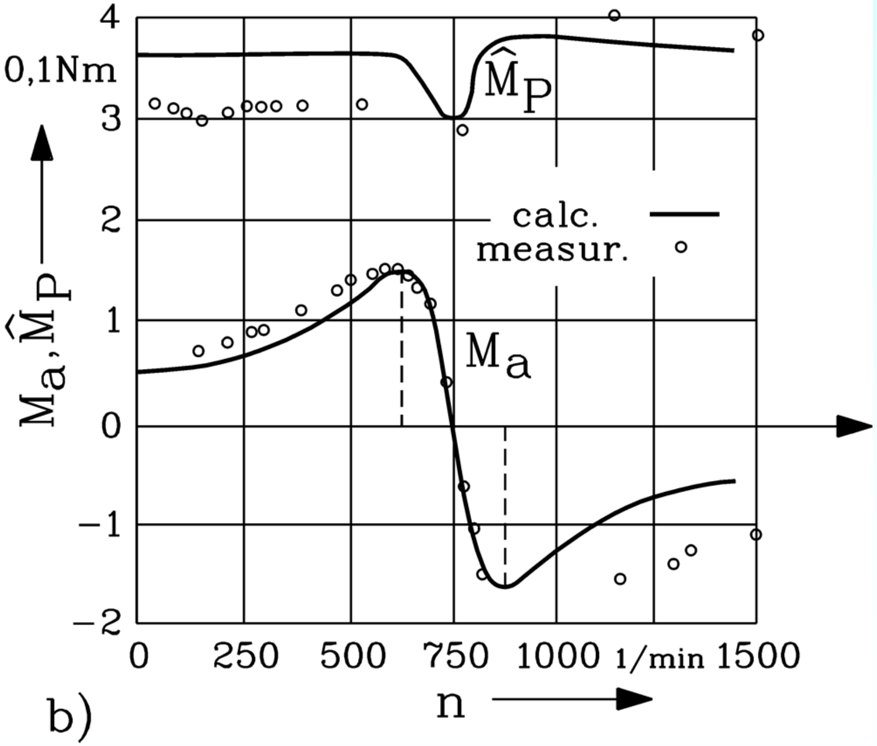
Source: Siemens AG. Germany

Asynchronous starting of reluctance machines

(a) Calculated and measured (dots) stator and additional stator current I_3 ,

(b) Asynchronous reluctance torque M_a and pulsating torque amplitude M_P





Source: Bausch, Jordan et al, ETZ-A

Asynchronous reluctance torque M_a and pulsating torque M_P

- Rotor reluctance modulates stator air gap field, resulting

$$B_\delta(\gamma,t) = \mu_0 V_s(\gamma,t)/\delta(\gamma,t) = \mu_0 V_s \cos(\gamma - \omega_s t)\cdot\left[\frac{1}{\delta_0} + \frac{1}{\delta_1}\cdot\cos(2\gamma - 2(1-s)\omega_s t)\right]$$

- stator fundamental with average air gap: $B_{s,1} = (\mu_0 V_s / \delta_0)\cos(\gamma - \omega_s t)$

- additional field with different frequency: $B_{s,3} = (\mu_0 V_s / 2\delta_1)\cos(\gamma - (1-2s)\omega_s t)$

Additional field induces in the stator windings a voltage system U_3 with frequency

$$f_3 = (1-2s)f_s$$

which causes an additional (small) stator current I_3.

a) Constant part of asynchronous reluctance torque: $M_a \sim I_s I_3$

b) Pulsating torque amplitude: $M_P \sim I_s I_3,\ I_s^2,\ I_3^2$ with frequency $\left|f_s - f_3\right| = 2sf_s$

GOERGES phenomenon of reluctance machines

At half synchronous speed $n = n_{syn} / 2 \quad \Leftrightarrow \quad s = 0.5$

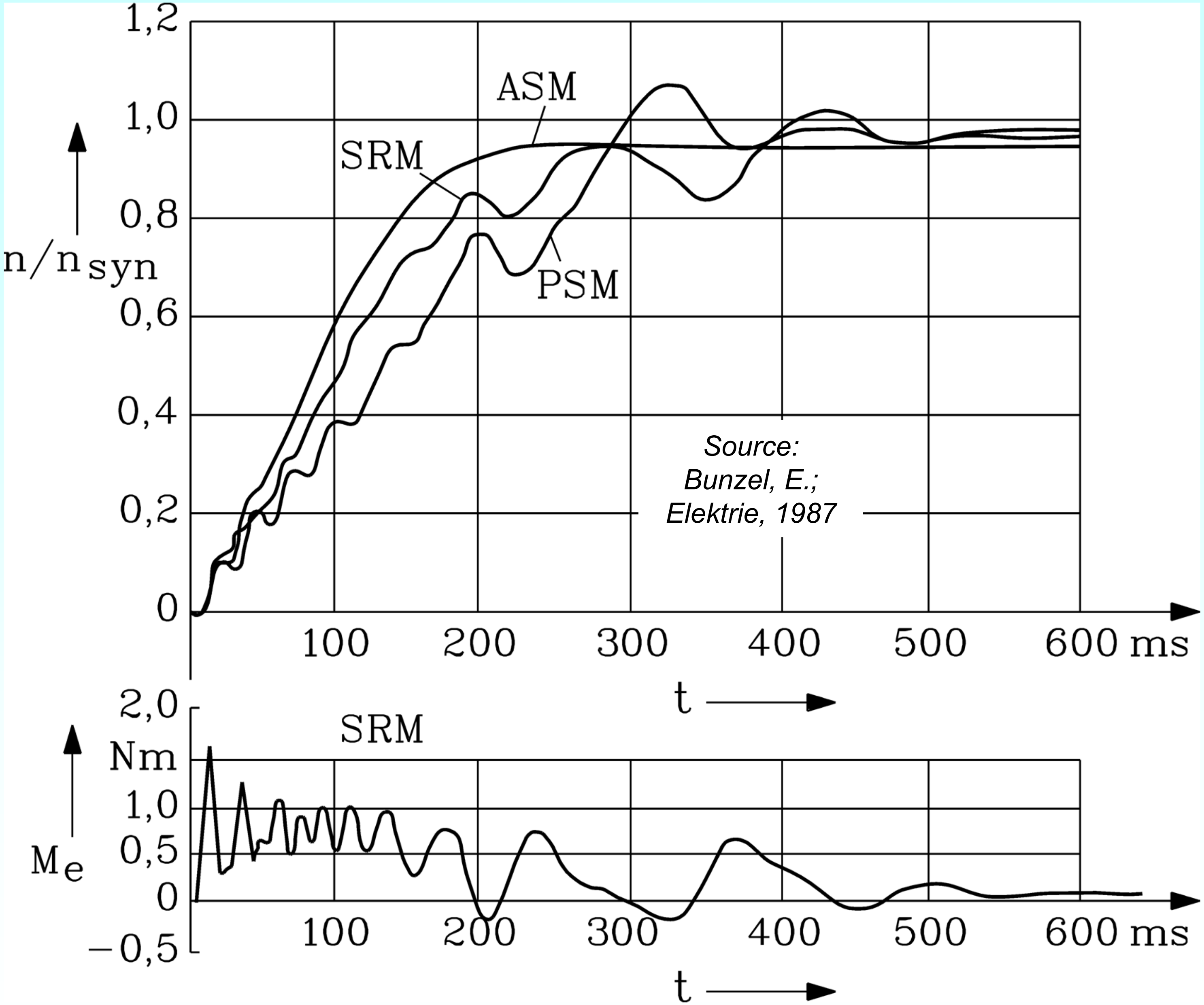
***f*$_3$** is zero, so **in that point *I*$_3$ = 0.**

Asynchronous reluctance torque M_a vanishes
Pulsating torque has a minimum, now depending only on I_s^2
(*Goerges*-phenomenon)

a) The current $i_3(t) = \hat{I}_3 \cdot \sin((1-2s)\omega_s t)$ changes sign at $s = 0.5$, therefore the real power flow of this current is also changing direction,
(1) being motor at $n < n_{syn}/2$
(2) generator at $n > n_{syn}/2$.

(b) Therefore the asynchronous reluctance torque is a
(1) driving (positive) torque for $n < n_{syn}/2$ and
(2) a braking (negative) torque for $n > n_{syn}/2$.

Calculated asynchronous starting



Comparison of

-induction machines (ASM),

- Synchronous reluctance machine (SRM)

- Permanent magnet synchronous machines with rotor cage (PSM)

- Pulsating torque with decreasing frequency

$$|f_s - f_3| = 2sf_s$$

clearly visible.

Synchronization after asynchronous start-up

- At synchronous speed the slip is zero: The asynchronous torque of the cage is zero.
- The speed of stator fundamental field wave and of the rotor with its variable reluctance is identical, so the field modulation effect vanishes. Hence the asynchronous reluctance torque is zero.
- The frequency of the stator current system I_3 is: $f_3 = (1-2s)f_s = f_s$
- Hence current I_s and I_3 unite as the total stator current I_s at synchronous speed.
- **The pulsating torque becomes the constant reluctance torque:**

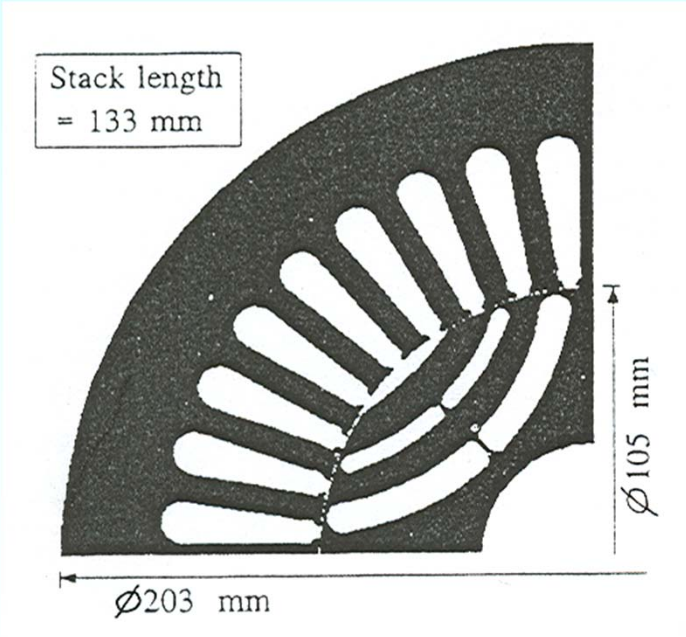
$$|f_s - f_3| = 2sf_s = 0 \qquad M_P \sim I_s I_3, I_s^2, I_3^2 \sim U_s^2 = M_e$$

- At s << 1 the frequency $2s \cdot f_s$ corresponds with a very slowly increasing load angle $\vartheta(t)$: $\hat{M}_P \cdot \sin(2 \cdot (2\pi \cdot sf_s \cdot t + \vartheta)) \Rightarrow \hat{M}_e \cdot \sin(2\vartheta)$

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

2. Reluctance machines

2.2.2 Inverter-operated synchronous reluctance machines



Source: M. Kamper, WCRR Conf, 1997

Synchronous reluctance machines for group drives

- Application: Fabrication of textile fibers
- Group drive: One big converter feeds ca. 100 synchronous reluctance machines in parallel
- All motors rotate synchronously without any speed control
- Feed forward *U*/*f*-converter operation with fixed voltage and frequency
- If one drive fails, it is stopped, while the others keep operating. After fault-clearing the stopped drive starts asynchronously via its starting cage at the group converter with fixed stator voltage and frequency.

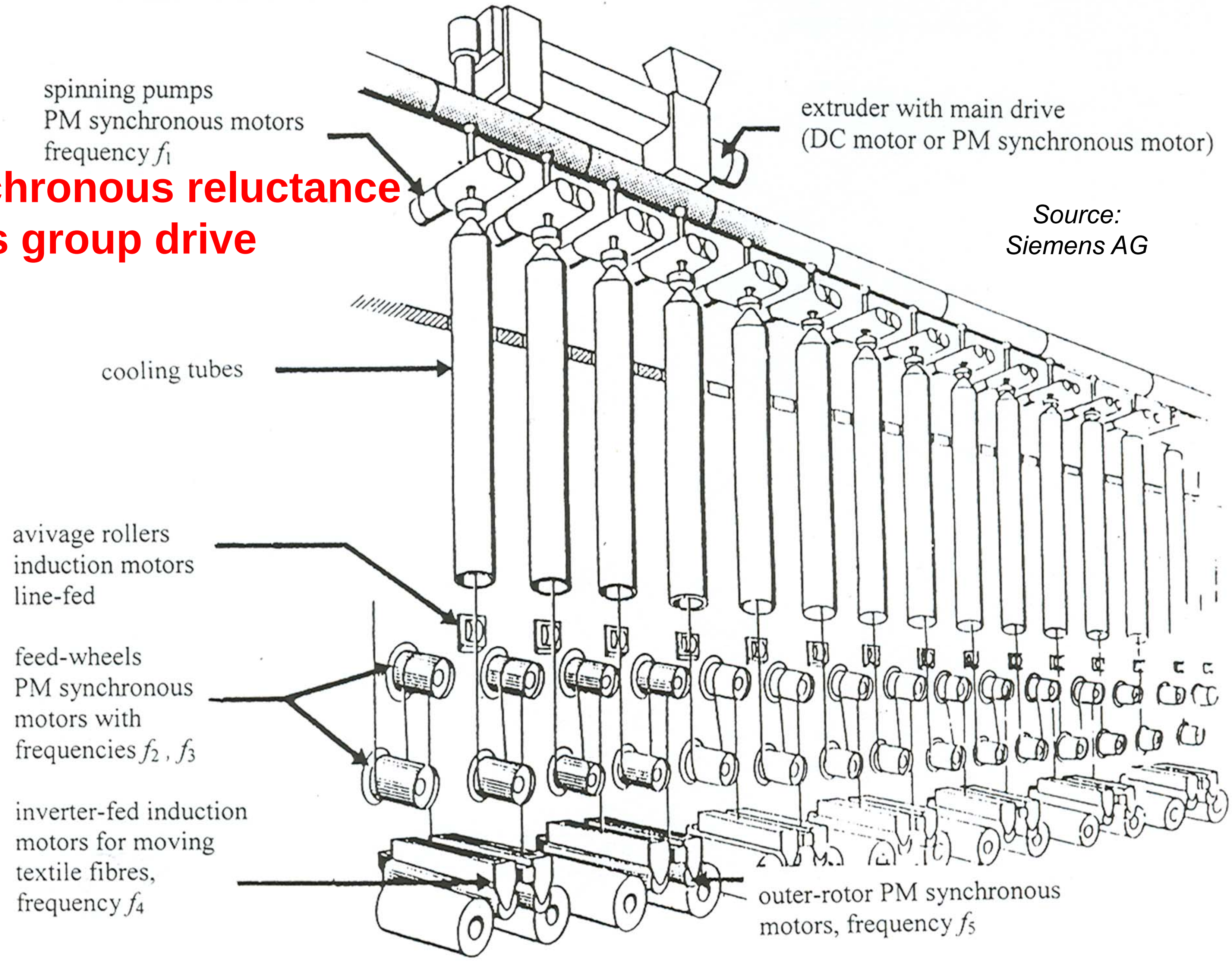
Application of synchronous reluctance machines as group drive

- Fabrication of textile fibers

- One big thread, coming from extruder, is separated into ca. 100 parallel thin threads

- Parallel and SYNCHRONOUS up-winding of threads is done by cheap reluctance motors or PM synchronous motors

- Motors must start separately, hence asynchronous start up

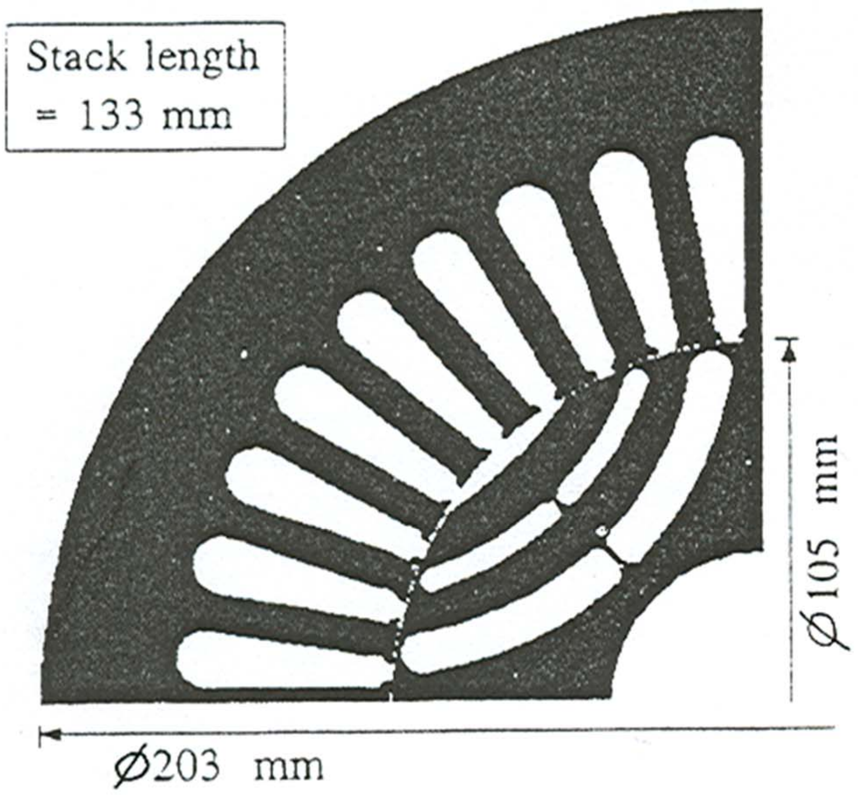


Source: Siemens AG

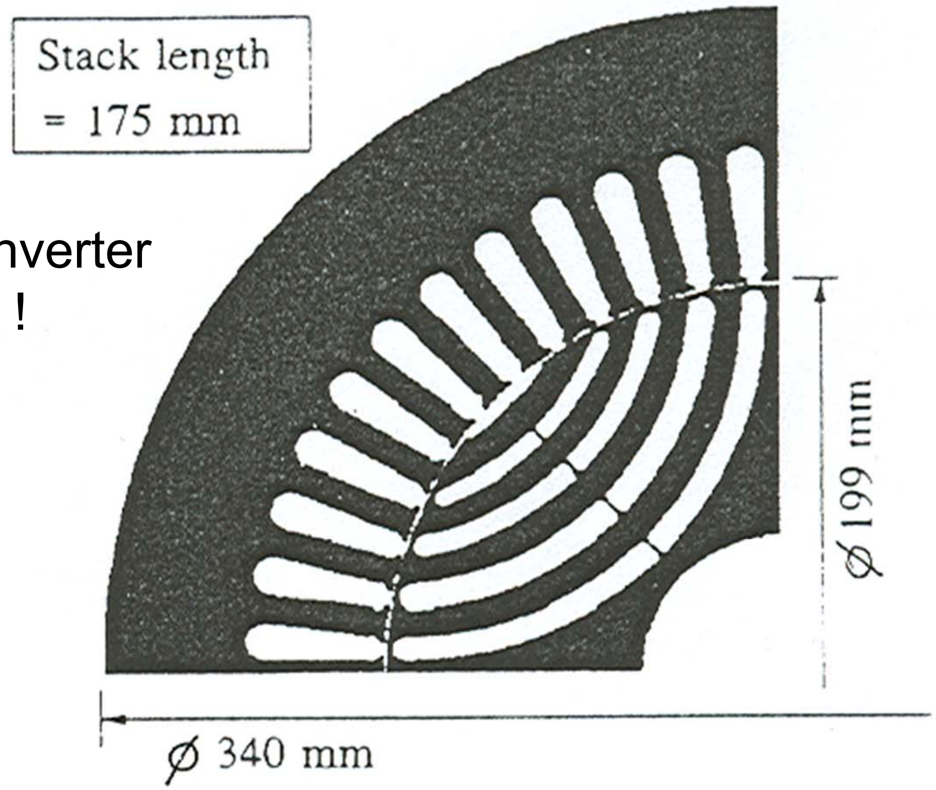
Variable speed synchronous reluctance drives without starting cage

- Special rotor design for big ratio X_d/X_q = ca. 8 … 10 allows motor utilization similar to cage induction machines
- These motors are operated as variable speed drives with IGBT voltage source inverters and rotor position control. So no group drive operation possible.
- Motors have nearly no rotor losses, so efficiency is higher than with comparable inverter-operated cage induction machines
- Synchronous motor operation without speed control possible
- Due to the big ratio X_d/X_q the power factor is increased up to 0.7 ... 0.8
- Field-oriented control (I_d, I_q) is possible, so high dynamic performance is inherently given.

Flux barrier rotor design for increased ratio X_d/X_q without cage



Only for inverter operation !

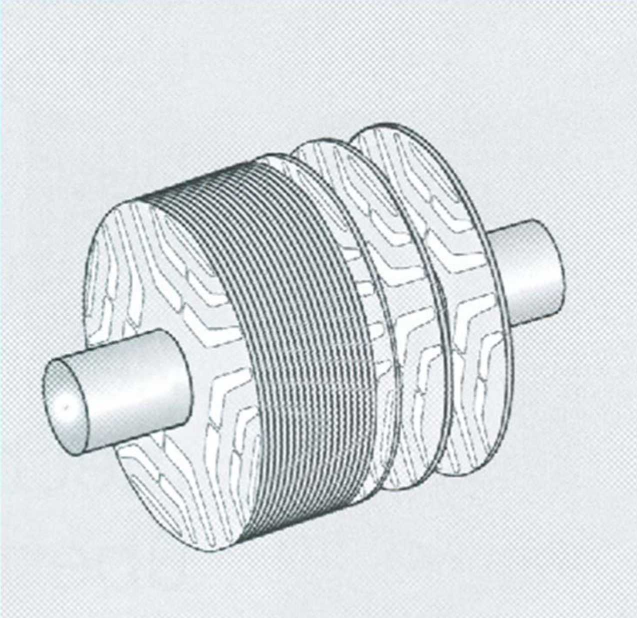


Source: M. Kamper, WCRR Conf, 1997

- X_d/X_q can be increased from about 5 to 8 … 10

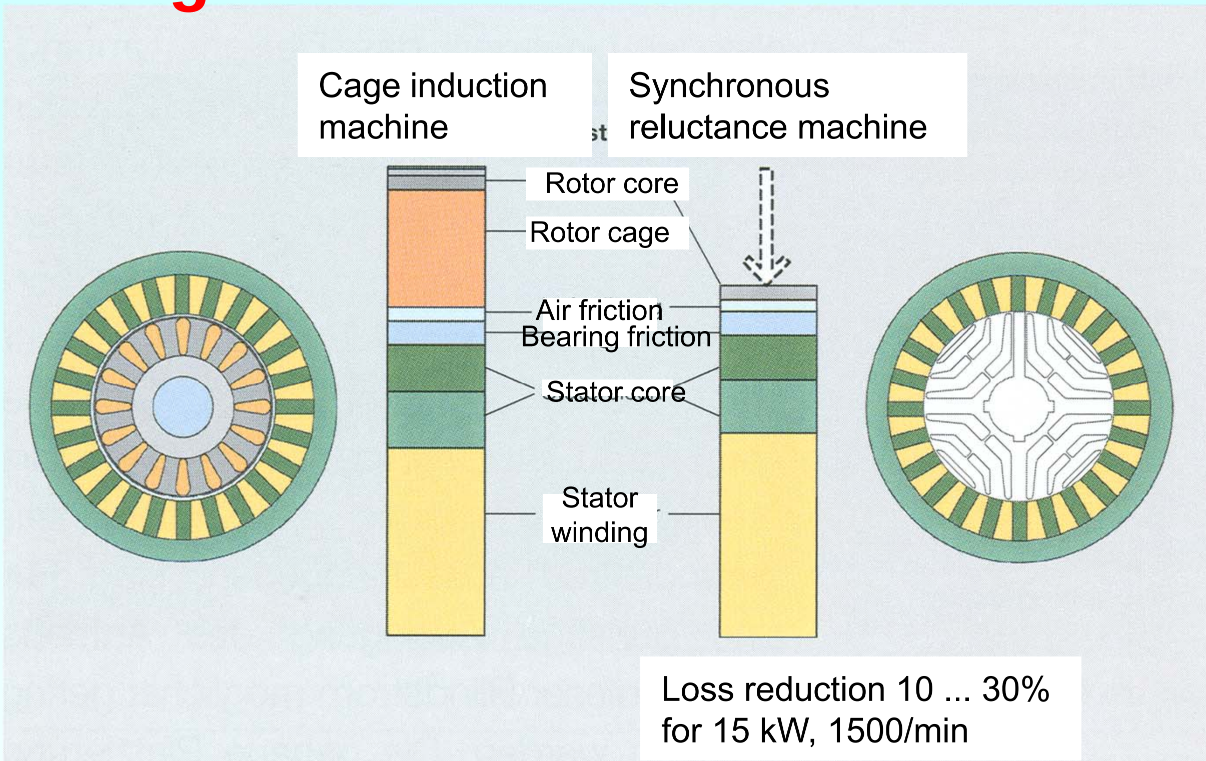
- Power factor increased up to 0.7 ... 0.8, thus nearly reaching the value of induction machines. An efficiency of 0.85 ... 0.9 is possible.

Comparison of losses for a 4-pole sync. reluctance machine with a cage induction machine



4-pole laminated reluctance rotor with flux barriers

Source: Lendenmann H, ABB review 2011

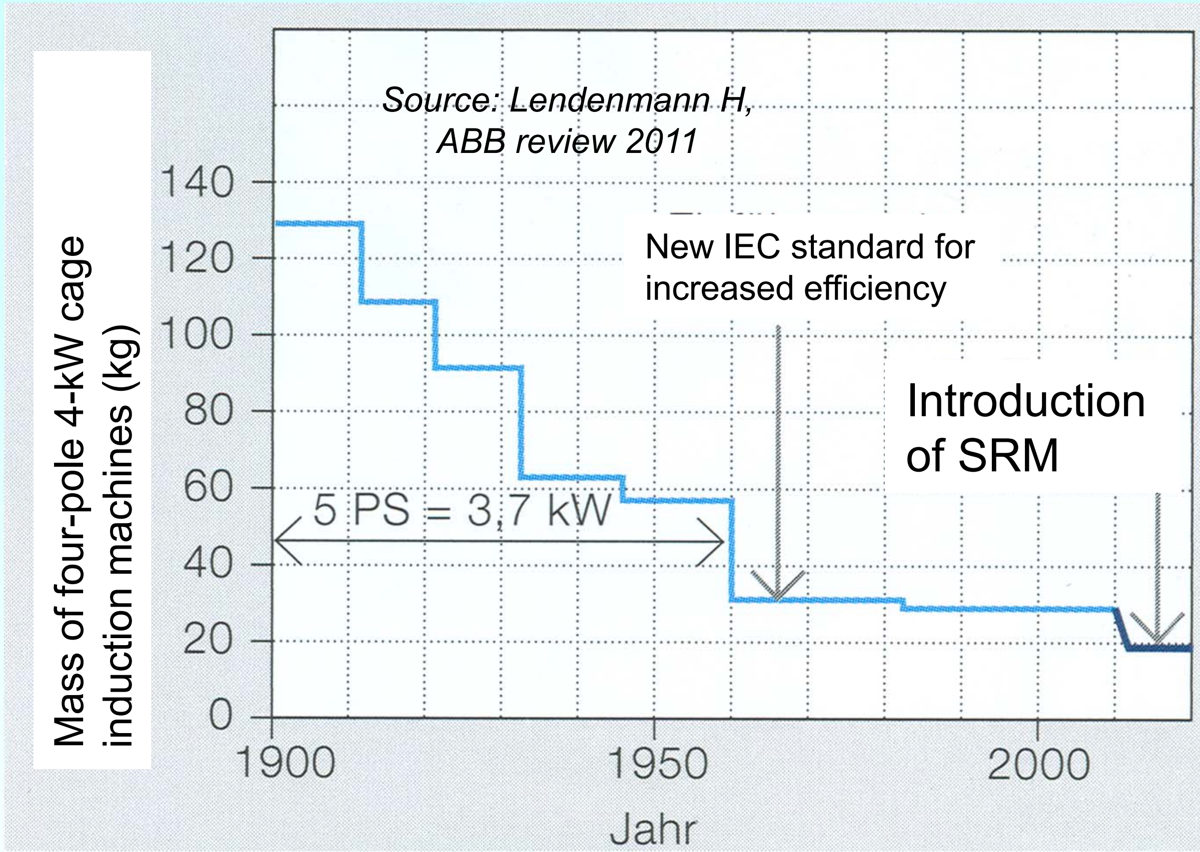


4-pole cage induction motor

4-pole synchronous reluctance motor

- Comparison at: 15 kW, 1500/min, 50 Hz: Due to the missing rotor I^2R losses the nominal efficiency of the synchronous reluctance machine is higher than for the cage induction machine, as the total losses a reduced by 10% … 30%.

Comparison of mass and output power of 4-pole synchronous reluctance machine to cage induction machine



Frame size	Cage induction machine	Syn. Rel. machine	Output power
100	3,3 kW η=83%	4,3 kW η=90%	+30–45%
160	22 kW	29 kW	+32%
280	90 kW	110 kW	+22%

Comparison of output power

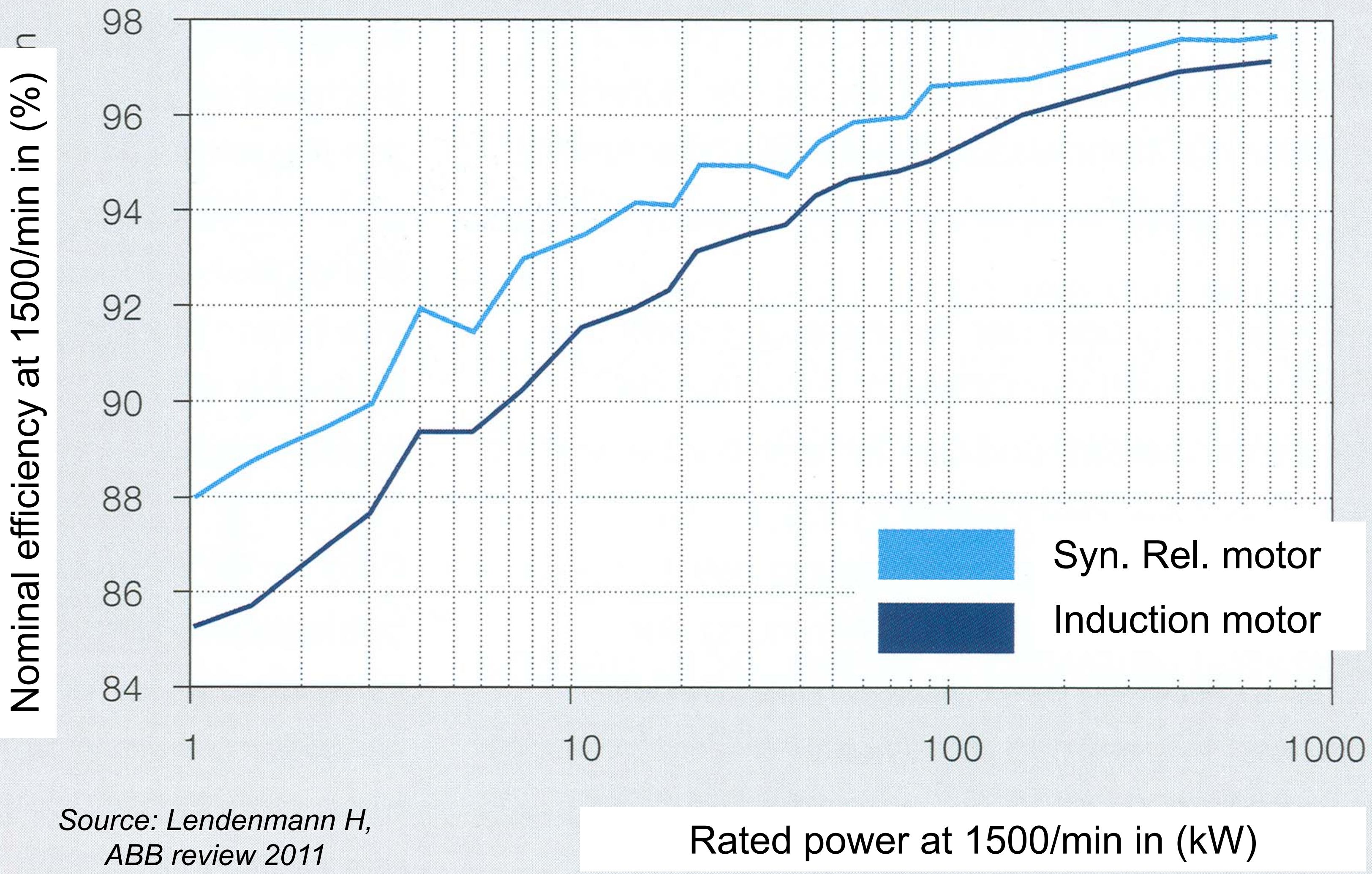
Motor mass reduction of induction machines due to increased motor utilization

Further mass reduction due to replacement by inverter-fed synchronous reluctance machines (SRM)

Increase of nominal power due to reduced losses within a given frame size of 20% … 30% with SRM

Efficiency increase with SRM

Comparison of nominal efficiency of inverter-fed 4-pole sync. reluctance machine to cage induction machines



Source: Lendenmann H, ABB review 2011