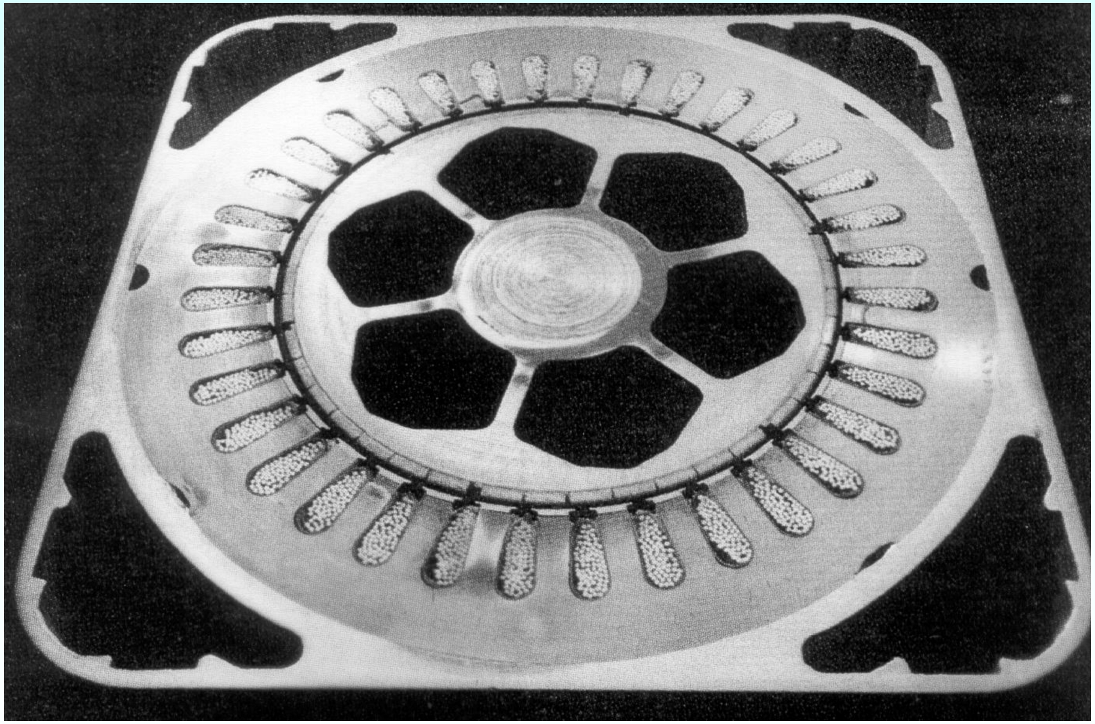
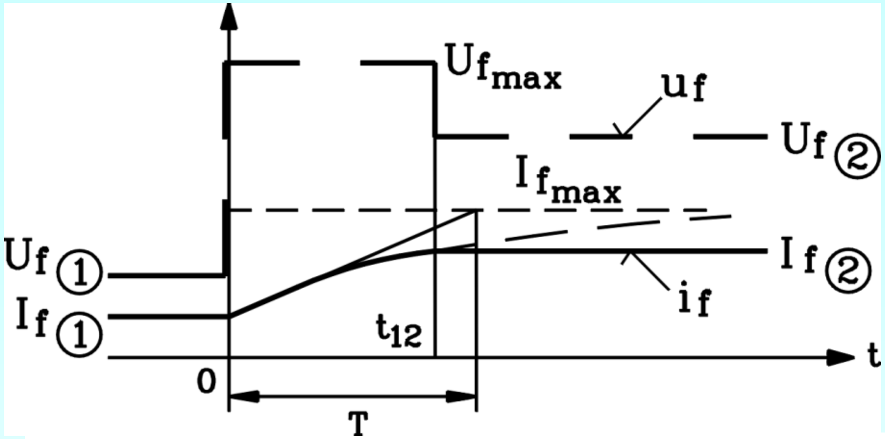
9. Electrically Excited and Permanent Magnet Synchronous Machines

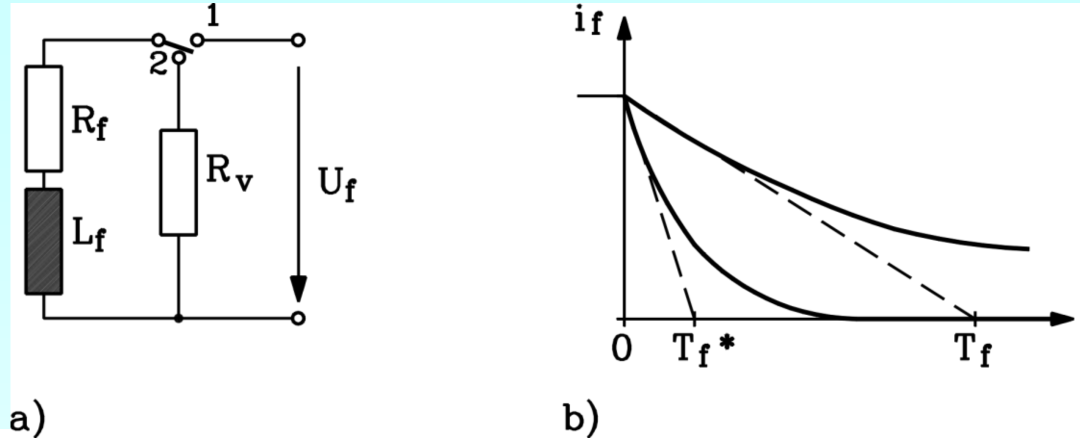


Source: Siemens AG

High-speed excitation and de-excitation



High speed excitation



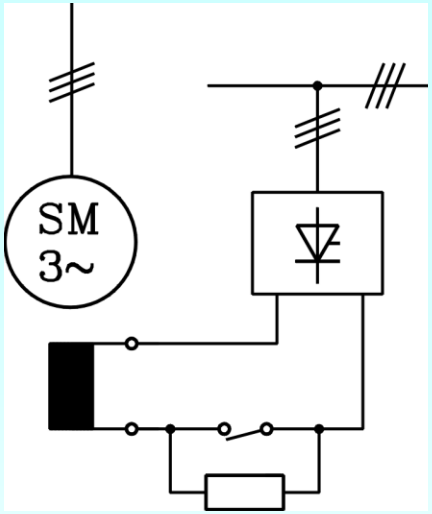
De-excitation: a) external resistance b) field current

- **High speed excitation**: Quick rotor field **build-up**: Applying of "ceiling voltage" U_{fmax} : Field current rises in minimum time t_{12} from starting value I_{f1} to set-point value I_{f2}. At stator no-load condition rotor electrical time constant T is **Rotor open-circuit time constant $T_f = L_f/R_f$.**
- **Quick de-excitation:** Quick **de-magnetization** of rotor field: Applying an external field resistor R_v (switch is in position 2) to reduce rotor winding time constant T_f .

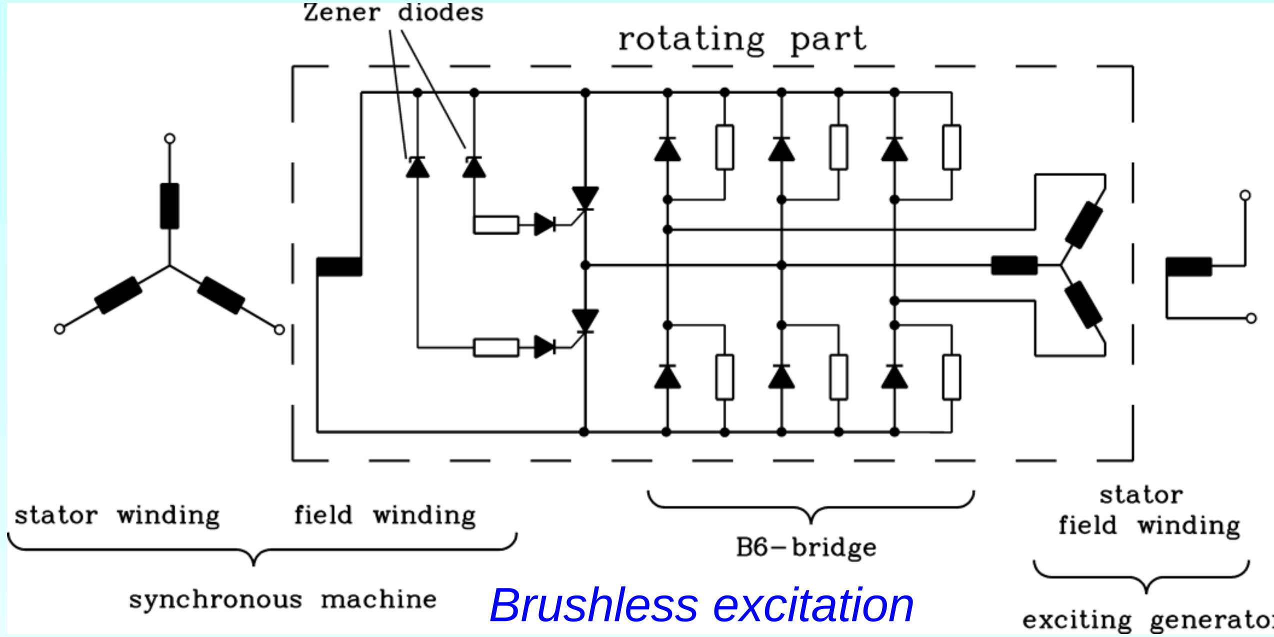
$$T_f{}^* = L_f /(R_f + R_v) = T_f /(1 + \frac{R_v}{R_f})$$

Example: At $R_v = 9R_f$ time-constant T is reduced to $T_f^* = T_f/10$, e. g. from 3 s to 0.3 s. After about 3 T_f^* = 1 s rotor field has decayed to zero.

Excitation systems



Converter excitation

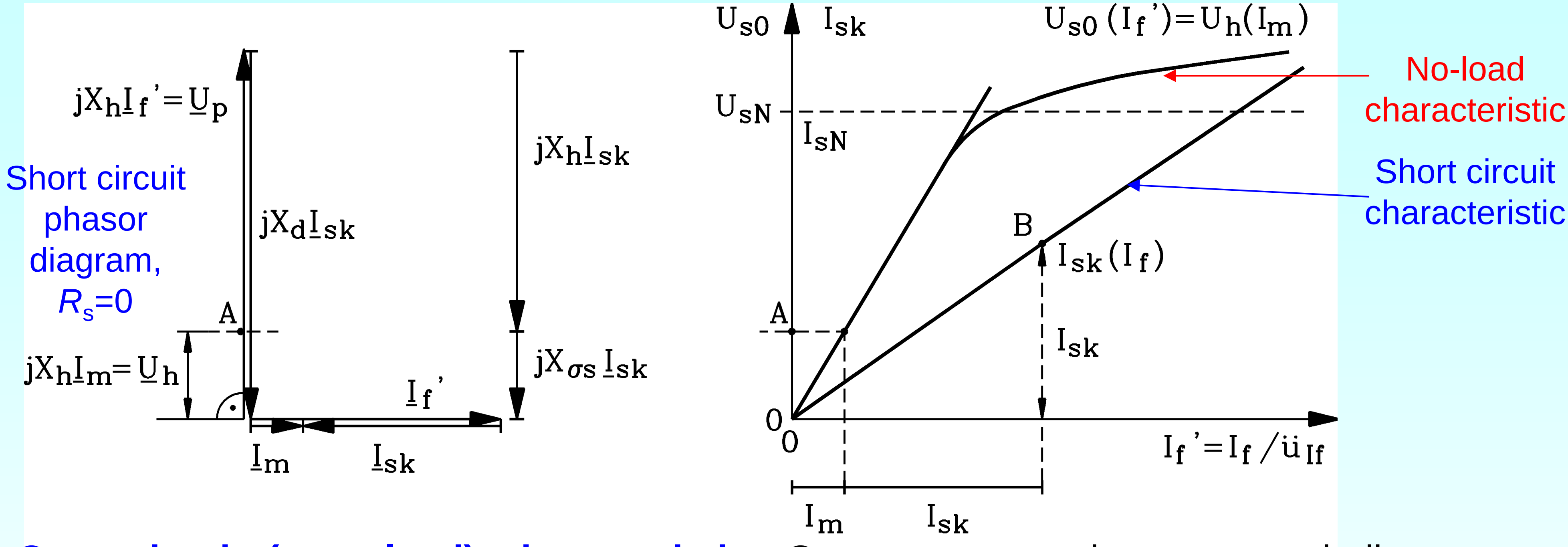


Brushless excitation

- **Converter excitation:** Controlled six-pulse rectifier bridge (B6C) generates from AC grid voltage a variable DC field voltage U_f, depending on thyristor ignition angle $\alpha \Rightarrow$ via 2 slip rings DC current flows to the rotor winding.

- **Brushless excitation:** Exciter generator is coupled to main synchronous machine rotor, being itself an **outer rotor synchronous machine:** Stator = "DC excited" magnetic field. Rotor: Three-phase AC winding, in which voltage U is induced. Rotating six-pulse B6-diode bridge rectifies U to DC field voltage U_f, being applied to rotor without any brushes or slip rings. By variable stator DC field current the rotor field voltage is varied.

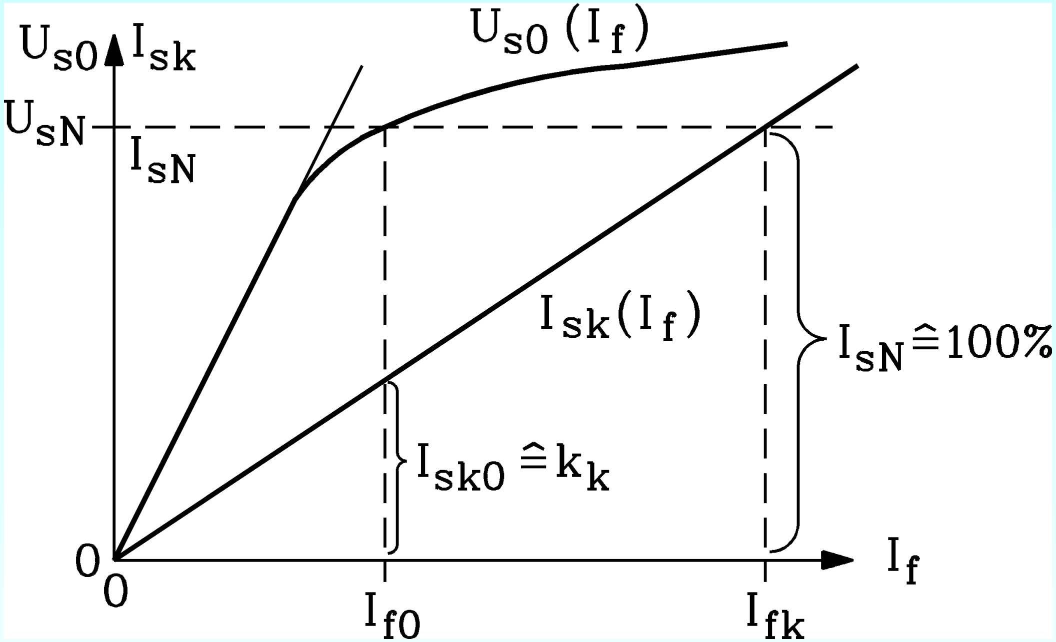
Measurement of equivalent circuit parameters (n = const.)



- **Open-circuit (= no-load) characteristic:** Generator operation, stator winding open circuit (I_s = 0): Measured stator voltage is "back EMF": $U_{s0}(I_f)$ or $U_{s0}(I'_f)$. $U_{s0} = U_p = U_h$ *and* $I_f = I_m$.
  At high current I_f (high rotor flux): iron part saturate: $U_{s0}(I_f)$ curbed characteristic.

- **Short-circuit characteristic:** Generator operation, short circuited stator winding: Stator current = short-circuit current I_{sk}. Acc. to a): $I_m = I'_f - I_{sk}$ small (U_h small: magnetic point of operation A) $\Rightarrow$ iron does not saturate. Characteristic $I_{sk}(I_f)$ or $I_{sk}(I'_f)$ is LINEAR.

Measurement of synchronous reactance



- Due to $I_{sk} = U_p / X_d$ (at $R_s = 0$) we get:
  At **"no-load field current"** I_{f0} the induced no-load voltage is rated phase voltage: $U_{s0} = U_{sN}$.
  At this field current in case of short-circuited stator winding the stator current is **short-circuit current I_{sk0}:**

$$I_{sk0} = \frac{U_p(I_{f0})}{X_d} = \frac{U_{s0}}{X_d} = \frac{U_{sN}}{X_d}$$

- **Synchronous reactance:** $\boxed{X_d = \frac{U_{sN}}{I_{sk0}}}$

- **Synchronous reactance x_d per unit of rated impedance** $Z_N = U_{sN} / I_{sN}$:

$$\boxed{x_d = \frac{X_d}{Z_N} = \frac{U_{sN}}{I_{sk0}} \cdot \frac{I_{sN}}{U_{sN}} = \frac{I_{sN}}{I_{sk0}} = \frac{I_{fk}}{I_{f0}}}$$

No-load / short-circuit ratio k_K

- The per unit synchronous reactance x_d is the ratio of short-circuit field current versus no-load field current. Its inverse is the **"no-load / short-circuit ratio"** $k_K = 1/x_d$.

$$\boxed{k_K = \frac{I_{f0}}{I_{fk}} = \frac{I_f(U_s = U_{sN}, I_s = 0)}{I_f(U_s = 0, I_s = I_{sN})} = \frac{1}{x_d}}$$

- At iron saturation no-load field current I_{f0} is higher than in *non-saturated case.* Hence **saturated no-load / short-circuit ratio** is bigger than nun-saturated one. So, ***saturated synchronous reactance*** is smaller than non-saturated value:

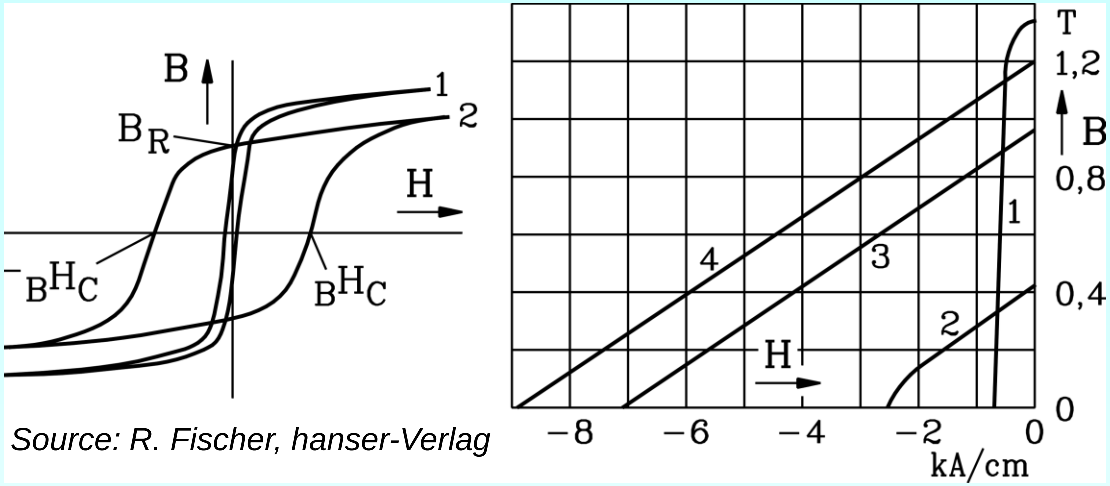
$$\boxed{x_{d,sat} < x_{d,unsat}}$$

- **Synchronous reactance** X_d ~ Magnetizing inductance $L_h \sim N_s^2 \tau_p / \delta$.

	Pole count $2p$	Synchronous reactance x_d/p.u.
Turbo generators (round rotor)	2	**2.0**
Salient pole machines	≥ 4	**0.8 ... 1.2**
PM-Machines with Surface magnet rotors	≥ 4	**0.3 ... 1.0**

Example:
From no-load/short-circuit curve (previous slide) we get: $k_K = 0.43$, $x_d = 1/0.43 = 2.32$ p.u.

Permanent magnet materials



Source: R. Fischer, hanser-Verlag

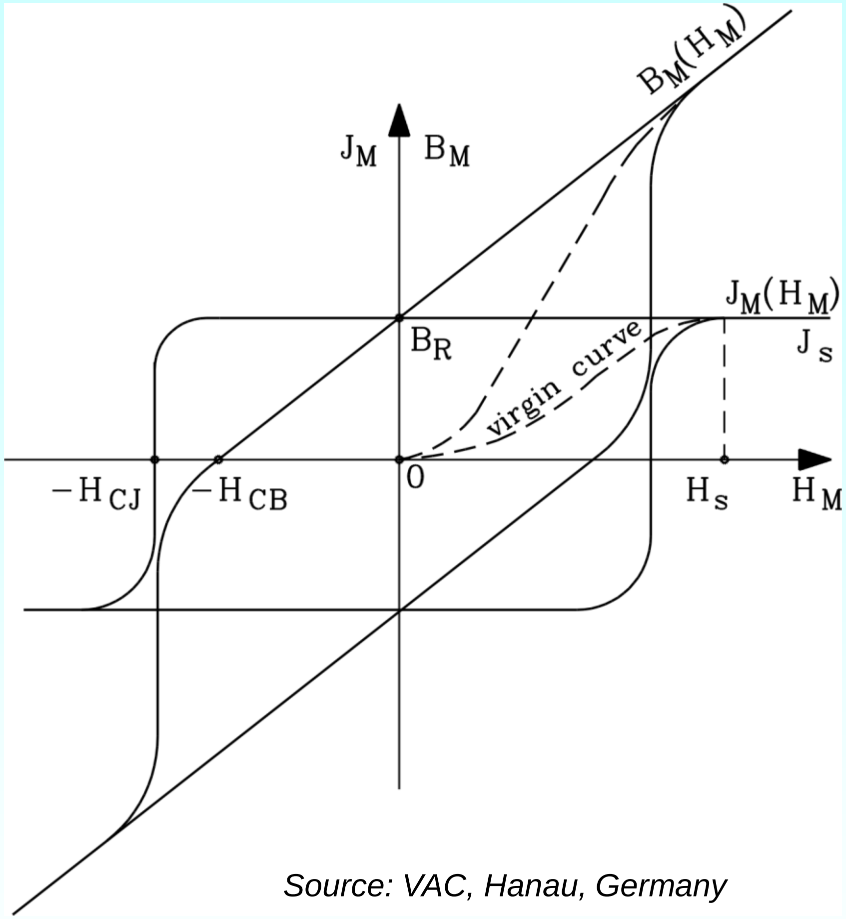
- **B_R: Remanence flux density**
- **$_BH_C$: Coercive field strength of *B(H)*-loop**
- **Material data *B(H)*:** static "hysteresis"-loop (here: at 20°C)

- **Soft magnetic materials (1):** Iron, nickel, cobalt: B_R and $_BH_C$ are small: Application in magnetic AC fields
- **Hard magnetic materials (2):** = Permanent magnet materials: B_R and $_BH_C$ big: Application for generation of magneto-static fields

1. **Aluminium-Nickel-Cobalt-Magnets** (Al-Ni-Co) high B_R, low $_BH_C$, cheap
2. **Ferrite** (e.g.. Barium-Ferrite) rather low B_R, but increased $_BH_C$
3. **Rare-Earth Magnets** Samarium-Cobalt: high B_R & $_BH_c$, small influence of temperature
4. **Rare-Earth Magnets** Neodymium-Iron-Boron: very high B_R & $_BH_C$, decreasing with increasing temperature

- Magnetic point of operation of PM: **in 2. quadrant of *B(H)*-loop**

Rare-earth magnets: Linear *B(H)*-Curve in 2. quadrant



Source: VAC, Hanau, Germany

- Self-field of permanent magnets is called **magnetic polarization J_M**, which adds to the external field H_M, yielding the resulting flux density B_M:

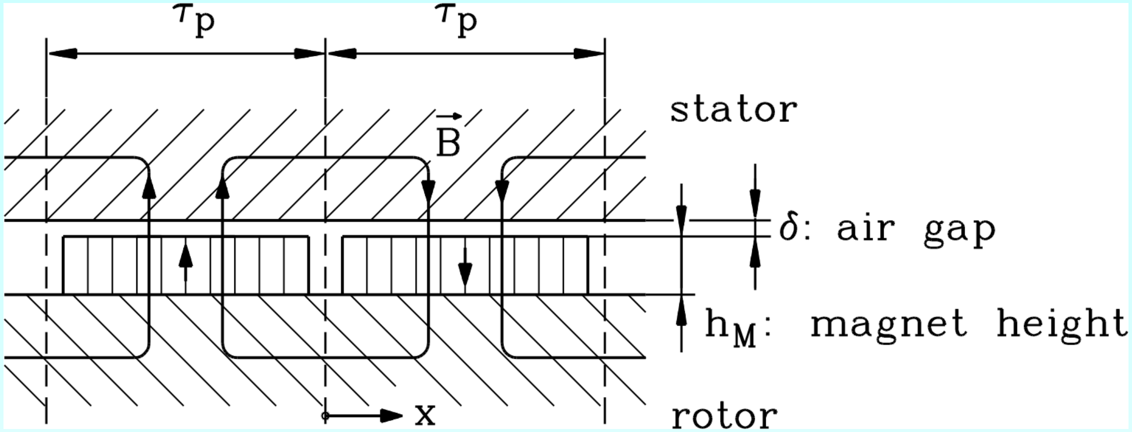
$$\boxed{\vec{B}_M = \mu_0 \vec{H}_M + \vec{J}_M}$$

- Rare-earth magnets are developed for high saturation polarization J_s .
- After turn-off of external field the **remanence flux density** $B_R = J_M(H_M = 0) = J_R$ remains.
- Two **coercive field strengths** H_C defined:
  a) At $-H_{CB}$ the resulting magnetic flux density B_M is zero.
  b) At $-H_{CJ}$ the magnetic polarization J_M within the magnet is zero.

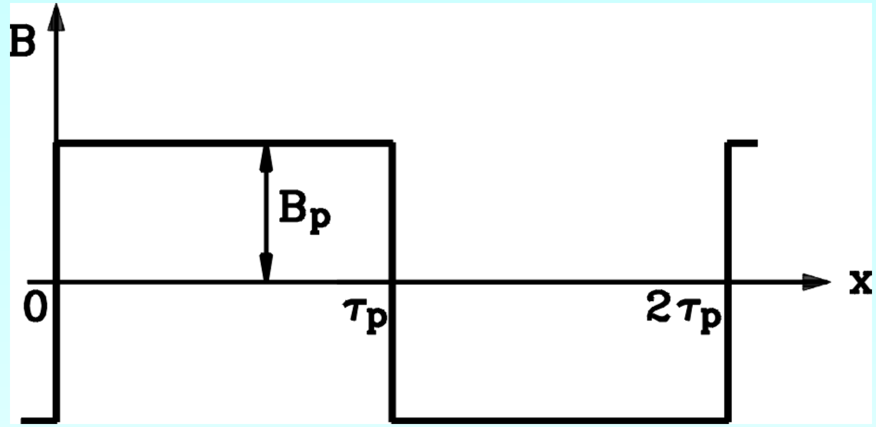
$B_M(H_M)$-loop results from adding the $J_M(H_M)$-loop and the straight line $B_M = \mu_0 H_M$. Hence it is **nearly linear** in the 2nd quadrant **:**

$$\boxed{B_M = B_R + \mu_M H_M , \quad \mu_M = ca.1.05\mu_0}$$

PM synchronous machines: Air gap flux density B_p



PM rotor with surface mounted magnets



Air-gap flux density distribution at no-load (I_s = 0)

- No-load air gap flux-density B_p: Approximation $\mu_M = \mu_0,\ B_M \cong B_R + \mu_0 H_M$ and $\mu_{Fe} \to \infty$.
- *AMPERE´s* law gives: No-load ($I_s = 0$) = electrical *Ampere* turns Θ are zero;

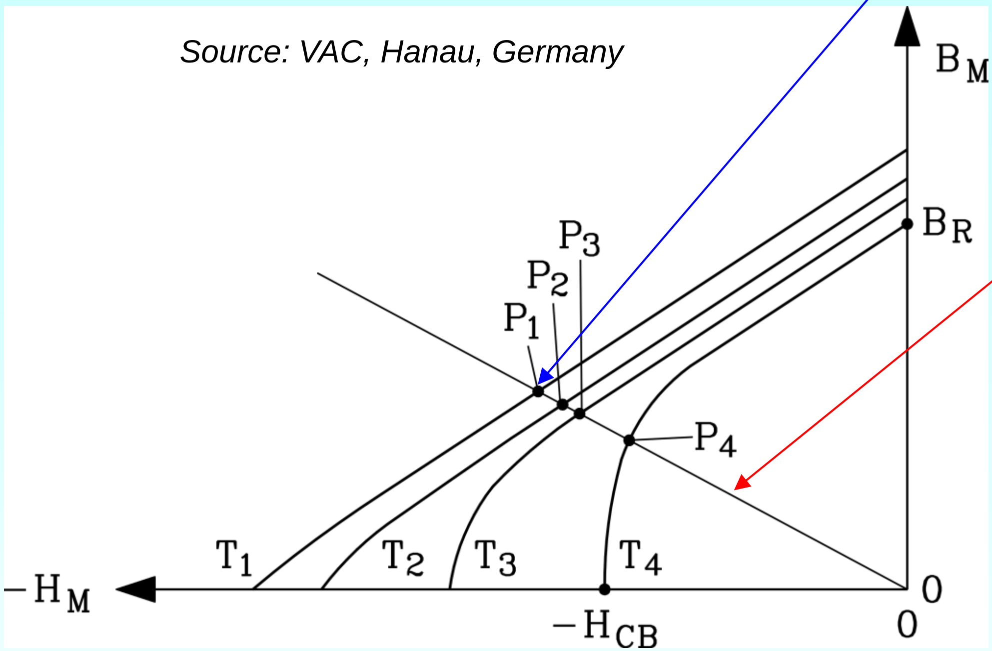
$$2(H_\delta \delta + H_M h_M) = \Theta = 0$$

- Constancy of flux between field lines $\Phi = B_M A_M = B_\delta A_\delta$
- Identical cross section areas $A_M = A_\delta$ in magnets and in air-gap give: $B_M = B_\delta$

$$\boxed{B_p = B_\delta = \mu_0 H_\delta = \underline{\underline{-\mu_0 \frac{h_M}{\delta} H_M}} = B_M}$$

magnetic operational line $B_M(H_M)$

PM synchronous machine: Magnetic point of operation *P*



- **Determination of magnetic point of operation *P*:**
  Intersection of **magnetic line of operation** and of $B_M(H_M)$-loop of PM material:
  Intersection point is *P* !

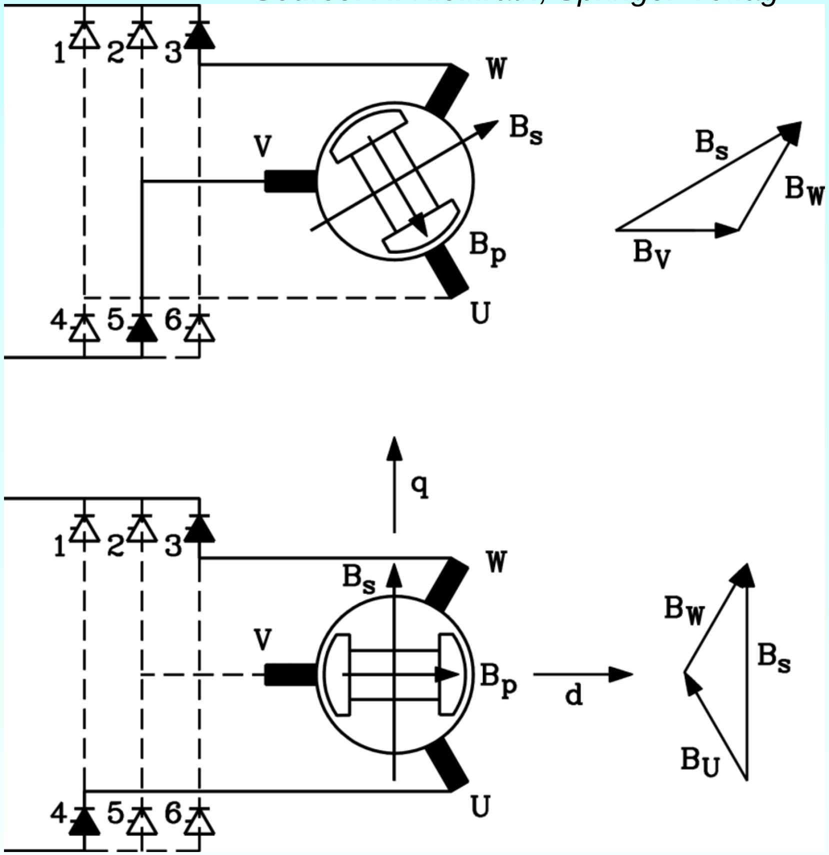
- **Temperature influence *T*:**
  $B_M(H_M)$- loop of material depends on T.
  With increasing temperature the magnetic flux decreases:
  Temperatures $T_1 < T_2 < T_3 < T_4$.

- At rotors with surface mounted permanent magnets the air gap flux density B_p is always **LOWER** than the remanence flux density B_R (the lower, the bigger the ratio "Air gap width / magnet height" is).

- Due to $\mu_M \cong \mu_0$ the stator magnetizing reactance for *d*- and *q*-axis is the same, if iron saturation is neglected: $X_d = X_q$. So, PM-machine with surface mounted magnets **may be regarded as round-rotor machine**.

Inverter operation - rotor position control

Source: H. Kleinrath, Springer-Verlag



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

- Depending on rotor position, the stator winding is fed with three-phase current system so, that stator field has always **a fixed relative position** to rotor field. Measurement of rotor position with e. g. **incremental encoder** or **resolver**. Rotor cannot be pulled out of synchronism, as stator field is always adjusted to rotor position.
- *Often used control method* with PM-drives: Stator current is fed as pure *q*-current:

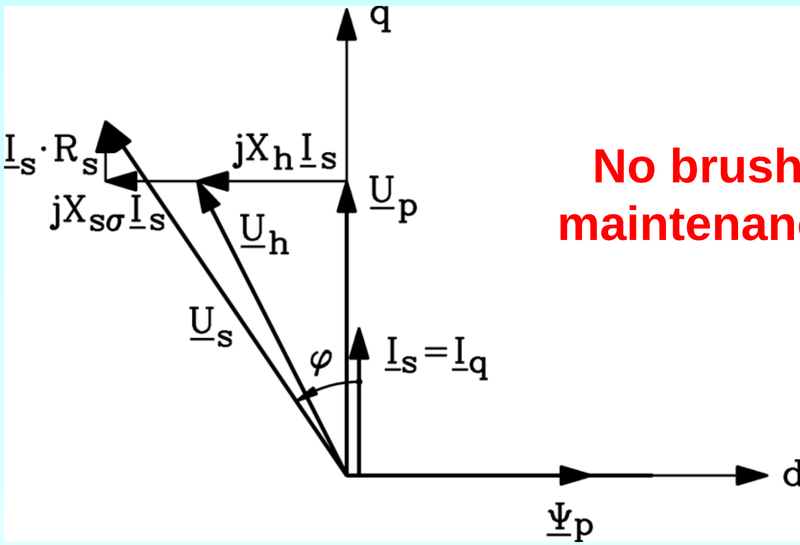
$$I_s = I_{sq}, I_{sd} = 0$$

Result: Stator field axis B_s is perpendicular to rotor field axis B_p.

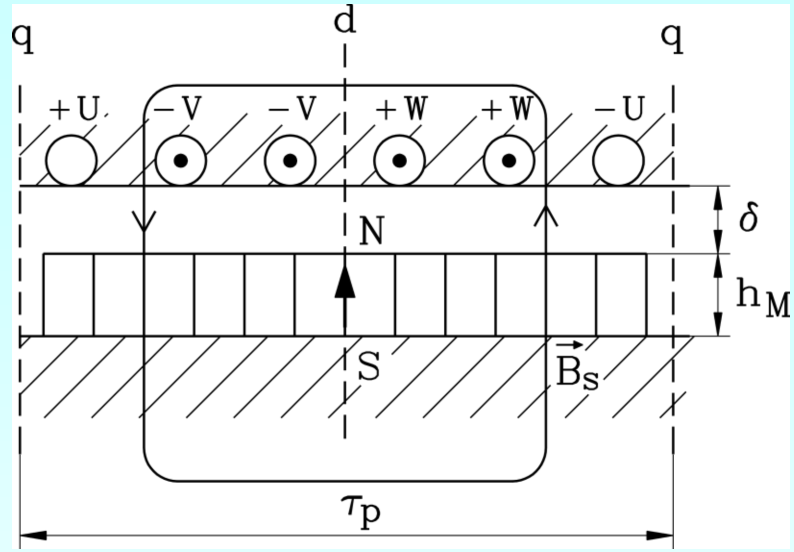
Torque for a given stator current I_s is maximum, because at $L_d = L_q$ only I_{sq} will produce torque with rotor field.

$\boxed{M_e = m_s \cdot U_p \cdot I_{sq} / \Omega_{syn}}$ or with $U_p = \omega_s \Psi_p / \sqrt{2}$: $\boxed{M_e = p \cdot m_s \cdot \Psi_p \cdot I_{sq} / \sqrt{2}}$

PM synchronous machine as "Brushless-DC"-drive



No brushes: Low maintenance costs !



- At $\underline{I}_{sq}$-operation $\underline{I}_s$ and $\underline{U}_p$ are in phase. All current-carrying conductors of same current flow direction are positioned in rotor field of the same polarity. So the *LORENTZ*-forces on all conductors coincide in tangential direction like in DC machines.
- For $R_s \cong 0$ we get from phasor diagram : $U_s = \omega_s \sqrt{L_q^2 I_{sq}^2 + (\Psi_p / \sqrt{2})^2}$

  Control law for inverter (like in induction machines): $\boxed{U_s \sim \omega_s}$

- Torque: $M_e \sim \Phi_p \cdot I_s$ in DC machines similar: $M_e \sim \Phi \cdot I_a$

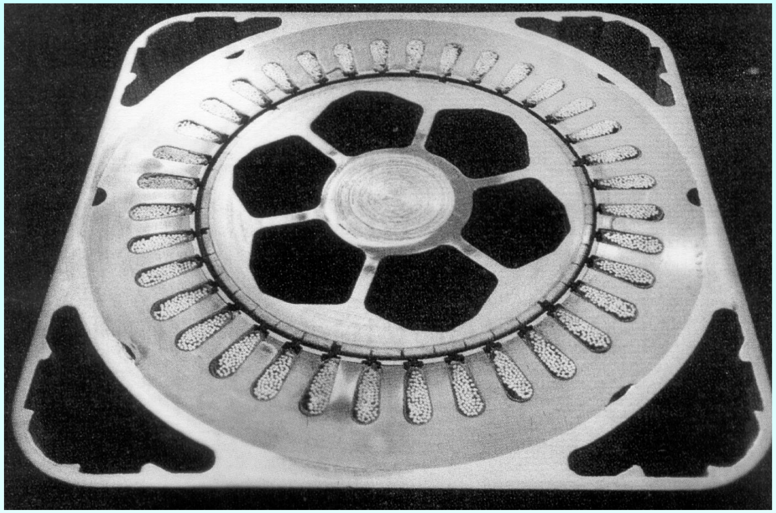
DC machine: *commutator + brushes* *rotor armature winding* *stator main poles*

"brushless DC"-drive: *inverter + encoder* *stator winding* *rotor poles*

Example: "Brushless-DC" robot drive

One-Arm-Robot with PM-Synchronous machines

Source: Kuka, Germany



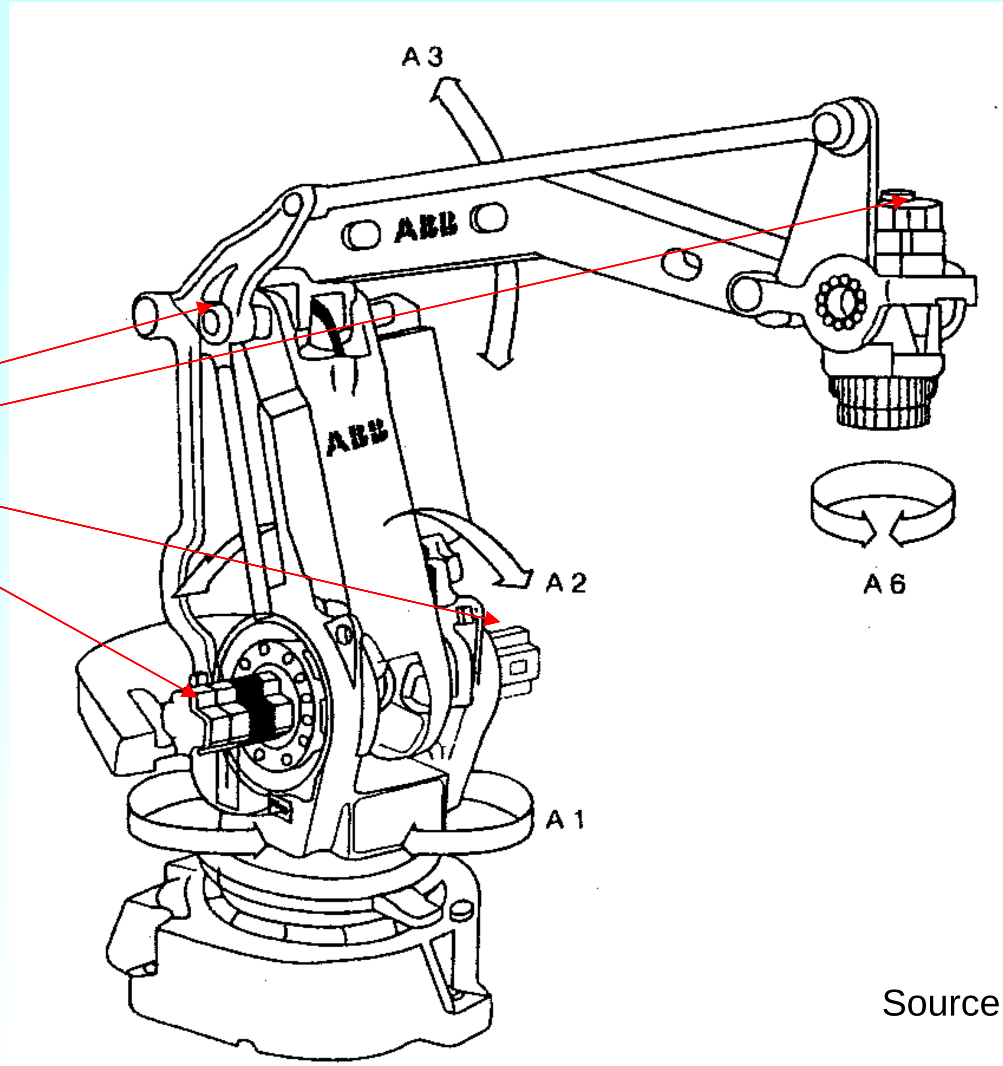
Cut view of 6-pole synchronous PM machine

Source: Siemens AG, Germany

- Each robot axis is moved by an inverter-fed synchronous PM-Motor. The rotor encoder is used also for position measurement of robot axis. So, position control of robot axes is achieved rather simple.
- No excitation losses due to PM: Motors operate without ANY cooling, yielding a very simple and robust drive system.
- For motor speed and torque control the stator current (*q*-axis current) is used, as it is directly proportional to torque, yielding a very simple motor control

Single-arm-robot with “brushless DC” PM synchronous motors

PM-synchronous motors with position control



Source: ABB Sweden

Example: Cylindrical rotor synchronous machine as variable speed rolling-mill drive

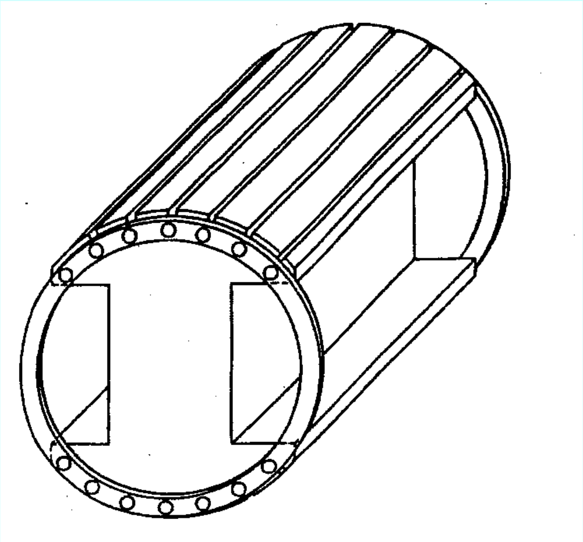
- Synchronous cylindrical rotor machine
- 12 poles, electrically excited
- Rated torque: 1.78 MNm, 0 … 58.5/min
- Rated power: 10.9 MW, 58.5 … 112.5/min
- Operated at $\cos\varphi = 1$
- 2.5-times short time overload:

  Max. torque: 4.3 MNm

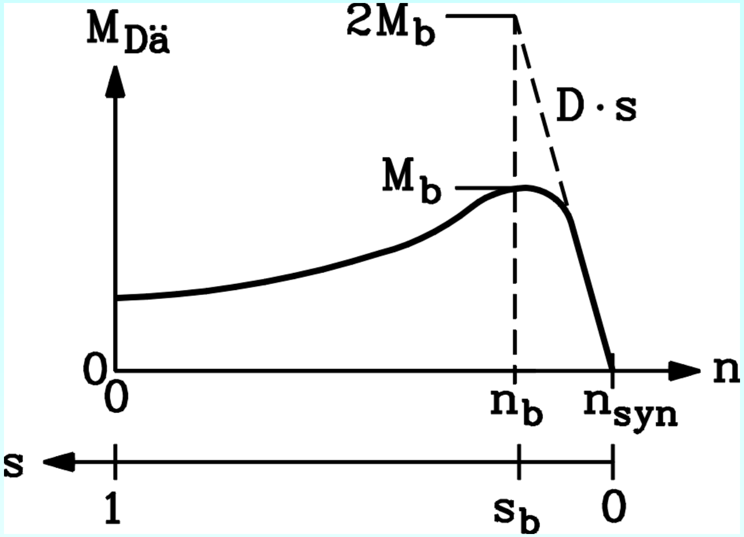
  Max. power: 26.5 MW
- 5.5m-heavy plate rolling-mill drive
- Dillinger Hüttenwerke AG

Source: Siemens AG, Germany

Damper cage in synchronous machines



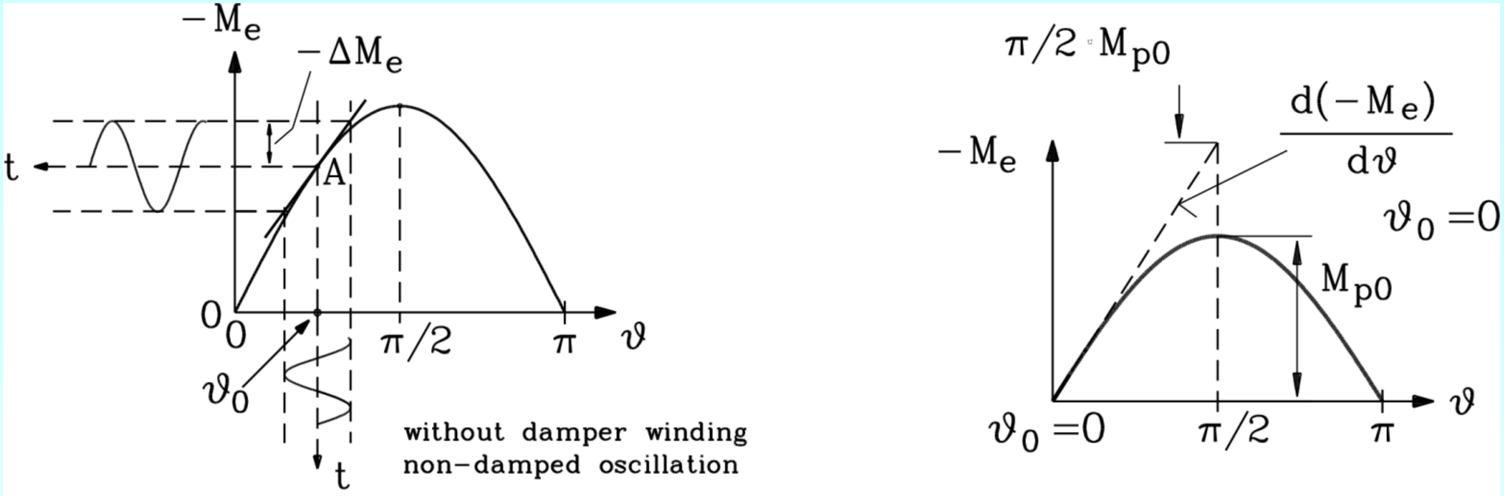
Damper cage of a 2-pole synchronous machine



Asynchronous torque of damper cage (KLOSS)

- Synchronous machines oscillate at each load step, when operating at "rigid" grid. The **damper cage** (= **squirrel cage** in rotor pole shoes) is damping these oscillations of load angle (and of speed) quickly.
- **Function of damper cage:** Speed oscillation leads to rotor slip *s*. ⇒ So stator field induces damper cage. Cage current and stator field give **asynchronous torque** $M_{Dä}$, which tries to accelerate / decelerate rotor to slip zero = it damps the oscillatory movement. The kinetic energy of oscillation is dissipated as heat in the damper cage.
- For asynchronous starting, a BIGGER starting cage is needed due to big cage losses.

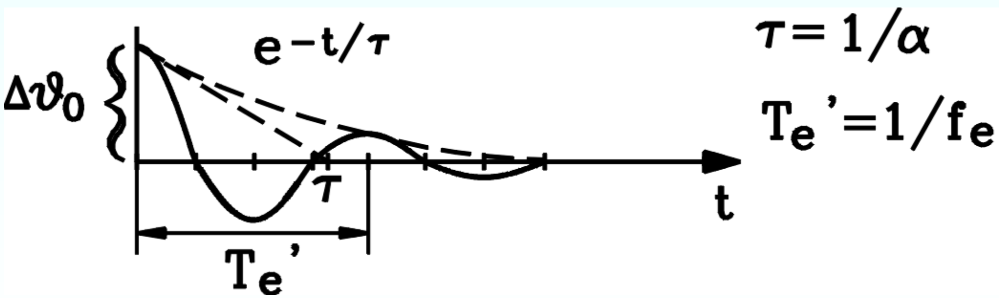
Damping of load angle oscillations



- Without damper cage: undamped oscillations at operation point: *A* (-M_e, ϑ_0):

$$f_e = \frac{1}{2\pi}\sqrt{\frac{p \cdot |c_\vartheta|}{J}}$$

- Damping asynchronous torque (*KLOSS*): (linearized) $M_{D\ddot{a}}(s) \approx \frac{2M_b}{s_b} s = D \cdot s$



$$\boxed{f_e' = \frac{\sqrt{(2\pi f_e)^2 - \alpha^2}}{2\pi}}$$

E.g.: $\tau = 1/\alpha = 1/0.7 = \underline{\underline{1.43 s}}$

$$f_e' = \sqrt{(2\pi \cdot 1.093)^2 - 0.7^2} / (2\pi) = \underline{\underline{1.087 Hz}}$$