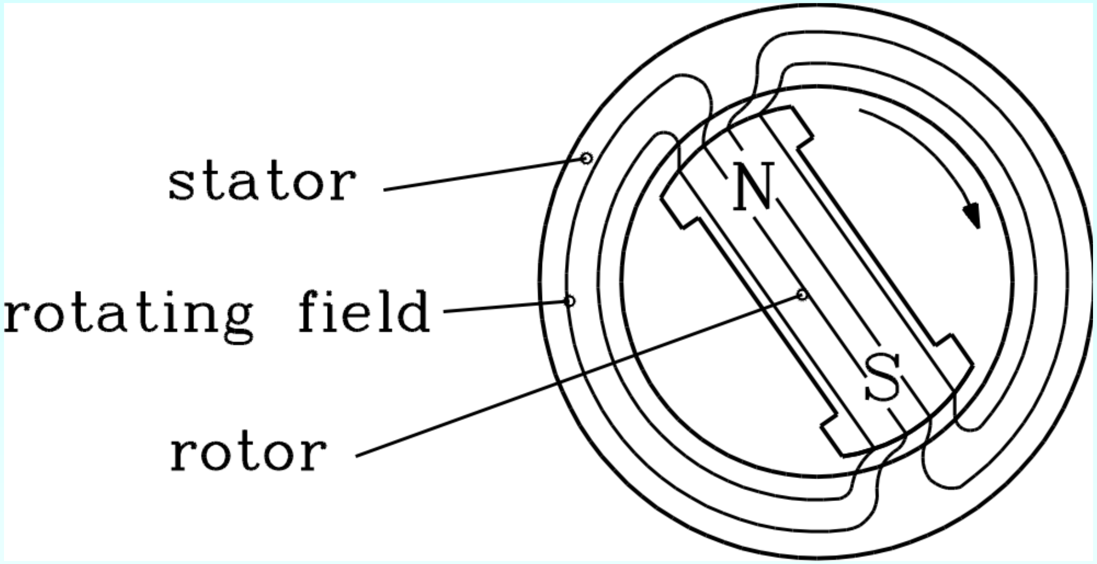
4. Electrically excited synchronous machines

Source:

Siemens AG, Germany

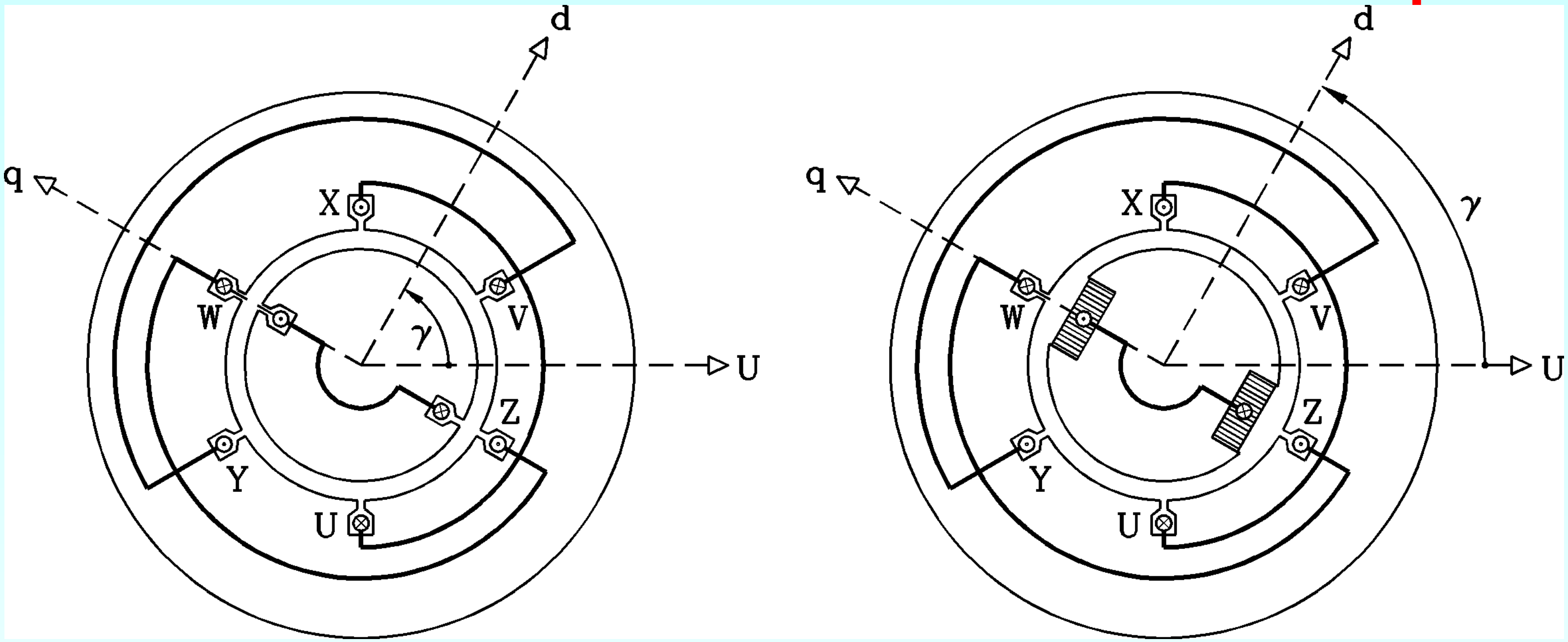
AC Rotating field machines: Basic principle

- AC rotating field machines: Induction machines, synchronous machines
- **Example:** Salient pole rotor synchronous machine: Working principle: 2-pole rotating field



- 3-phase sinus current system (rms I_s) in stator 3-phase winding excites rotating stator field.
- Exciting rotor winding (“**salient poles**”) fed via 2 slip rings with DC current: “**field current I**
  A 2-pole rotor magnetic DC field is excited.
- The 2-pole stator rotating field pulls via magnetic force the rotor **SYNCHRONOUSLY**.
- For calculating the operational performance of **AC rotating field machines** the calculation of the rotating field and its effects (voltage induction, torque generation) is needed. We use *AMPERE*´ s law, *FARADAY*´ s induction law, winding schemes and *FOURIER*-analysis.

Synchronous machine with round rotor and salient pole rotor

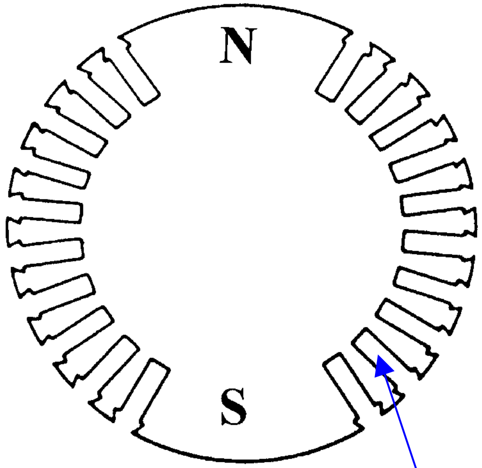


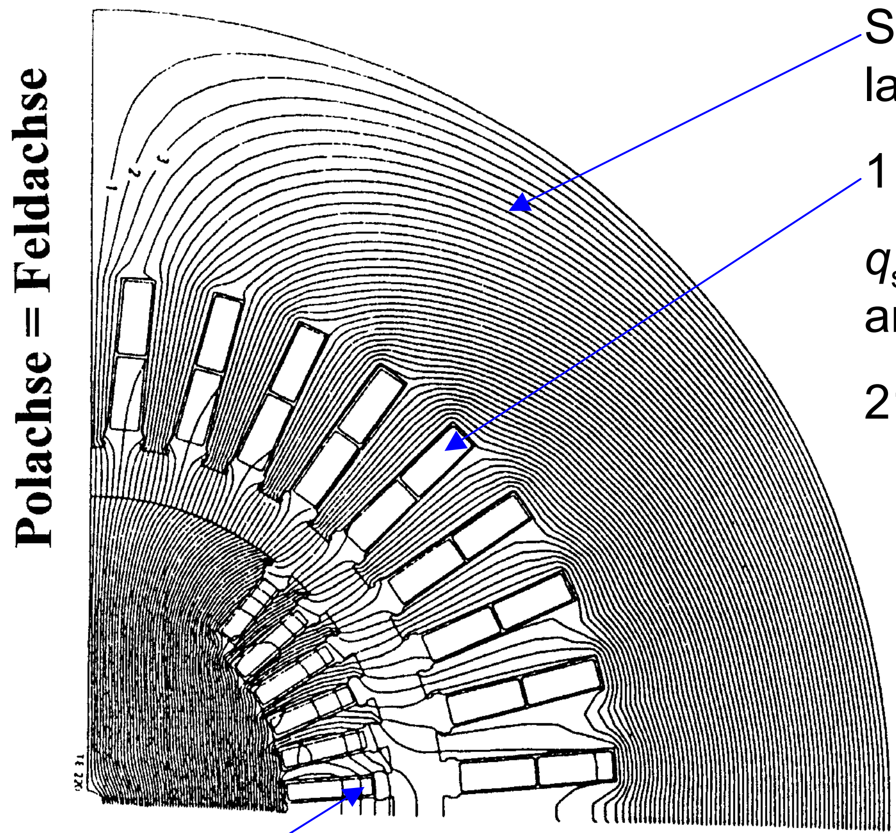
ROUND ROTOR: Field winding distributed in rotor slots; constant air gap

SALIENT POLE ROTOR: concentrated field winding on rotor poles; air gap is minimum at pole centre

- **Synchronous machine:** Rotor field winding excites static magnetic rotor field with DC field current I_f.
- **MOTOR**-operation: Stator 3-phase ac current system I_s excites **stator rotating air gap field.** This field rotates with $n = f_s/p$ and attracts rotor magnetic field, which has same number of poles. So rotor will rotate ***synchronously*** with stator field.
- **GENERATOR**-mode: Rotor is driven mechanically, and induces with rotor field in the stator winding a 3-phase voltage system with frequency $f_s = n \cdot p$. Stator current due to this voltage excites stator field, which rotates **synchronously with rotor.**

Synchronous machine with round rotor: Turbine generator for thermal power plant





Stator: 36 slots, two-layer winding,

1 turn/coil

q_s = 6 slots per pole and phase

21 kV rated voltage

Source:

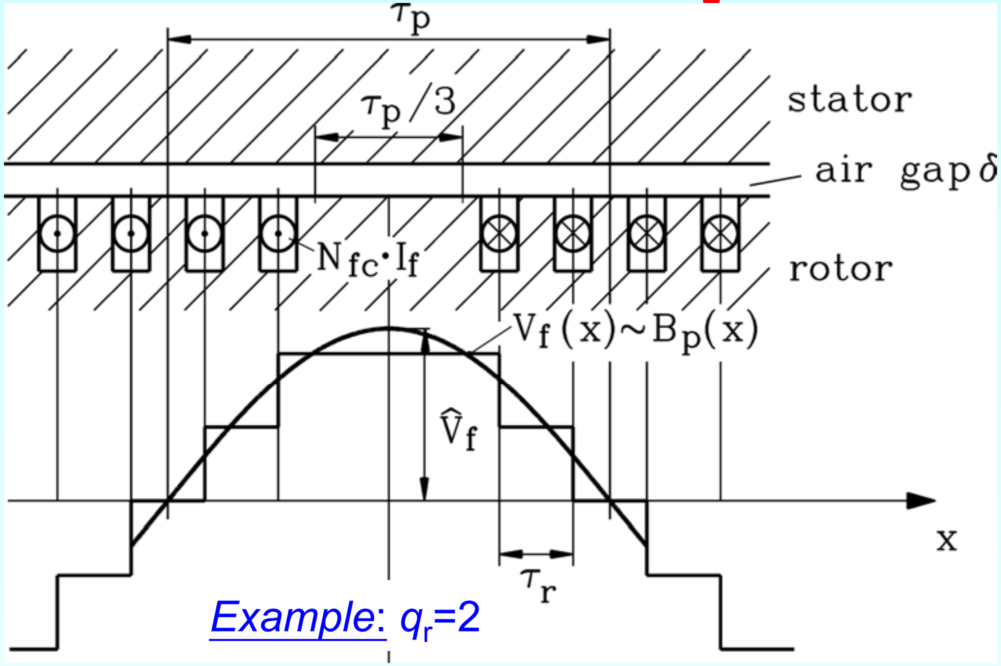
Siemens AG, Germany

Two-pole configuration: Rotor winding in rotor slots;

left: cross section with q_r = 5 rotor coils per pole

right: no-load field plot with q_r = 6 rotor coils per pole, stator current is zero

Rotor air gap field and stator back EMF of round rotor synchronous machine



- **Rotor m.m.f. and air gap field distribution have steps due to slots and contain fundamental** (μ = 1):

$$\hat{V}_f = \frac{2}{\pi} \cdot \frac{N_f}{p} \cdot (k_{p,f} k_{d,f}) \cdot I_f$$

$$\hat{B}_p = \mu_0 \frac{\hat{V}_f}{\delta}, \quad N_f = 2p \cdot q_r \cdot N_{fc}$$

$$k_{p,f} = \sin\left(\frac{W}{\tau_p} \cdot \frac{\pi}{2}\right) = \sin(\pi/3) = \frac{\sqrt{3}}{2}$$

$$k_{d,f} = \frac{\sin(\pi/6)}{q_r \sin(\pi/(6q_r))}, \quad k_{wf} = k_{pf} k_{df}$$

- **Back EMF U_p (synchronously induced stator voltage):** Rotor field fundamental B_p induces **in 3-phase stator winding** at speed n a 3-phase voltage system U_p:

$$U_p = \omega \cdot \Psi_p / \sqrt{2} = \omega \cdot N_s k_{w,s} \cdot \Phi_p / \sqrt{2} = \sqrt{2}\pi f \cdot N_s k_{w,s} \cdot \frac{2}{\pi} l \tau_p \hat{B}_p$$

with **frequency** $f_s = n \cdot p \Rightarrow$ Current I_s will flow in stator winding.

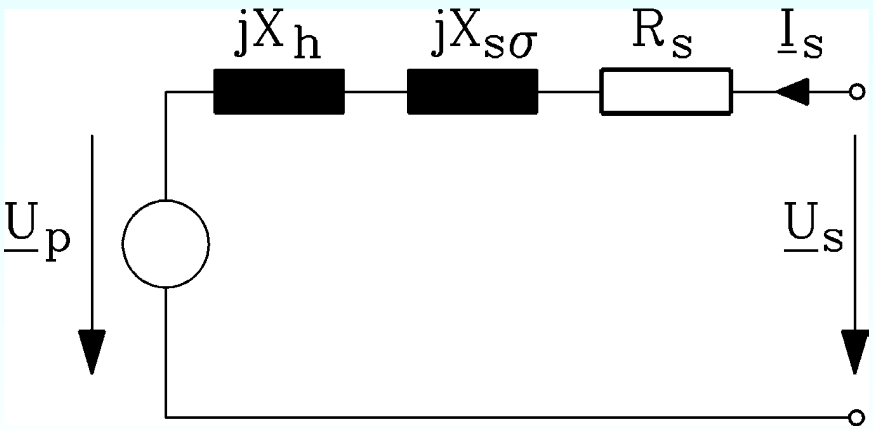
Round rotor synchronous machine: Equivalent circuit

- **Stator winding:** Three phase AC winding like in induction machines with *self-induced voltage* due to stator rotating magnetic field, described by stator air gap field main reactance X_h and stator leakage flux reactance $X_{s\sigma}$. With stator phase resistance R_s we get stator voltage equation per phase:

$$\underline{U}_s = \underline{U}_p + jX_h \underline{I}_s + jX_{s\sigma} \underline{I}_s + R_s \underline{I}_s \qquad \underline{U}_s = \underline{U}_p + jX_d \underline{I}_s + R_s \underline{I}_s$$

"synchronous reactance": $X_d = X_{s\sigma} + X_h$ contains effect of total stator magnetic field !

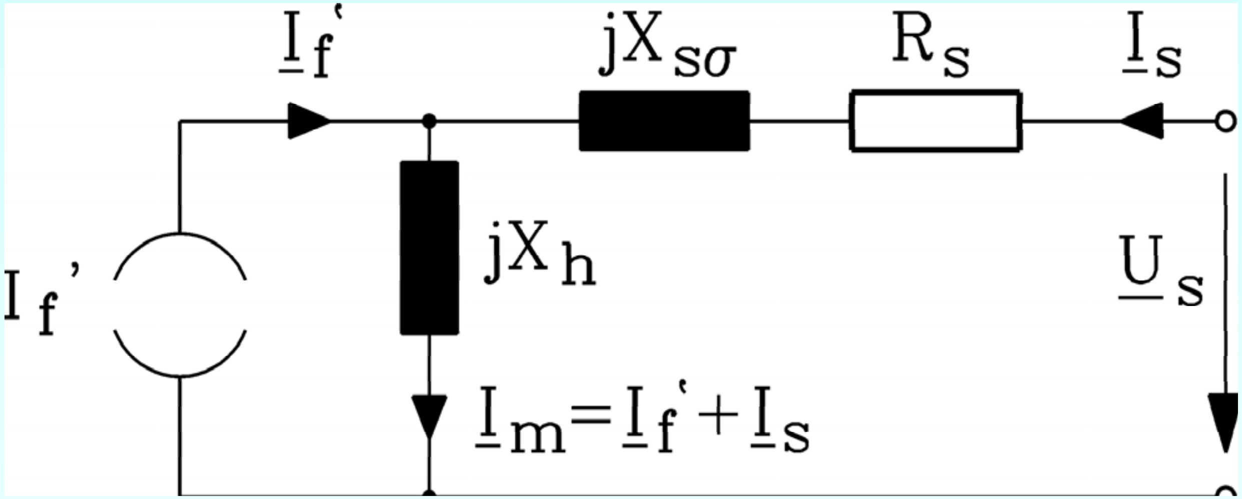
- **Equivalent circuit per stator phase:** for stator voltage equation (ac voltage and current). In rotor winding only DC voltage and current: $U_f = R_f \cdot I_f$



- **Rotor electric circuit:**
U_f: Rotor dc field voltage: (exciter voltage):
U_f impresses via 2 slip rings and carbon brushes a rotor DC current **(field current I_f)** into rotor field winding. Field winding resistance is R_f .

Alternative “current-source” equivalent circuit

$$\underline{U}_s = \underline{U}_p + jX_d \underline{I}_s + R_s \underline{I}_s$$



Current source equivalent circuit, where voltage drop of $\underline{I}'_f$ at jX_h gives $\underline{U}_p$!

$$\underline{U}_p = jX_h \underline{I}'_f$$

Amplitude and phase shift of $\underline{U}_p$ may be described in equivalent circuit by **fictive AC stator current** $\underline{I}'_f$ **!**

Transfer ratio for rotor field current

- **Stator self-induced voltage:** $\underline{U}_{s,s} = jX_h \underline{I}_s$ by stator air-gap field
- **Back EMF $\underline{U}_p$:** Induced by rotor air gap field. It may be changed by field current I_f arbitrarily DURING OPERATION = **" synchronous machine is controlled voltage source".**

a) Amplitude of $\underline{U}_p$ is determined via I_f .

b) Phase shift of $\underline{U}_p$ with respect to stator voltage $\underline{U}_s$ is determined by relative position of rotor north pole axis with respect to stator north pole axis. Rotor pole position is described by **load angle ϑ.**

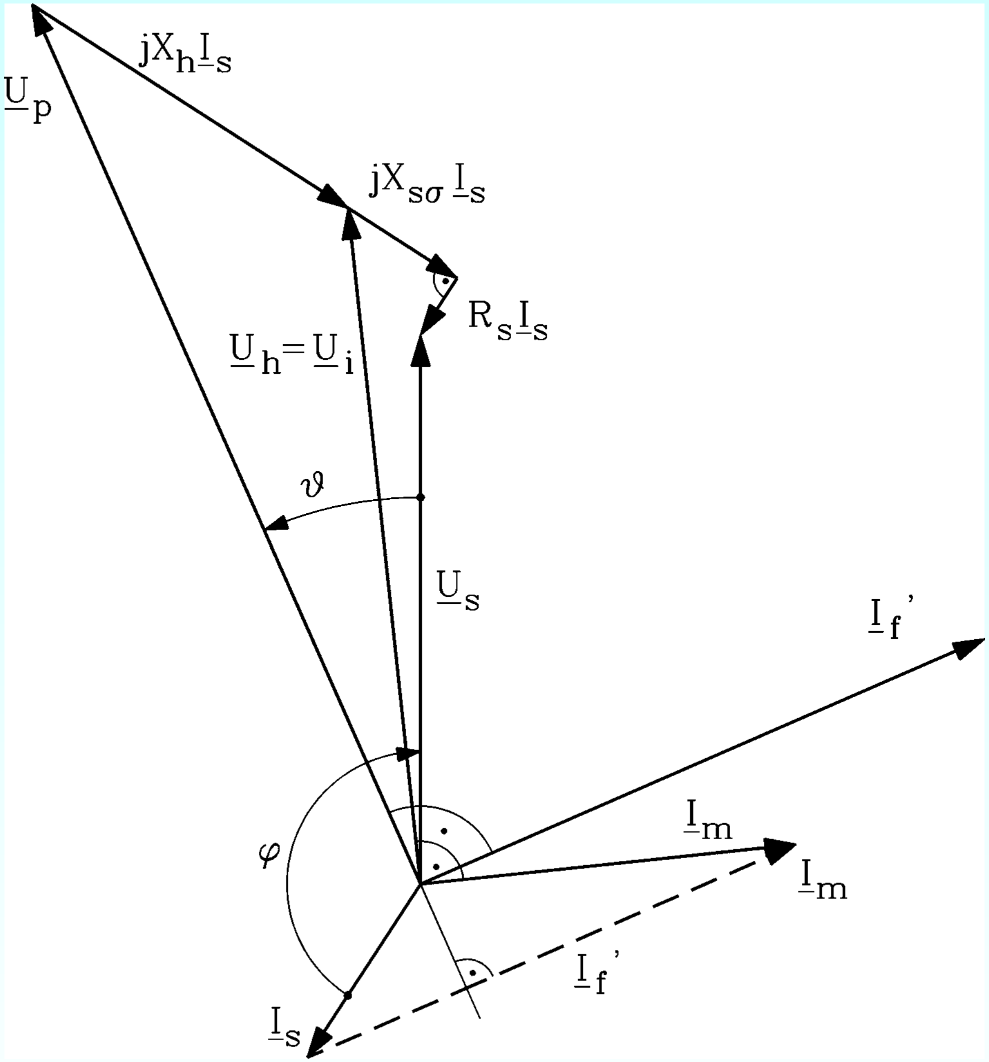
- **Amplitude and phase shift of $\underline{U}_p$:** may be described in equivalent circuit by **fictive AC stator current $\underline{I}'_f$:** $\underline{U}_p = jX_h \underline{I}'_f$
- **This defines transfer ratio of field current $\ddot{u}_{If}$:** $I'_f = \frac{1}{\ddot{u}_{If}} I_f$

$$I'_f = \frac{U_p}{U_{s,s}} I_s = \frac{B_p}{B_{s,\delta}} I_s = \hat{V}_f \cdot \frac{I_s}{\hat{V}_s} : \quad shall\_be \quad \frac{1}{\ddot{u}_{If}} I_f$$

With $\hat{V}_f = \frac{2}{\pi} \cdot \frac{N_f}{p} \cdot k_{wf} \cdot I_f , \quad \hat{V}_s = \frac{\sqrt{2}}{\pi} \cdot \frac{m_s N_s}{p} \cdot k_{ws} \cdot I_s$ we get:

$$\ddot{u}_{If} = \frac{m_s N_s k_{ws} \sqrt{2}}{2 N_f k_{wf}}$$

Phasor diagram of round rotor synchronous machine



- ***Example:*** **Generator, over-excited:**
- **a) electrical active power:**

$$P_e = m_s U_s I_s \cos\varphi$$

Phase angle φ between -90° and -180° : Hence $\cos\varphi$ negative: P_e is negative = power delivered to the grid (GENERATOR).

$P_e < 0$: **Generator**,

$P_e > 0$: **Motor** .

- **b) electrical reactive power:**

$$Q = m_s U_s I_s \sin\varphi$$

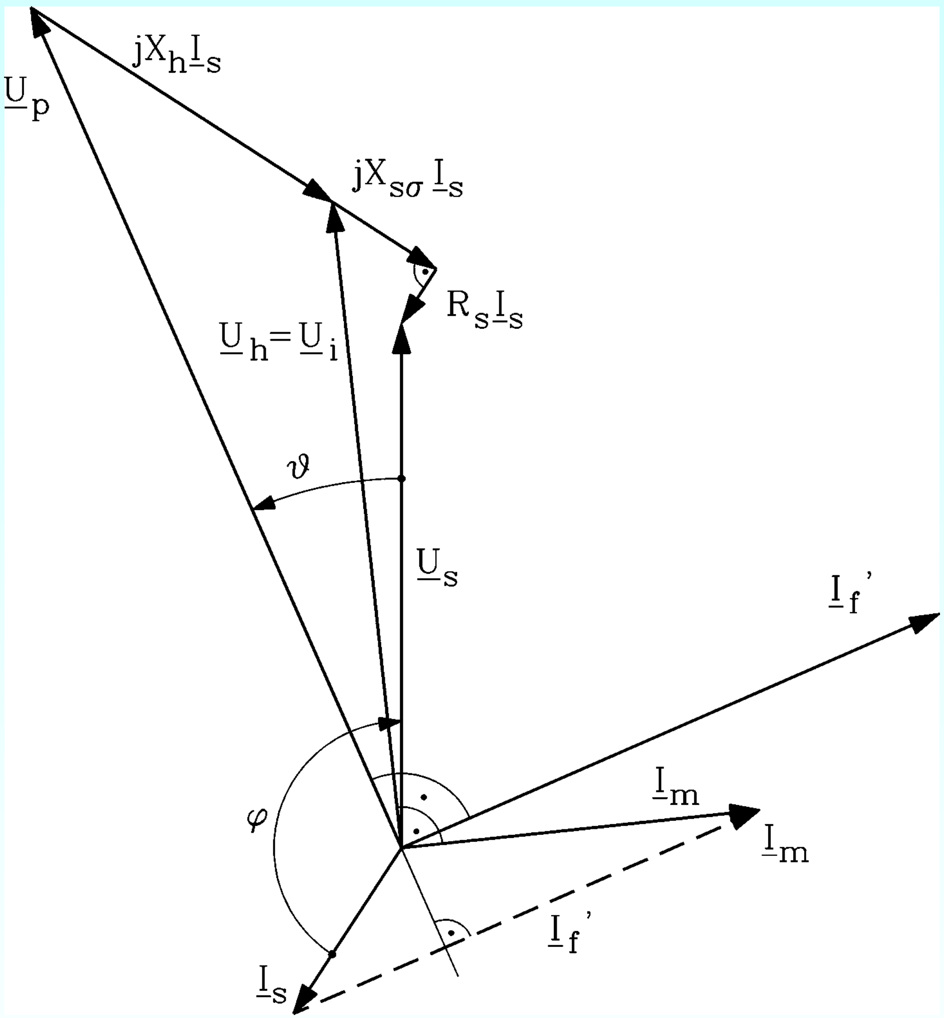
Phase angle φ negative = stator current LEADS ahead stator voltage:

$\sin\varphi$ negative: Q is negative = capacitive reactive power: Machine is **capacitive consumer.**

$Q < 0$: **over-excited,** capacitive consumer.

$Q > 0$: **under-excited**, inductive consumer.

Load angle ϑ, internal voltage U_h, magnetising current I_m



- **Load angle** ϑ between stator phase voltage $\underline{U}_s$ and back EMF phasor $\underline{U}_p$. Counted in mathematical positive sense (counter-clockwise).

- **Internal voltage U_h** is induced in stator winding by resulting air gap field (rotor and stator field):

$$\underline{U}_h = \underline{U}_p + jX_h \underline{I}_s$$

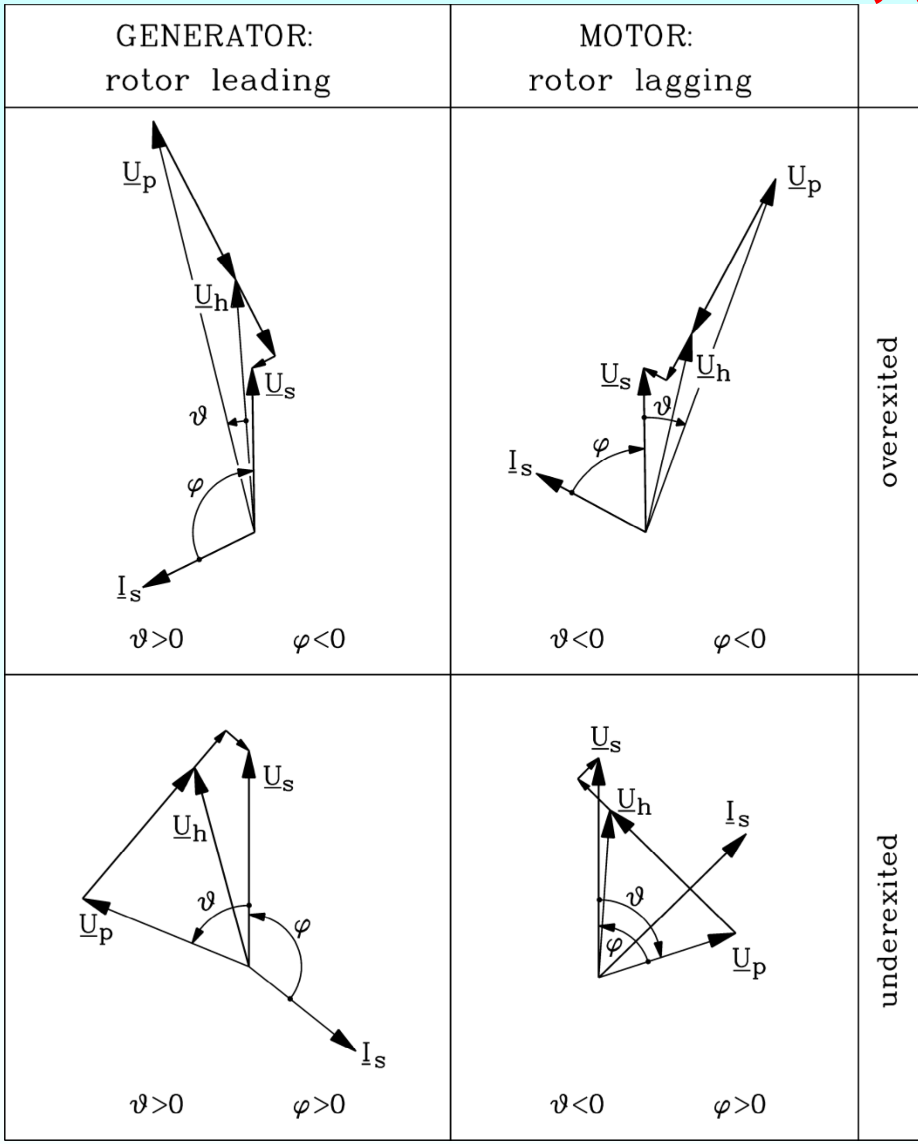
- **Magnetising current I_m:**

Fictitious stator current to excite resulting air gap field (rotor and stator field):

$$\underline{I}_m = \underline{I}'_f + \underline{I}_s$$

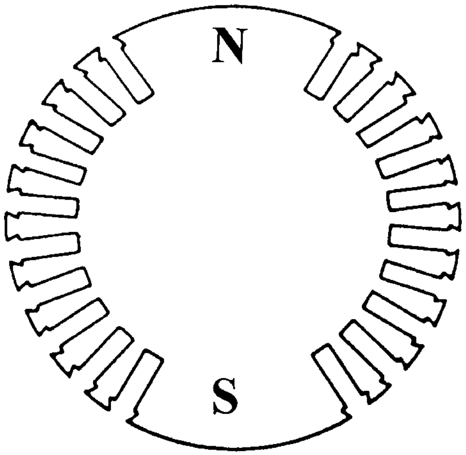
- Voltage triangle $\underline{U}_p, jX_h \underline{I}_s, \underline{U}_h$ and current triangle $\underline{I}'_f, \underline{I}_s, \underline{I}_m$ are of the same shape, but shifted by 90° .

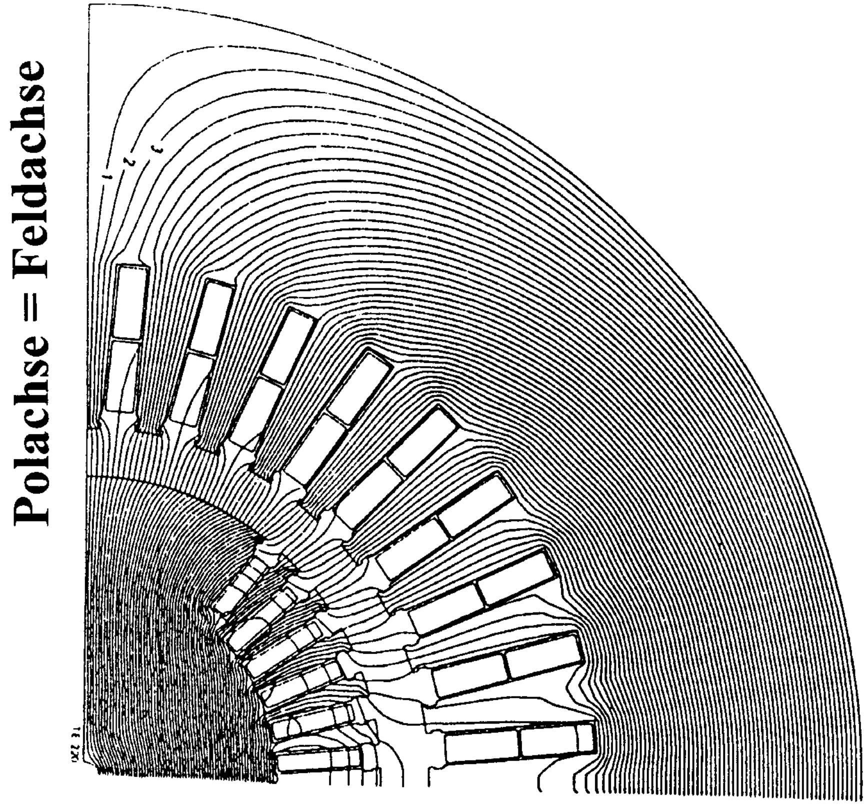
Over-/under-excitation, generator/motor-mode



- **Generator mode: $\vartheta > 0$:** *Rotor LEADS ahead of resulting rotating magnetic field = Phasor $\underline{U}_p$ LEADS ahead of $\underline{U}_h$.*
- **Motor mode: $\vartheta < 0$:** *Rotor LAGS behind resulting magnetic field = Phasor $\underline{U}_p$ LAGS behind $\underline{U}_h$.*
- **Over-excitation: Machine is capacitive consumer:** *Phasor $\underline{U}_p$ is longer than phasor $\underline{U}_h$: big field current I_f is needed.*
- **Under-excitation: Machine is inductive consumer:** *Phasor $\underline{U}_p$ is shorter than phasor $\underline{U}_h$: small field current I_f is needed.*
- ***Facit:***
  Stator- and rotor field rotate always synchronously. Generator- and motor mode are only defined by sign of load angle ϑ.

Round rotor synchronous machine: Magnetic field at no-load





Rotor cross section without field winding:

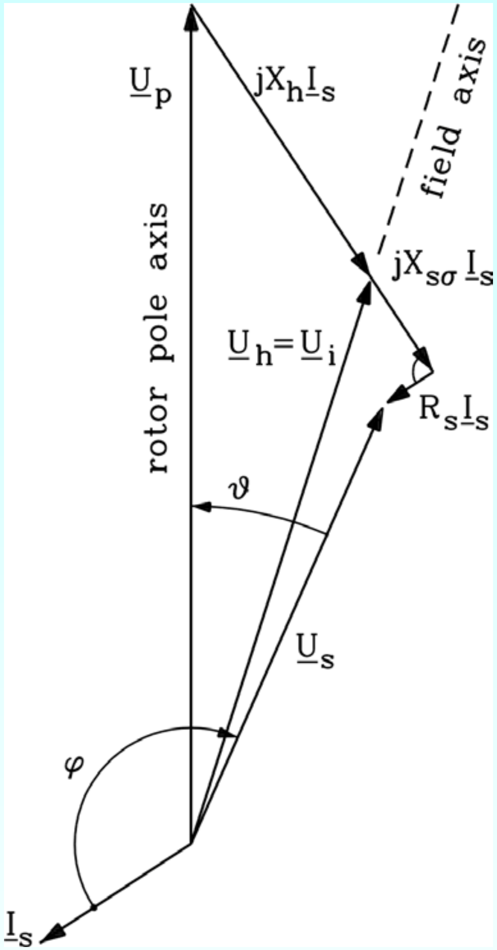
- Slots per pole $2q_r = 10$, 2-pole rotor
- Rotor may be constructed of massive iron, as rotor contains only **static magnetic field !**

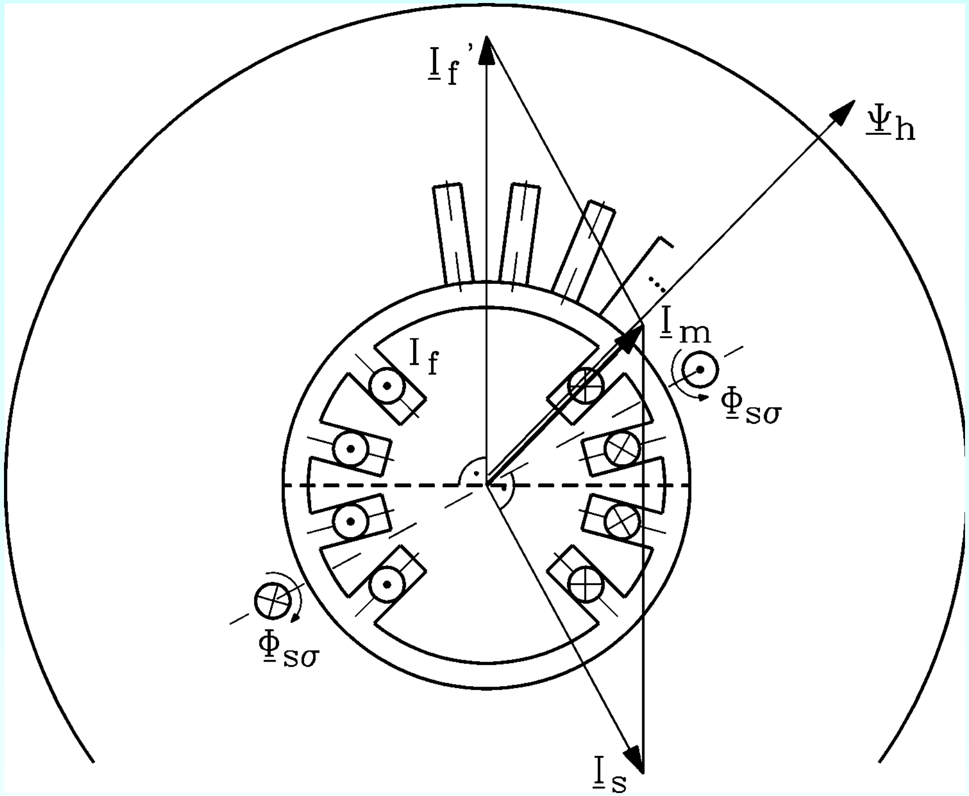
Magnetic field at no-load ($I_s = 0$, $I_f > 0$):

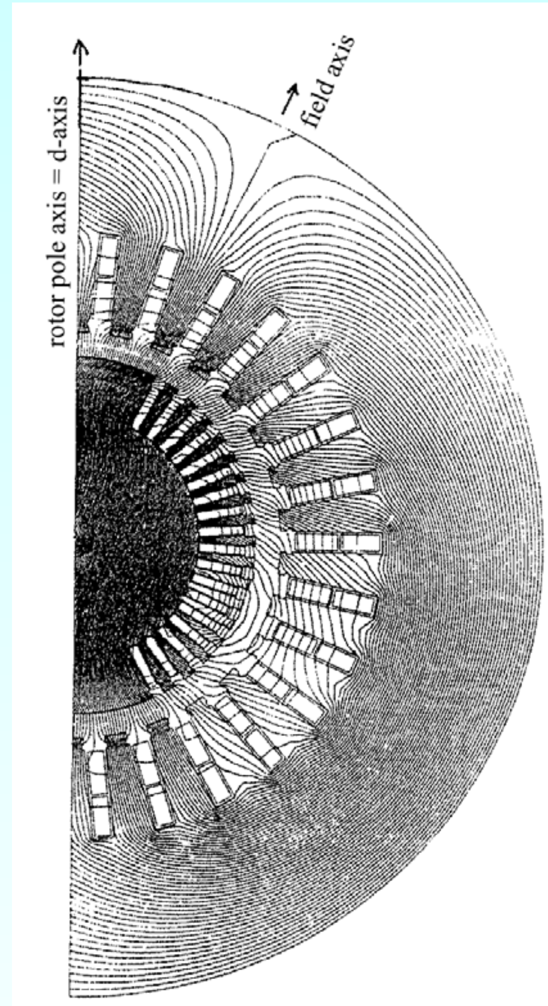
- Field winding excited by I_f
- Stator winding without current **(no-load)**
- Field lines in air gap in radial direction = no tangential magnetic pull = **torque is zero !**

(*Example:* $2p = 2$, $q_s = 6$, $q_r = 6$)

Round rotor synchronous machine: Magnetic field at load







- Magnetic field at load ($I_s > 0$, $I_f > 0$): Rotor pole axis = Direction of $\underline{U}_p$, resulting field axis = Direction of $\underline{U}_h$
- Field lines in air gap have also tangential component = tangential magnetic pull = torque !

Round rotor synchronous machine for 10 poles

Stator housing

stator three-phase winding

stator winding star connected

stator terminals U, V, W and star point N

(short-circuited for protection during assembly)

Field winding

Damper cage

Rotor spider

Source:

Siemens AG, Germany

Round rotor synchronous machine for 4 poles

Stacking of rotor with iron sheets

Rotor slots for field coils

Damper cage

Concentric field coils

Source:

VATech Hydro, Austria

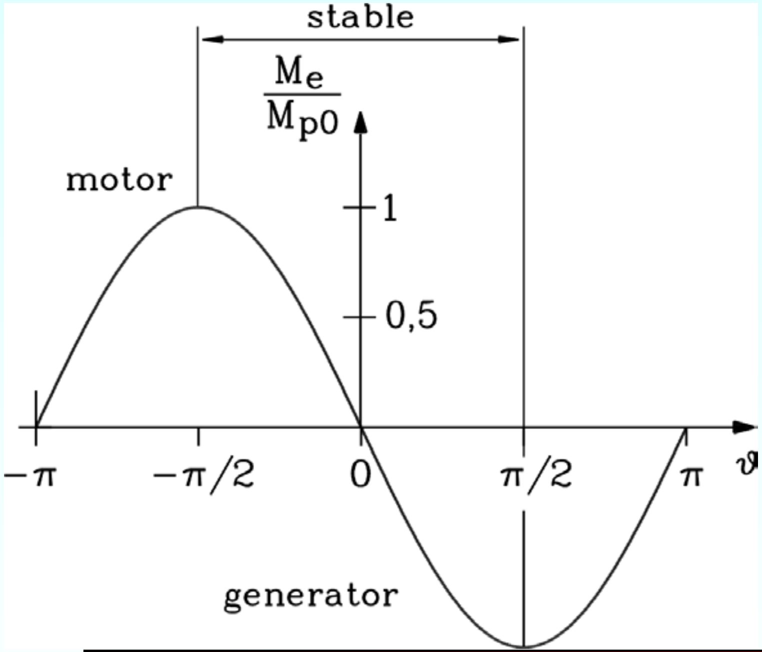
Torque of round rotor synchronous machine at U_s = const. & R_s = 0

- **Machine operates at RIGID grid:** $\underline{U}_s$ = constant = U_s (= phasor put in real axis of complex plane):

$$\underline{U}_p = U_p(\cos\vartheta + j\cdot\sin\vartheta) \text{ and } \underline{I}_s = (U_s - \underline{U}_p)/(jX_d) \Rightarrow \underline{I}_s^* = (U_s - \underline{U}_p^*)/(-jX_d)$$

- **Active power P_e :** $P_e = m_s U_s I_s \cos\varphi = m_s \cdot \mathrm{Re}\{\underline{U}_s \underline{I}_s^*\}$ (*: conjugate complex)

$$P_e = m_s \cdot \mathrm{Re}\left\{U_s \cdot \frac{U_s - U_p(\cos\vartheta - j\cdot\sin\vartheta)}{-jX_d}\right\} = -m_s \frac{U_s U_p}{X_d}\sin\vartheta$$

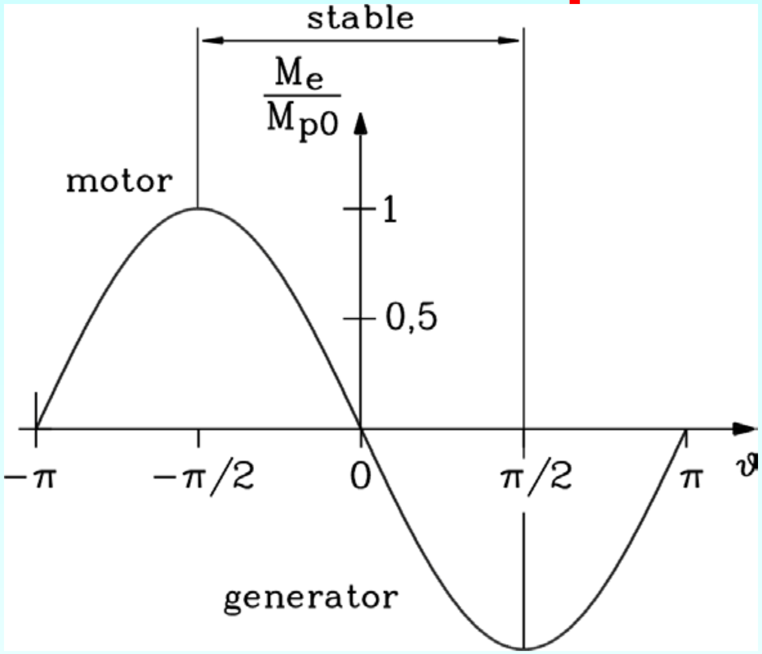


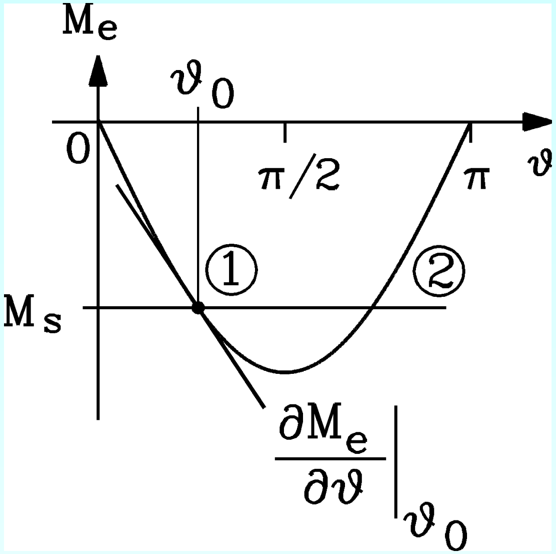
- **Electromagnetic torque:**

$$M_e = \frac{P_m}{\Omega_{syn}} = \frac{P_e}{\Omega_{syn}} = -\frac{m_s}{\Omega_{syn}} \cdot \frac{U_s U_p}{X_d}\sin\vartheta = -M_{p0}\sin\vartheta$$

Note:
All losses neglected ("unity" efficiency).
Negative torque: Generator: M_e is braking
Positive torque: Motor: M_e is driving
Machine speed is always synchronous speed !

Stable points of operation





- ***Example:*** Torque-load angle curve $M(\vartheta)$: in generator mode the mechanical driving shaft torque M_s is determining operation points 1 and 2.
- Operation point 1 is ***stable***, operation point 2 is ***unstable***. The **stability limit** is at load angle $\pi/2$ (generator limit) and $-\pi/2$ (motor limit).

Facit: *Synchronous motor and generator* ***pull-out torque*** $\pm M_{p0}$ *occurs at* ***pull-out load angle*** $\pm\pi/2$. *Rotor is "* ***pulled out****" of synchronism, if load torque exceeds pull-out torque. Result: Pulled-out rotor does not run synchronously with stator magnetic field, which is determined by the grid voltage. The rotor slips ! No active power is converted any longer.*

Stability analysis of operation points

- **Torque-load angle curve** $M_e(\vartheta)$ linearized in operation point ϑ_0: **Tangent** as linearization: $M_e(\vartheta) \cong M_e(\vartheta_0) + \partial M_e / \partial\vartheta \cdot \Delta\vartheta$ with $\Delta\vartheta = \vartheta - \vartheta_0$

$$c_\vartheta(\vartheta_0) = \partial M_e / \partial\vartheta \big|_{\vartheta_0}$$: **Equivalent spring constant** $\Leftrightarrow$ $\Delta M_e = c_\vartheta \cdot \Delta\vartheta$

- **Change of** load angle with time causes **change of speed** $\Delta\Omega_m$:

$$d\Delta\vartheta / dt = p \cdot \Delta\Omega_m \quad \Rightarrow \quad \Omega_m(t) = \Omega_{syn} + \Delta\Omega_m(t)$$

- **NEWTON´ s law of motion:** $J\dfrac{d\Omega_m}{dt} = M_e(\vartheta) - M_s(\vartheta) = c_\vartheta \cdot \Delta\vartheta = J\dfrac{d\Delta\Omega_m}{dt}$ leads to

$$J\frac{d^2\Delta\vartheta}{dt^2} - p \cdot c_\vartheta \cdot \Delta\vartheta = 0$$

a) $|\vartheta| < \pi/2$: $c_\vartheta = -|c_\vartheta|$ <0, b) $|\vartheta| > \pi/2$: $c_\vartheta = |c_\vartheta|$ >0

a) $|\vartheta| < \pi/2$: $\Delta\ddot{\vartheta} + (p \cdot |c_\vartheta| / J) \cdot \Delta\vartheta = 0 \Rightarrow \Delta\ddot{\vartheta} + \omega_e^2 \Delta\vartheta = 0 \Rightarrow \Delta\vartheta(t) \sim \sin(\omega_e t)$

Deviation of load angle from steady state point of operation remains limited: STABLE operation

b) $|\vartheta| > \pi/2$: $\Delta\ddot{\vartheta} - (p \cdot |c_\vartheta| / J) \cdot \Delta\vartheta = 0 \Rightarrow \Delta\ddot{\vartheta} - \omega_e^2 \Delta\vartheta = 0$

$\Rightarrow \Delta\vartheta(t) \sim \sinh(\omega_e t)$ **Deviation of load angle from operation point increases: UNSTABLE**

Torsional oscillations of synchronous machine

- **Deviation of load angle in stable point of operation due to disturbance:**

$$|\vartheta| < \pi/2: \quad \Delta\ddot{\vartheta} + (p\cdot|c_\vartheta|/J)\cdot\Delta\vartheta = 0 \Rightarrow \boxed{\Delta\ddot{\vartheta} + \omega_e^2\Delta\vartheta = 0} \Rightarrow \Delta\vartheta(t) \sim \sin(\omega_e t)$$

leads to differential equation **with oscillation as solution.** Rotor oscillates around steady state point of operation ϑ_0, which is defined by the stator field, that is generated by the "rigid" grid. **Natural frequency of oscillation (eigen-frequency):**

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

***Facit:* The synchronous machine is performing like a (non-linear) torsional spring.**

Example: Operation at no-load ($M_e = 0$, $\vartheta_0 = 0$): $\boxed{|c_\vartheta| = |-M_{p0}\cdot\cos(0)| = M_{p0}}$

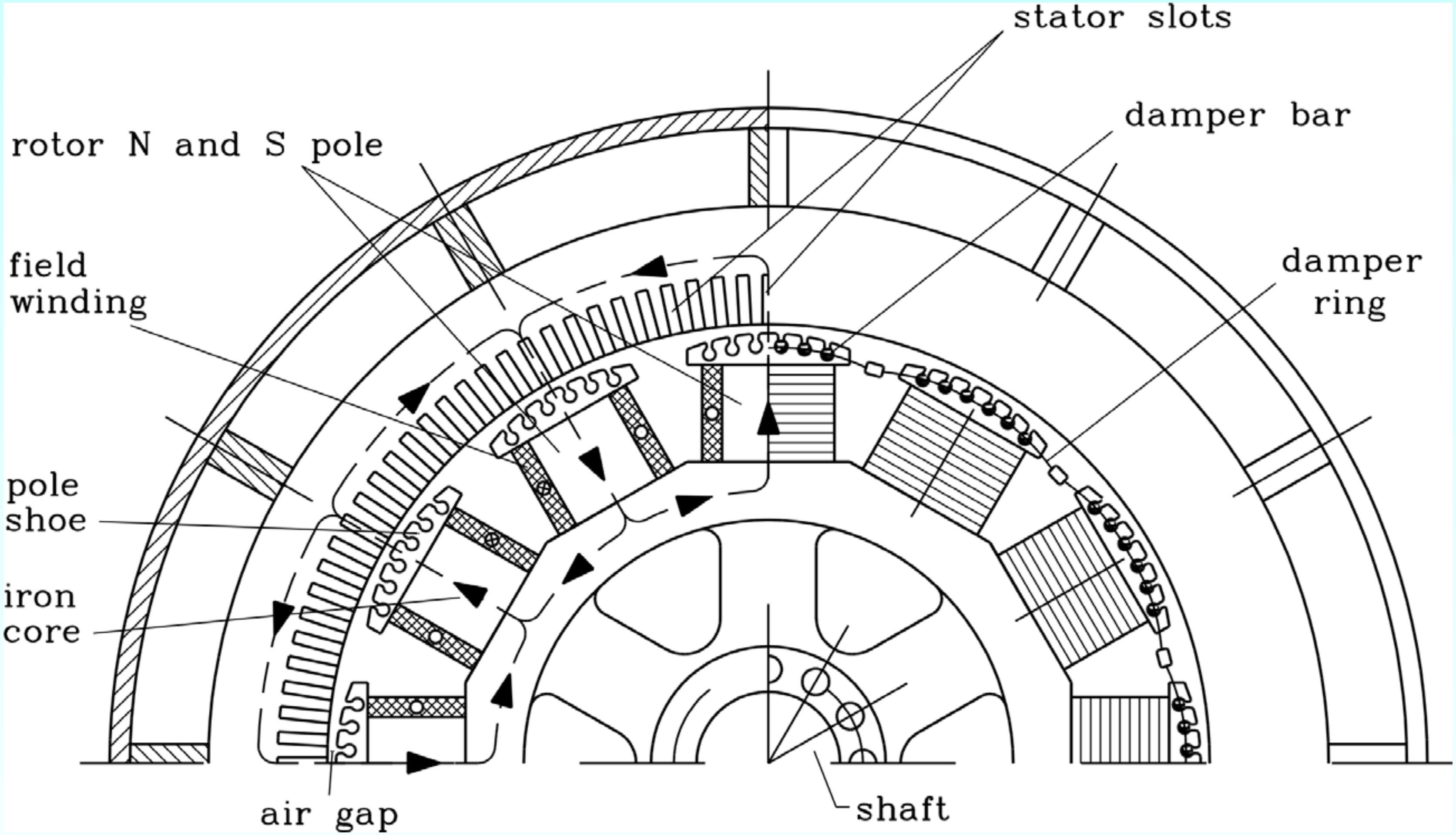
With $p\Omega_{syn} = \omega_N$ and rated acceleration time $T_J = \frac{J\cdot\Omega_{syn}}{M_N}$ we get: $f_e = \frac{1}{2\pi}\sqrt{\frac{\omega_N}{T_J}\cdot\frac{M_{p0}}{M_N}}$

Synchronous motor driving a fan blower for a wind tunnel:

$P_N = 50$ MW, $f_N = 50$ Hz, $T_J = 10$ s, $M_{p0}/M_N = 1.5$,

$$f_e = \frac{1}{2\pi}\sqrt{\frac{2\pi 50}{10}\cdot 1.5} = \underline{\underline{1.09\,Hz}}$$

Synchronous machine with salient pole rotor



12 pole configuration, for direct grid operation, damper cage to extinguish load angle oscillations

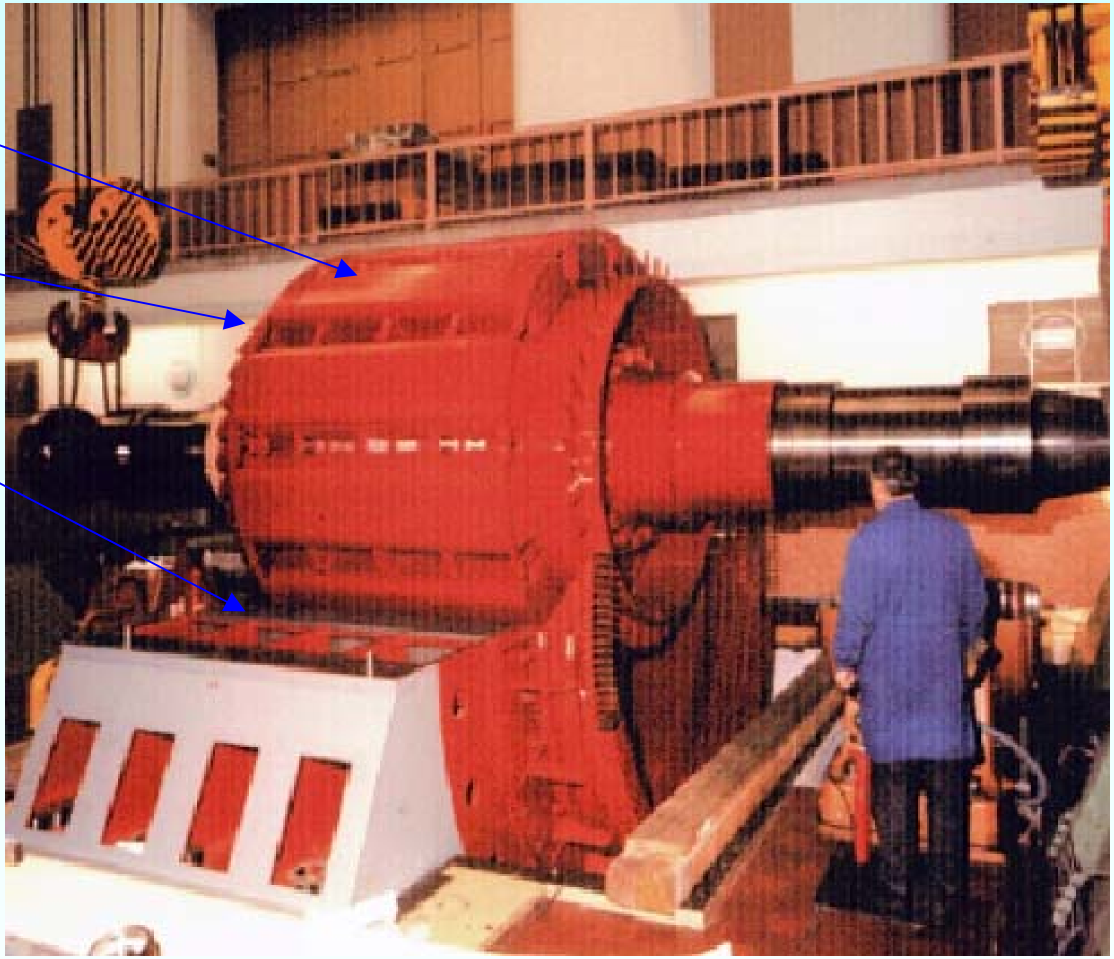
Salient eight pole rotor of pump storage power plant *Kaprun/Austria* during inserting

Rotor pole

damper ring

lower stator half

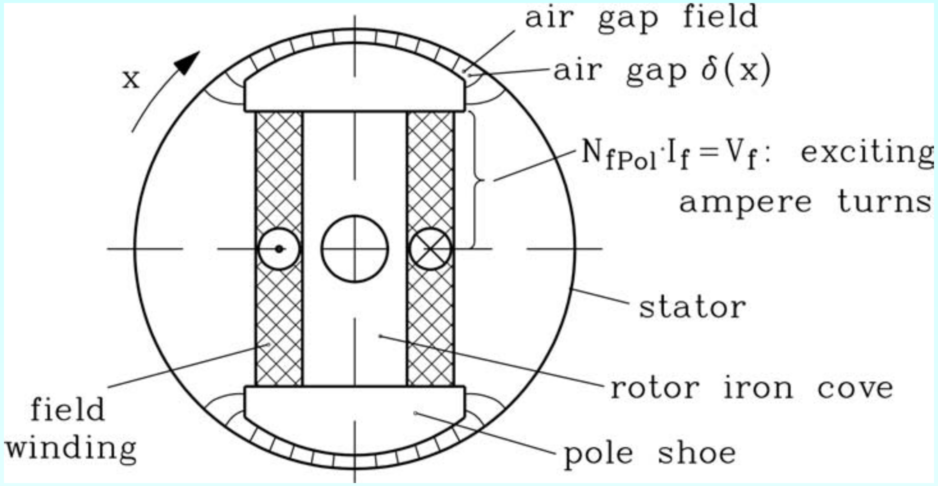
(upper stator half mounted afterwards, needs completion of stator winding on site)

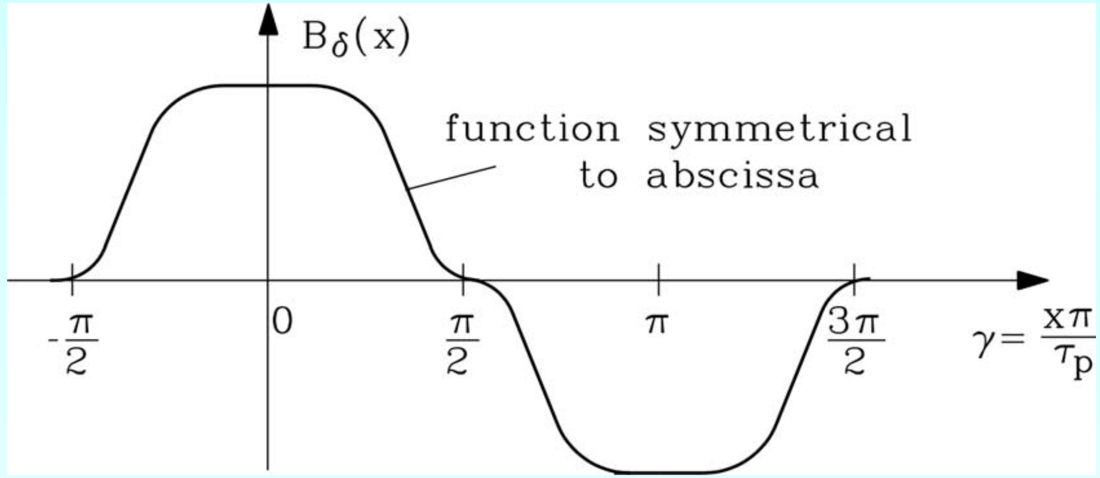


Source:

VATech Hydro, Austria

Rotor field and back EMF of salient pole synchronous machine





- **Bell shaped rotor air gap field curve $B_\delta(x)$:** A constant m.m.f. V_f excites with a variable air gap $\delta(x)$ a bell shaped field curve. Fundamental of this "bell-shape" ($\mu = 1$):

$$B_\delta(x) = \mu_0 \frac{V_f}{\delta(x)} \quad \rightarrow \quad \text{FOURIER-fundamental wave: Amplitude } \hat{B}_p \text{ proportional to } I_f$$

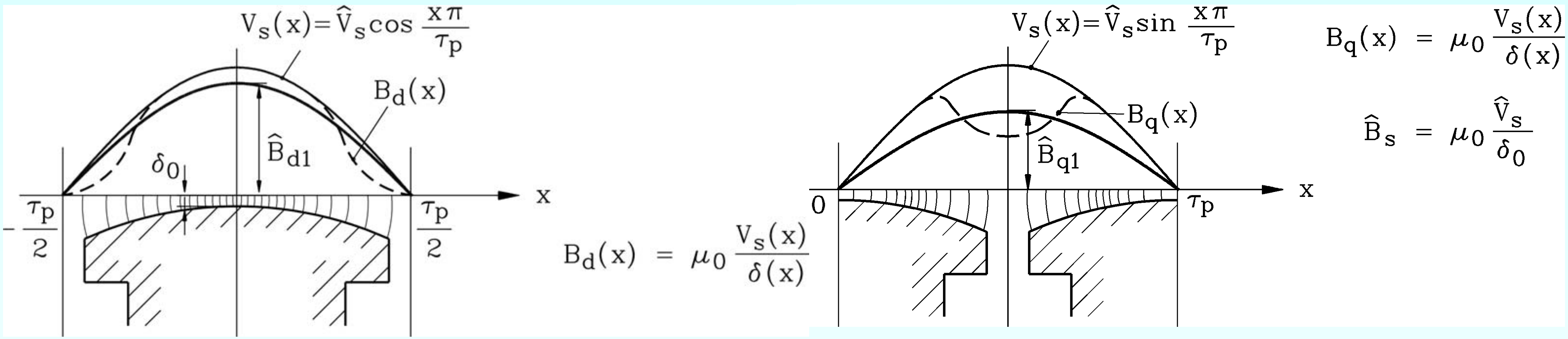
- **Back EMF U_p:** Sinusoidal rotor field fundamental wave B_p induces **in three-phase stator winding** at speed n a three-phase voltage system U_p

$$U_p = \omega \cdot \Psi_p / \sqrt{2} = \omega \cdot N_s k_{w,s} \cdot \Phi_p / \sqrt{2} = \sqrt{2}\pi f \cdot N_s k_{w,s} \cdot \frac{2}{\pi} l \tau_p \hat{B}_p$$

with **frequency** $f = n \cdot p \Rightarrow$ Stator current I_s is flowing in stator winding.

Salient pole synchronous machine: Magnetizing inductance L_h

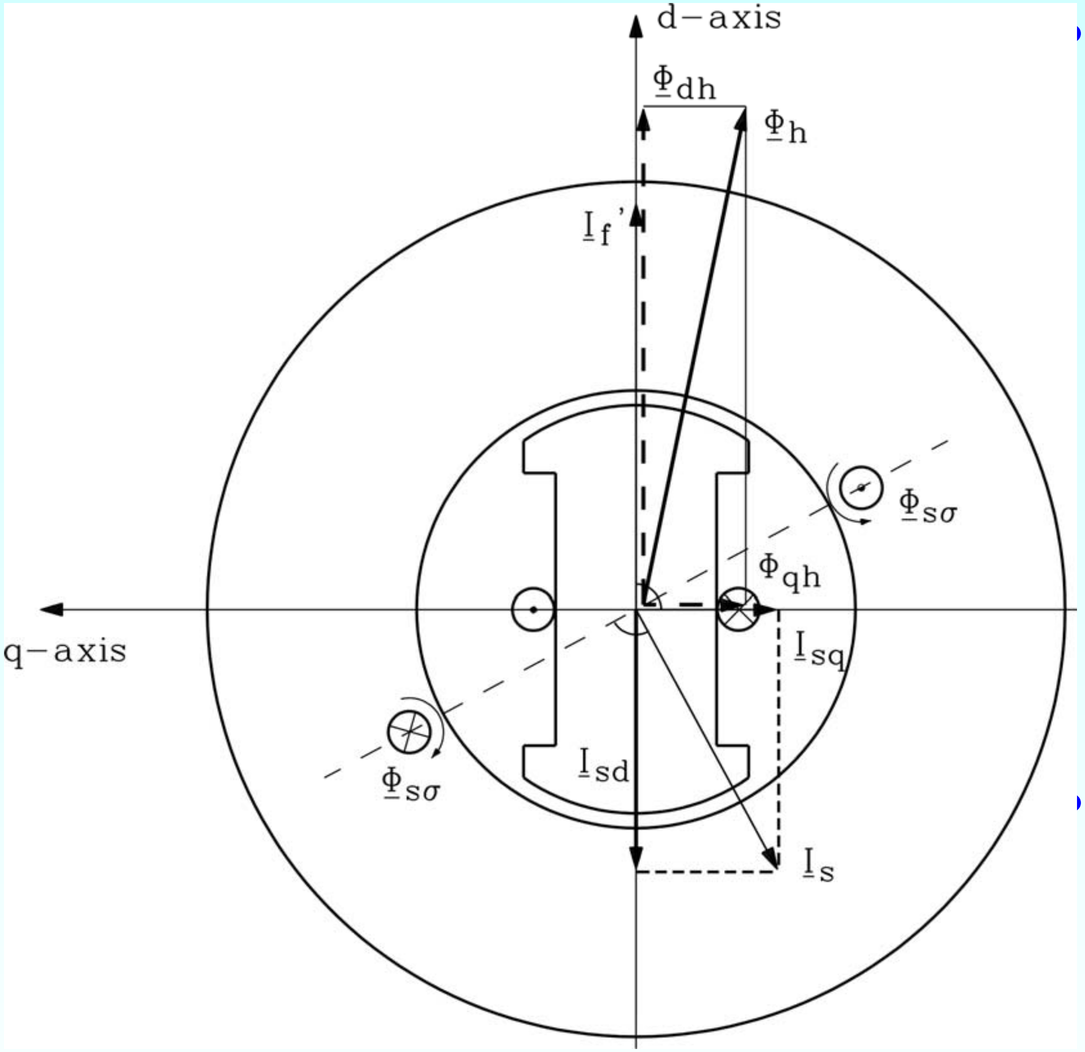
- **Stator winding** is three-phase winding like in induction machines, BUT the air gap is **LARGER in neutral zone (inter-pole gap of *q*-axis)** than in **pole axis (*d*-axis)**. Hence for equal m.m.f. V_s (sinus fundamental $\nu = 1$) the corresponding air gap field is **SMALLER** in *q*-axis than in *d*-axis and NOT SINUSOIDAL.



- **Stator field in *d*-axis (direct axis):** Fundamental of field a little bit smaller than for constant air gap δ_0: $c_d = \hat{B}_{d1} / \hat{B}_s < 1$ **ca. 0.95, thus:** $L_{dh} = c_d \cdot L_h$

- **Stator field in *q*-axis (quadrature axis):** Fundamental of field significantly smaller than at constant air gap δ_0: $c_q = \hat{B}_{q1} / \hat{B}_s << 1$ **ca. 0.4 ... 0.5, thus** $L_{qh} = c_q \cdot L_h$

Stator current I_s: *d*- and *q*-component



- **Stator current phasor** $\underline{I}_s$ decomposed into *d*- and *q*-component:

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

$\underline{I}_{sd}$ is in phase or opposite phase with fictitious current $\underline{I}'_f$. So it excites a stator air gap field in *d*-axis (in rotor pole axis), which together with rotor field gives d-axis air gap flux Φ_{dh}.

$\underline{I}_{sq}$ is phase-shifted by 90° to $\underline{I}_{sd}$ and excites therefore a stator air gap field in *q*-axis (inter-pole gap). The corresponding air gap flux is Φ_{qh}.

- **Stator self-induced voltage** consists of two, by 90° phase shifted components:

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

and of self-induced voltage of stator leakage flux: $j\omega_s L_{s\sigma} \underline{I}_s$

Stator voltage equation of salient pole synchronous machine

- **Stator voltage equation per phase:** Considering self-induction of main and leakage flux L_{dh}, L_{qh}, $L_{s\sigma}$ and of rotor phase resistance R_s we get :

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

or

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

- X_d: **"synchronous d-axis reactance"**: $X_d = X_{s\sigma} + X_{dh} = \omega_s L_{s\sigma} + \omega_s L_{dh}$

  X_q: **"synchronous q-axis reactance"**: $X_q = X_{s\sigma} + X_{qh} = \omega_s L_{s\sigma} + \omega_s L_{qh}$

- **Typical values**: Due to inter-pole gap it is $X_d > X_q$ (typically: $X_q = (0.5 ... 0.6) \cdot X_d$) e.g. salient pole hdro-generators, diesel engine generators, reluctance machines, ...

- *Note:* **Round rotor synchronous machine** may be regarded as " special case" of salient pole machine for $X_d = X_q$.

  The slot openings of rotor field winding in round rotor machines may also be regarded as non-constant air gap, yielding also $X_d > X_q$ (typically: $X_q = (0.8 ... 0.9) \cdot X_d$)

Torque of salient pole machine at U_s= const. & R_s=0

- **OPERATION at " rigid" grid:** $\underline{U}_s$ = constant

  We choose: *d*-axis = Re-axis, *q*-axis = Im-axis of complex plane:

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

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

- **Active power P_e :**

$$P_e = m_s U_s I_s \cos\varphi = m_s \cdot \mathrm{Re}\{\underline{U}_s \underline{I}_s^*\} = m_s (U_{sd} I_{sd} + U_{sq} I_{sq})$$

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

- **Electromagnetical torque:**

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

- **Two torque components:**

  a) prop. U_p as with round rotor machines

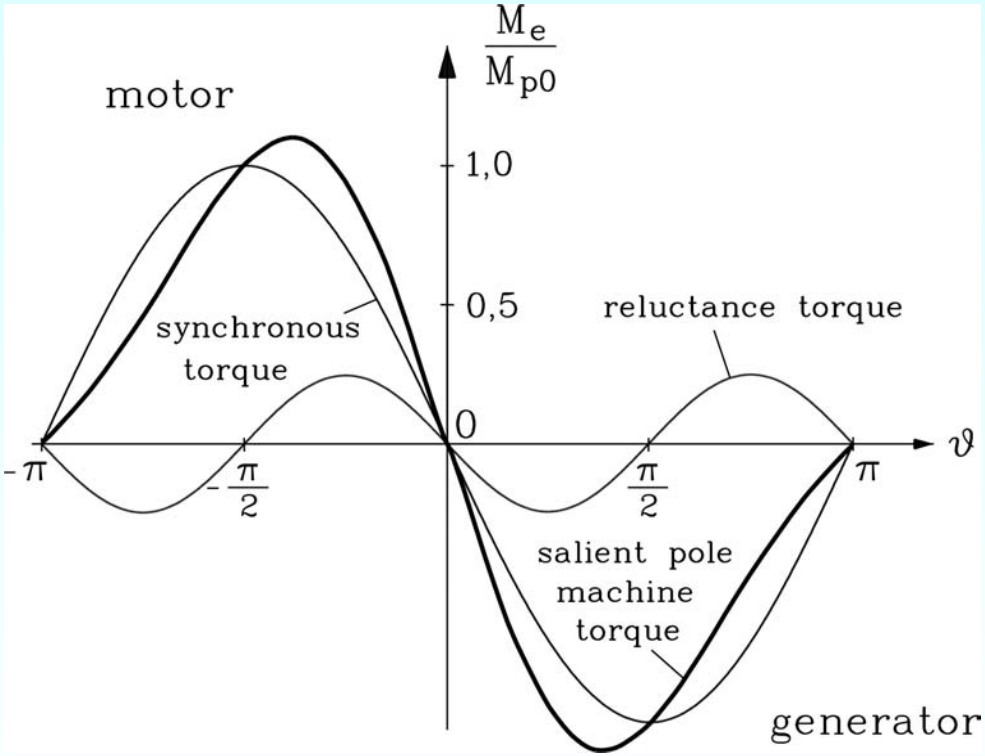
  b) **"Reluctance" torque** due to $X_d \neq X_q$. NO rotor excitation is necessary !

  Synchronous reluctance machine: Reluctance torque = robust rotor WITHOUT ANY winding, but DEEP inter-pole gaps.

Torque-load angle curve $M_e(\vartheta)$

- **Torque is expressed by stator voltage, back EMF and load angle:** I_{sd}, I_{sq} are expressed by U_s, ϑ:

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

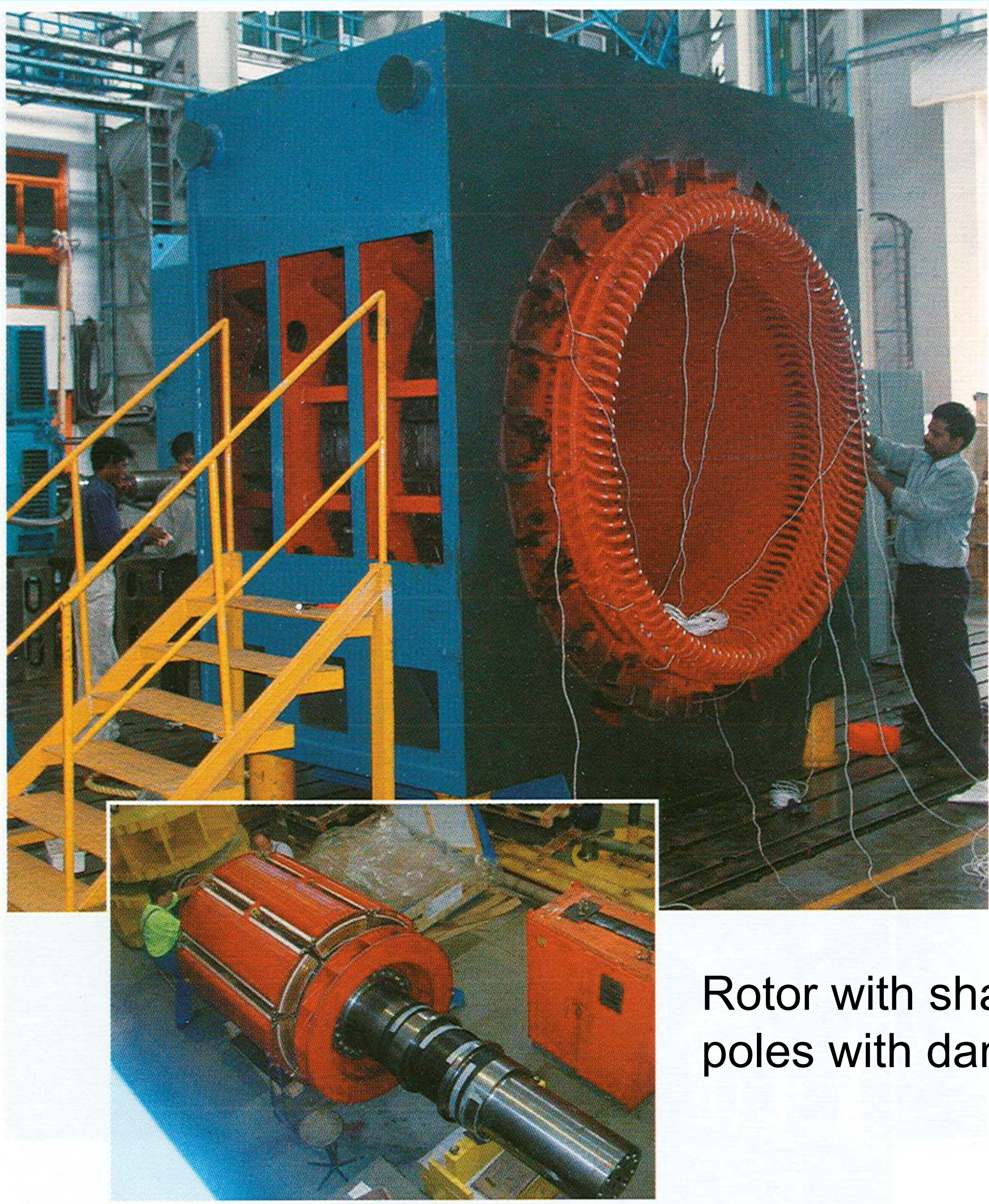


Absolute value of pull-out load angle is < 90°, as pull-out torque of reluctance torque occurs at load abgle ±45° .

Pull-out torque is increased by reluctance torque.

Equivalent spring constant c_ϑ bigger than in round rotor machines, as reluctance torque adds ("stiffer" $M_e(\vartheta)$-curve).

Aseembling of salient pole synchronous generator (8 poles)



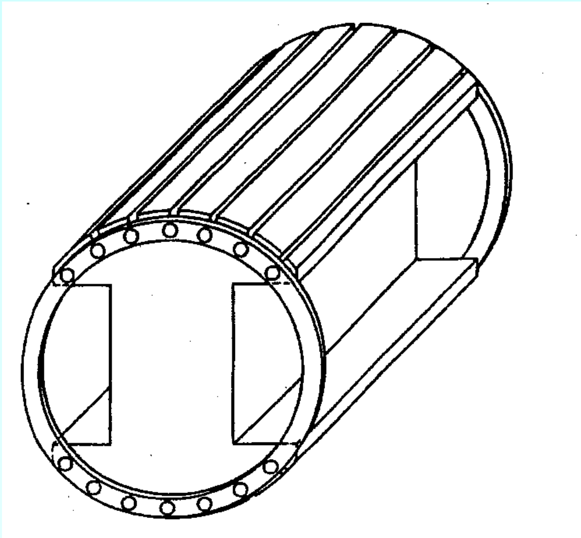
Stator with two layer high voltage winding for air cooling

Rotor with shaft mounted fan and 8 rotor poles with damper cage

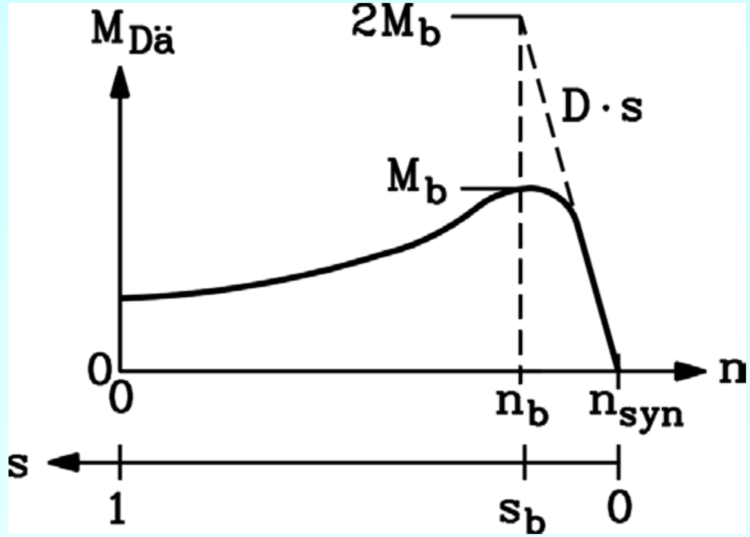
Source:

VATech Hydro, Austria

Damper cage in synchronous machines



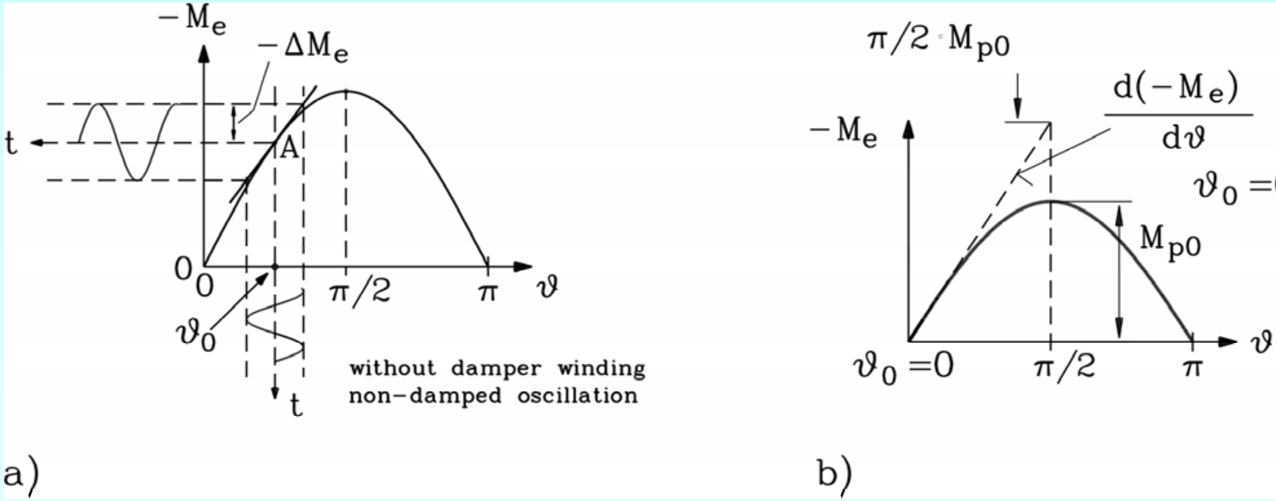
Damper cage of a 2-pole synchronous machine



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.

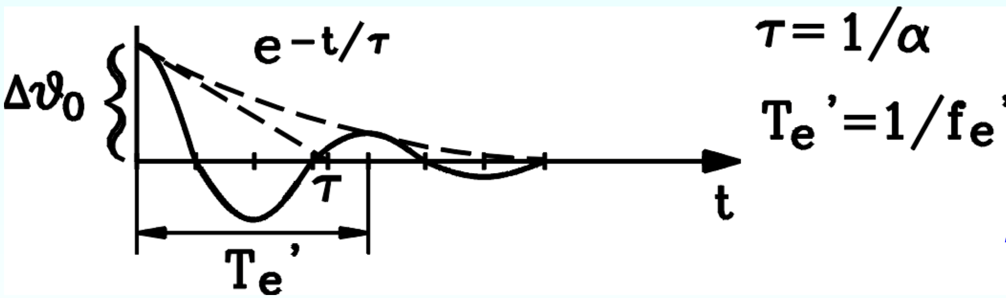
Damping of load angle oscillations



- 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) $M_{D\square}(s) \approx \frac{2M_b}{s_b} s = D \cdot s$



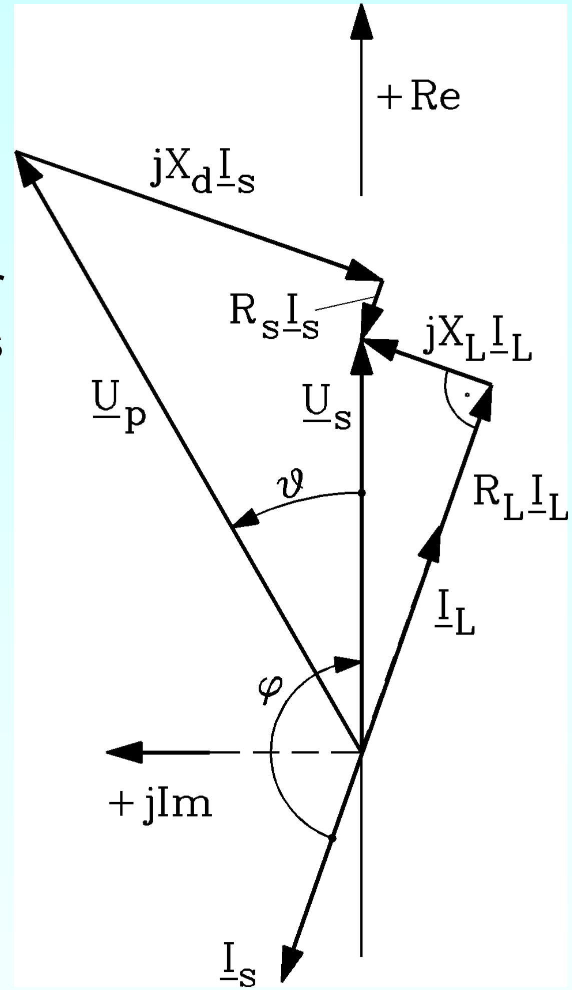
$$f_e' = \frac{\sqrt{(2\pi f_e)^2 - \alpha^2}}{2\pi}$$

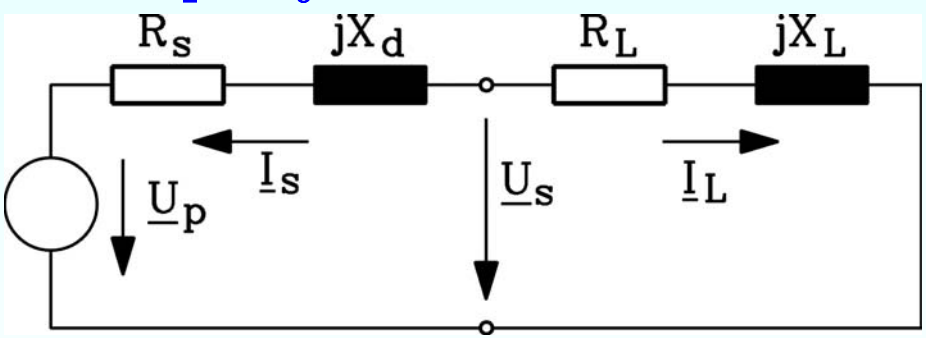
E.g.: $\tau = 1/\alpha = 1/0.7 = \underline{\underline{1.43 s}}$

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

Synchronous machine in stand-alone operation

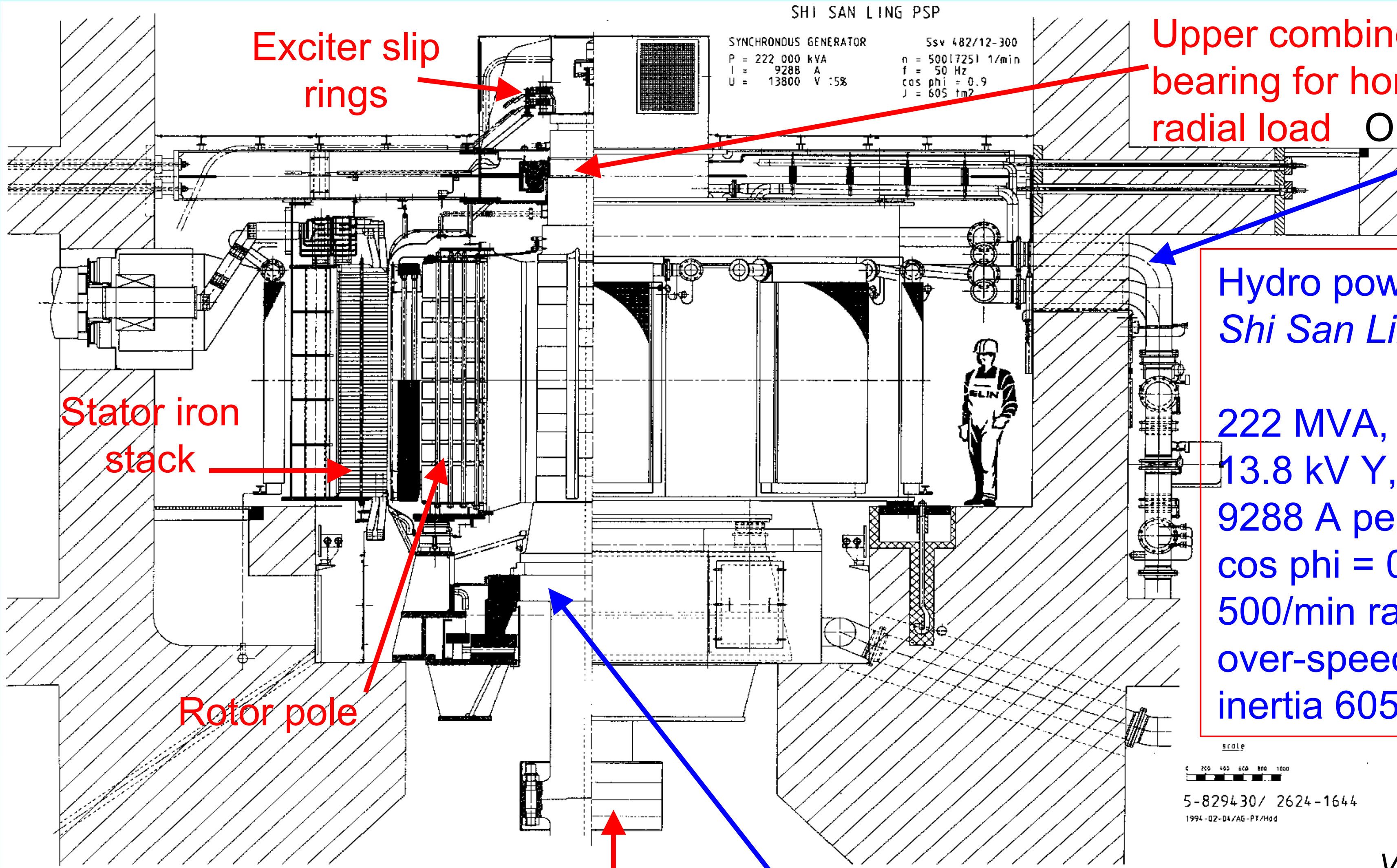
- *Examples:* Automotive generator, Air plane / ship generator, generator stations on islands, off-shore platforms, oasis, mountainous regions, emergency generators in hospitals, military use (e.g. radar supply)
- **No " rigid" grid available: U_s is NOT constant:** Rotor is excited and driven, field current I_f, back EMF U_p is induced as "voltage source", $\underline{U}_s$ is depending on load.
  E.g.: round rotor synchronous machine:
  No $M_e \sim \sin\vartheta$ - curve,
  No rotor pull out at $\vartheta = \pm 90°$
- *Example:* Mixed *OHM´* ic-inductive load $\underline{Z}_L$ (Load current $\underline{I}_L = -\underline{I}_s$)





Load impedance: $\underline{Z}_L$ (here: $\underline{Z}_L = R_L + jX_L$)

Vertically mounted salient pole "big hydro" generator



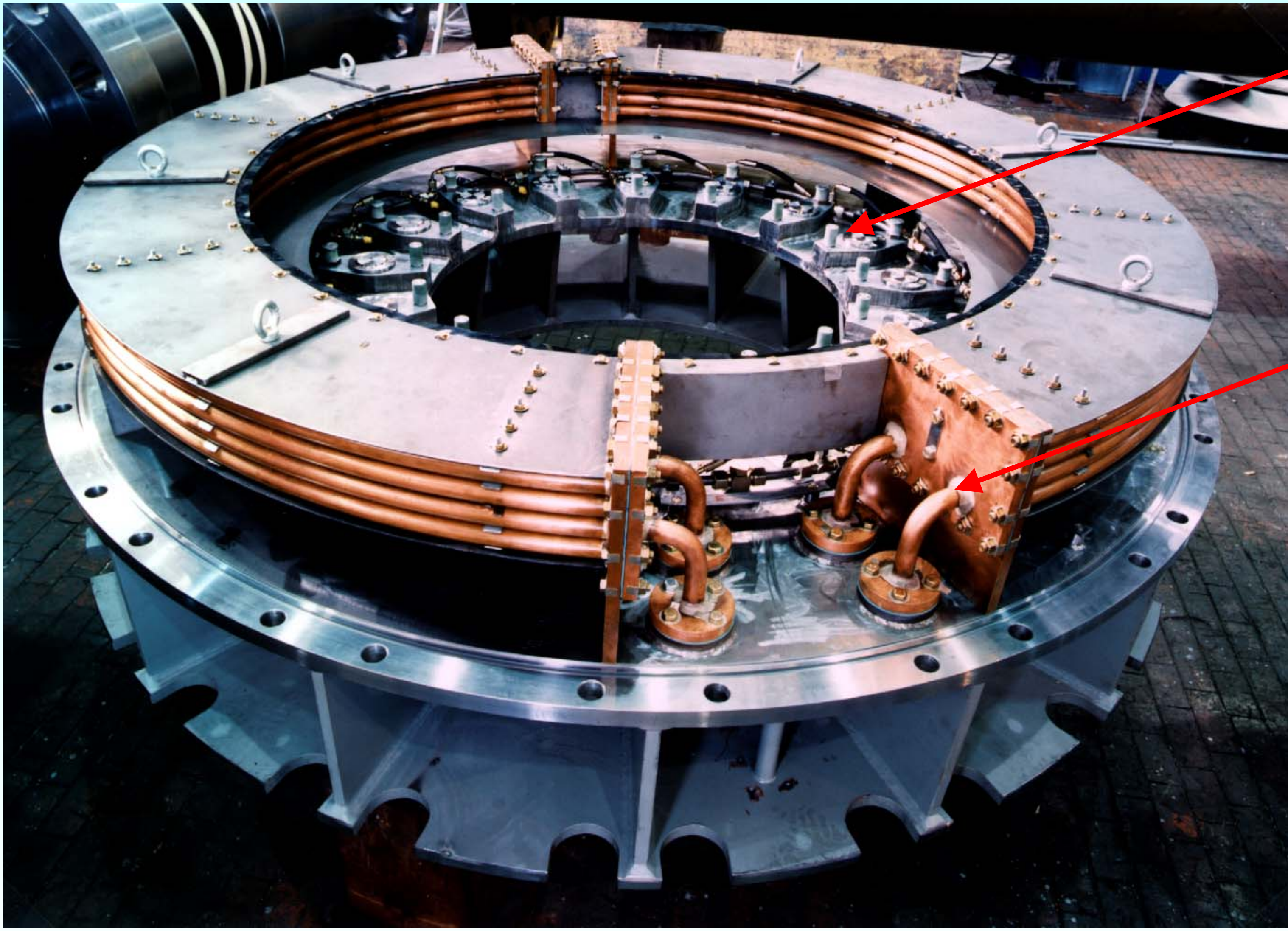
Hydro power plant
Shi San Ling / China

222 MVA, $2p = 12$
13.8 kV Y, 50 Hz
9288 A per phase
cos phi = 0.9 over-excited
500/min rated speed
over-speed 725/min
inertia 605 000 kg·m^2

Source:

VATech Hydro, Austria

Segment sleeve bearing for vertical load



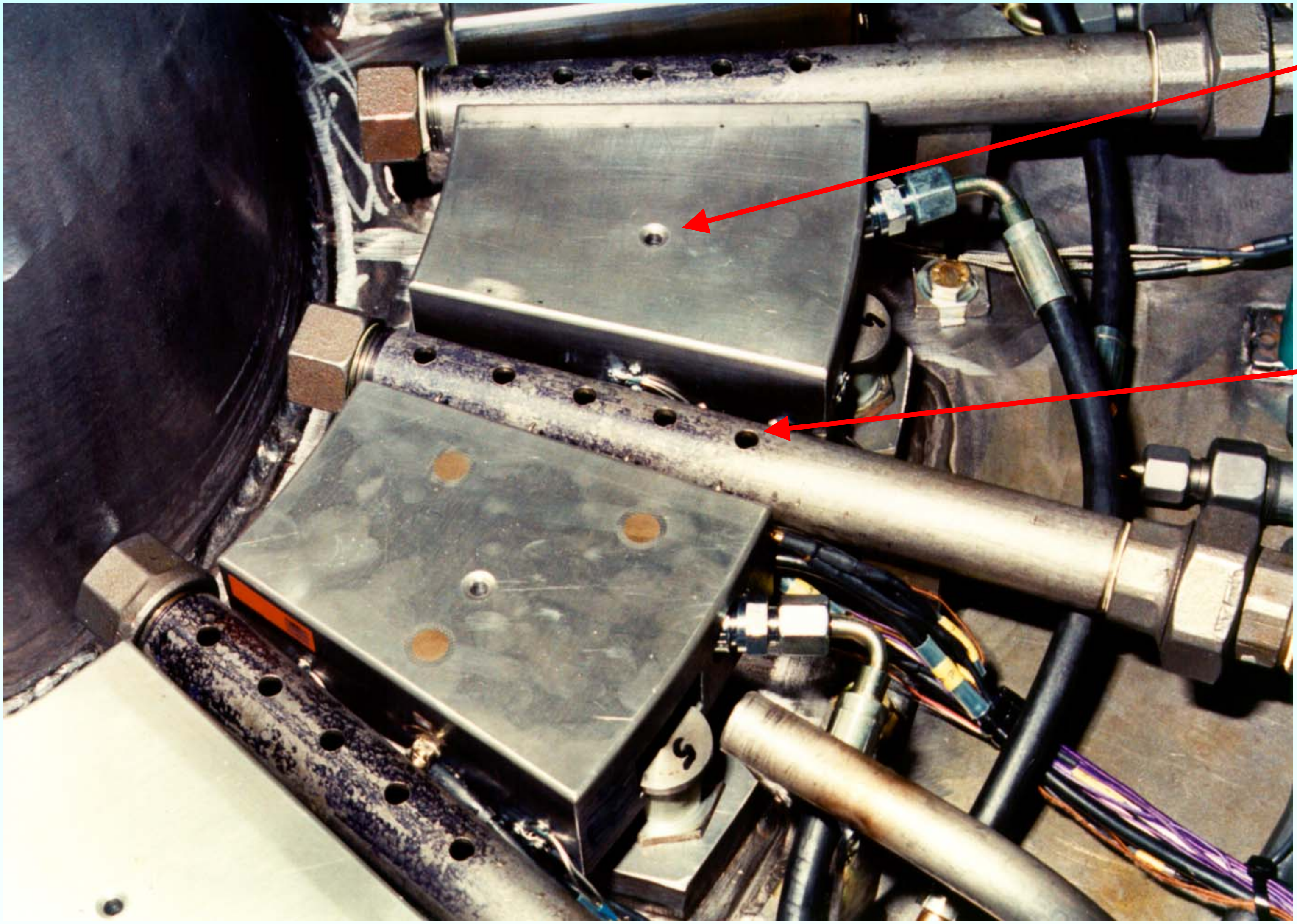
Bolts for bearing segments

Oil supply for lubrication and cooling

Source:

VATech Hydro, Austria

Segment sleeve bearing for vertical load



Bearing segments for vertical load

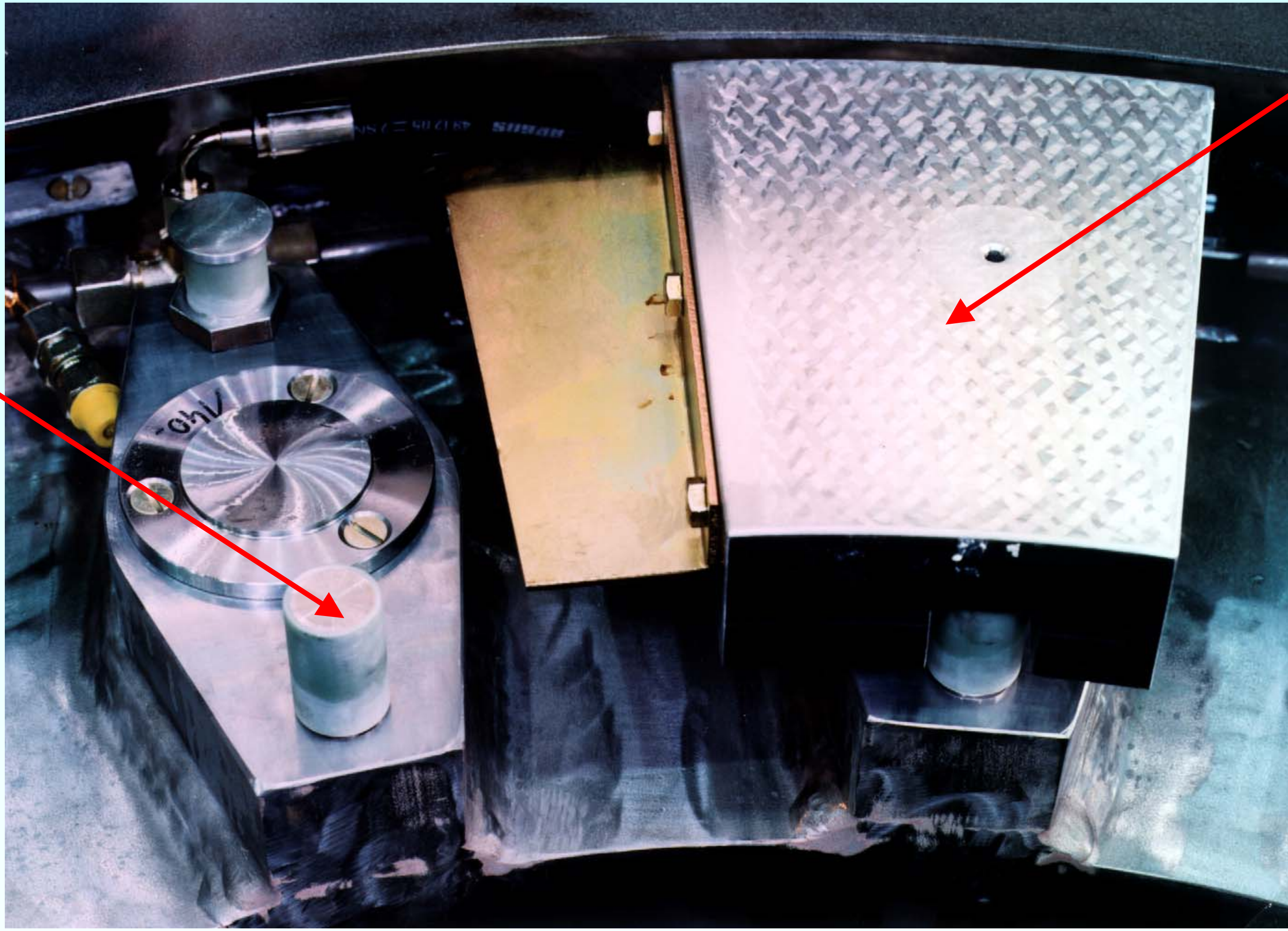
Oil outlet for lubrication

Source:

VATech Hydro, Austria

Mounting of sleeve bearing segments for vertical load

Bolts for segments

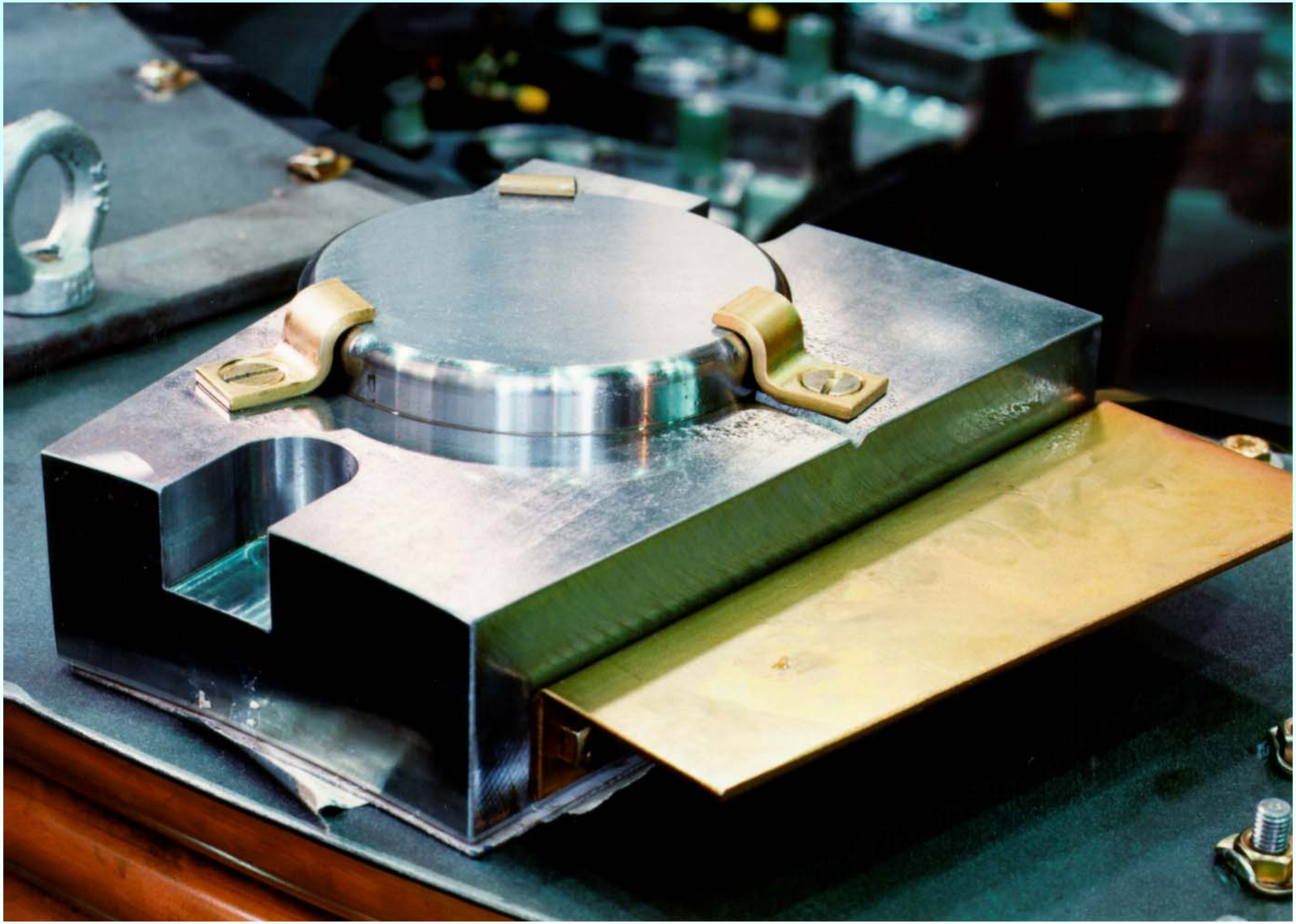


Bearing segments for vertical load

Source:

VATech Hydro, Austria

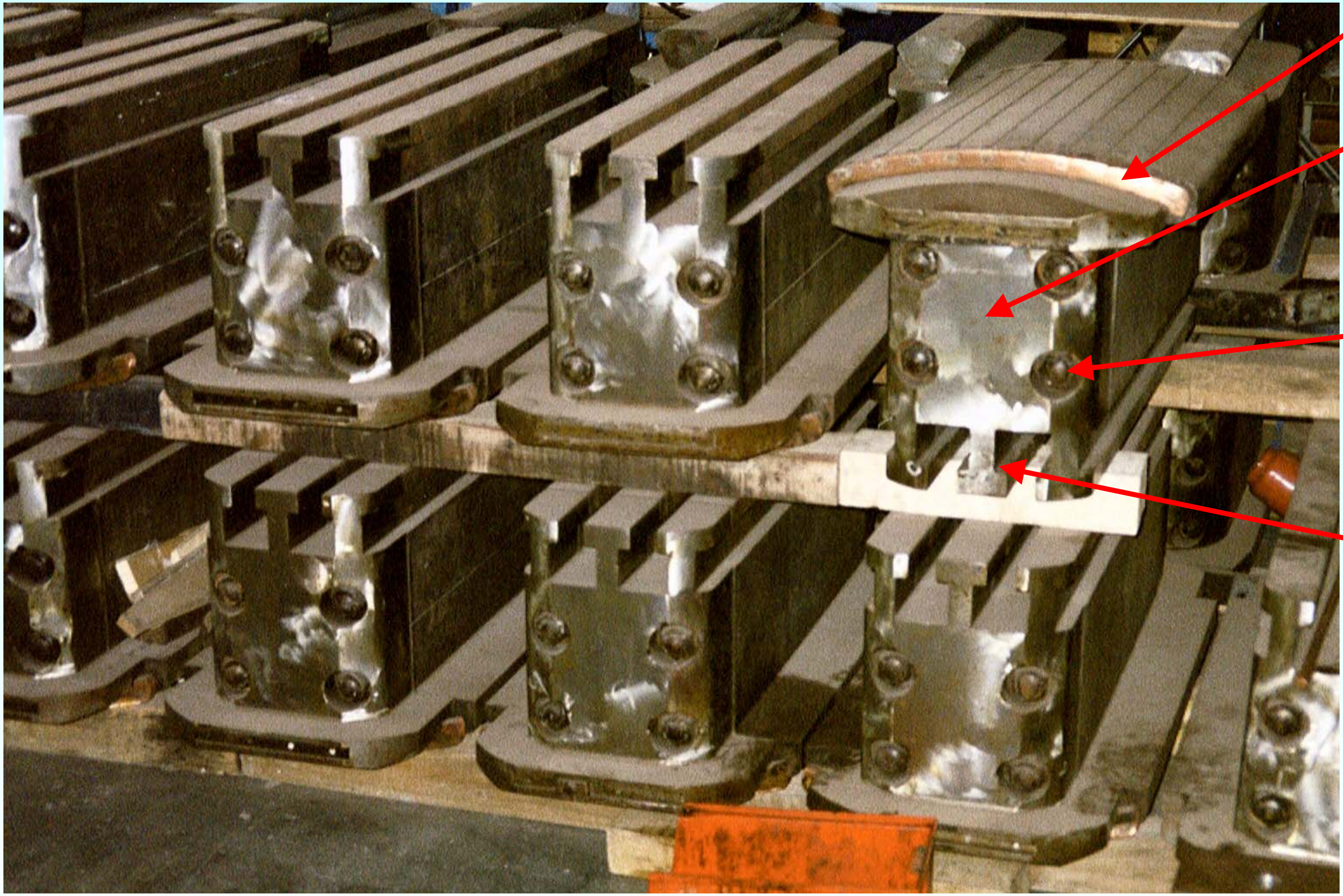
Detailed view of bearing segments for vertical load



Source:

VATech Hydro, Austria

Fixation of rotor poles for high centrifugal forces (e.g. pump storage plants)



Damper ring segment

pole press plate

pole joint bolts

three-fold hammer head fixation

Source:

VATech Hydro, Austria

Manufacturing of field winding for salient pole machines

Non-insulated flat copper winding provides good heat transfer to cooling air at front sides

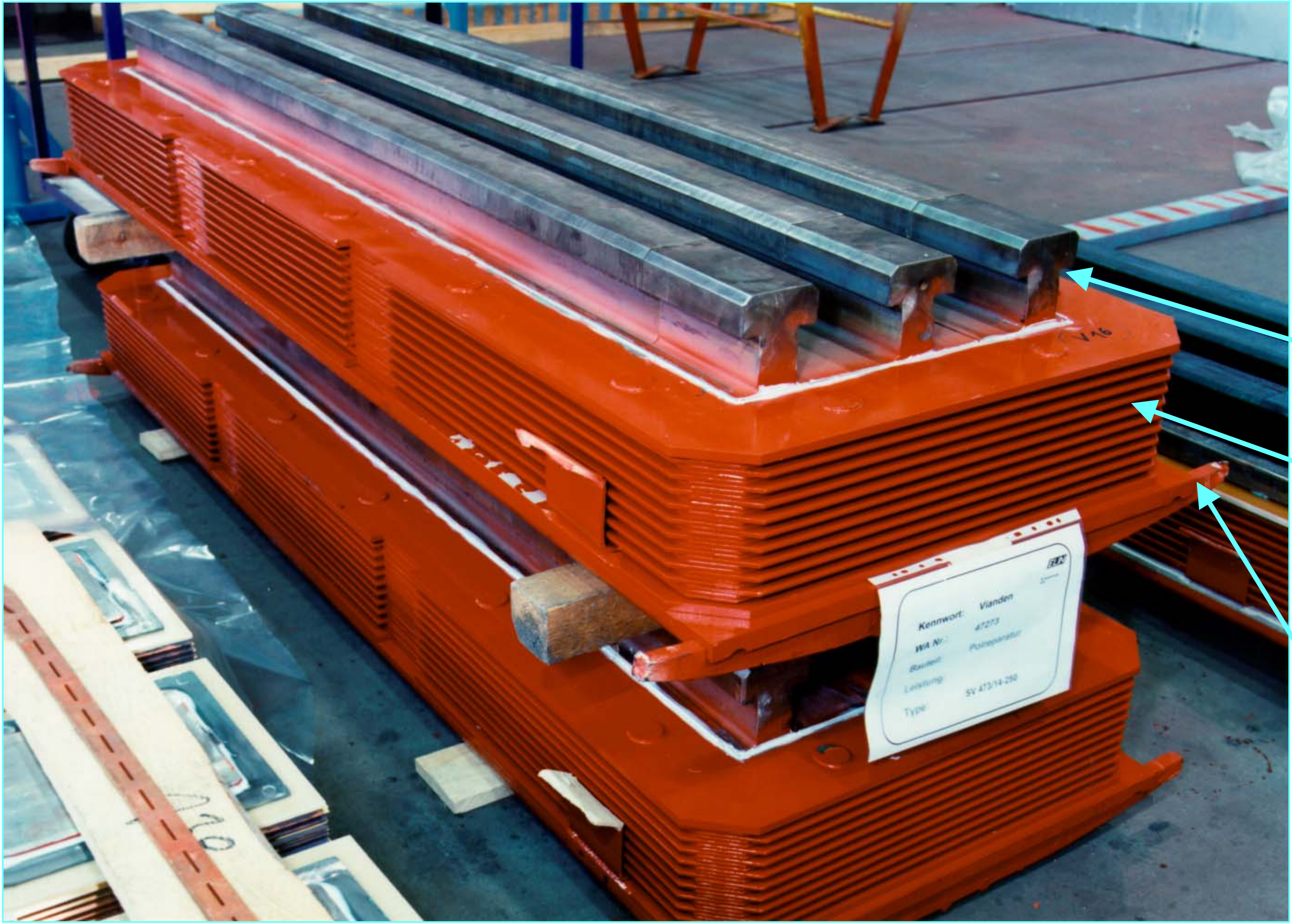
Inter-turn insulation

"Cooling fins" by increased copper width

Source:

VATech Hydro, Austria

Completed salient pole before mounting



Pump storage hydro power plant *Vianden/Belgium*

Refurbishment

Three-fold hammer head fixation

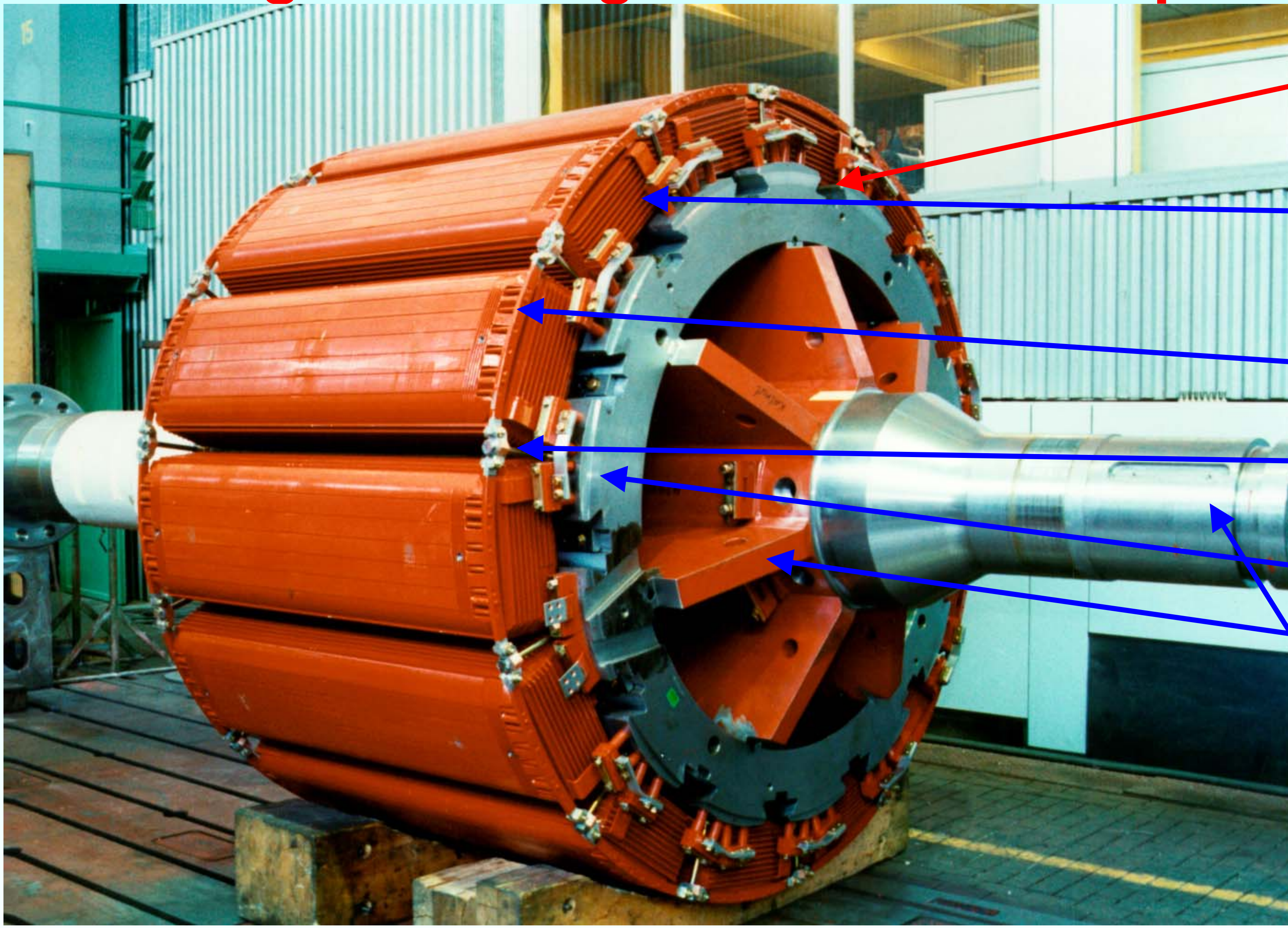
"Cooling fins" by increased copper width

Damper ring segments

Source:

VATech Hydro, Austria

Completed "big hydro" salient pole synchronous rotor for high centrifugal force at over-speed, 14 poles



Dove tail fixation of rotor poles

"Cooling fins" by increased copper width

Damper ring

Damper retaining bolts

Rotor back iron

Rotor spider

Generator shaft

Source:

VATech Hydro, Austria

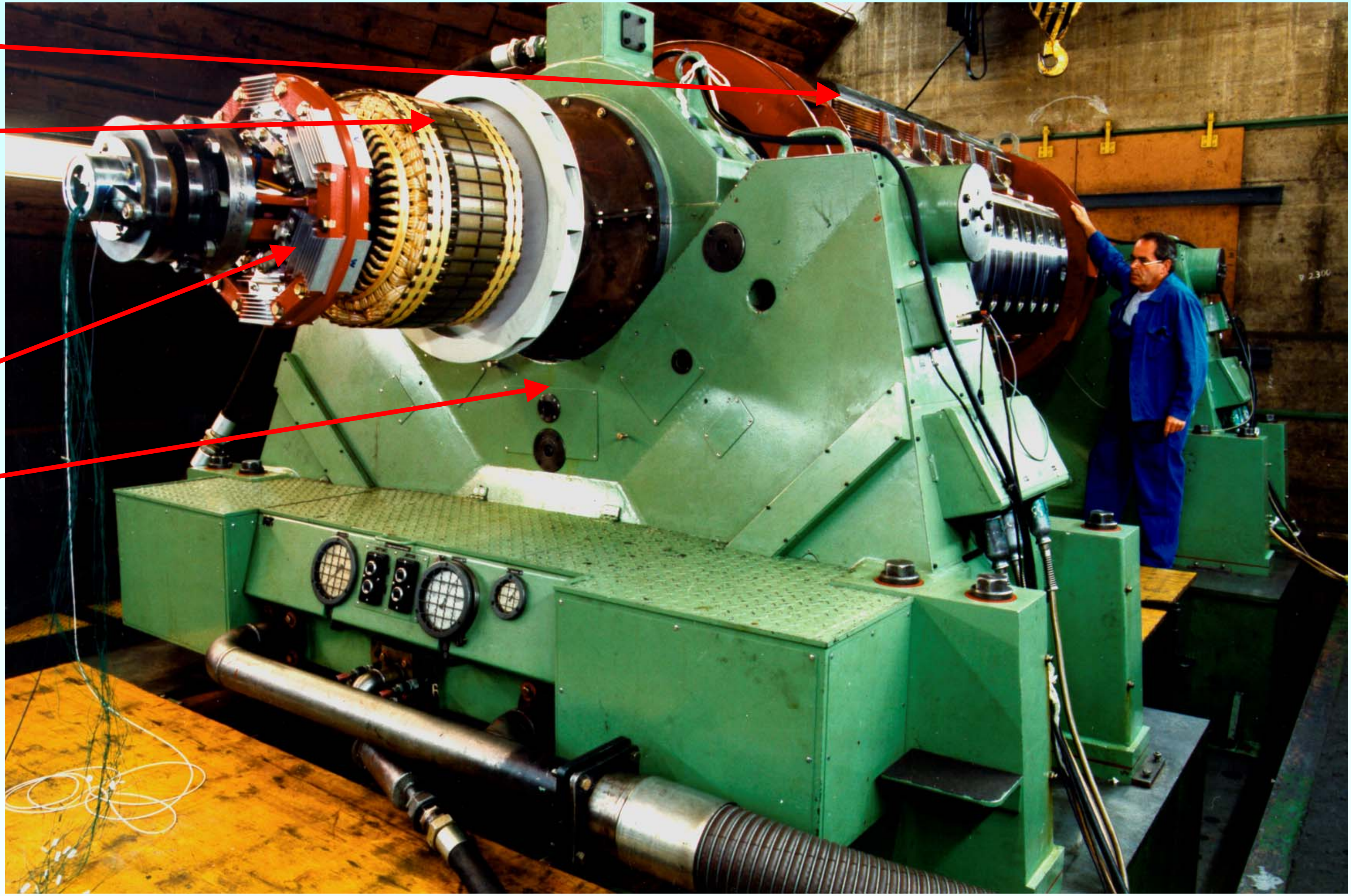
Balancing & over-speed test of salient 4 pole rotor in test tunnel

4 pole rotor

Exciter generator 3-phase winding

Rotating diode rectifier

Balancing bearing (Schenck Company, Darmstadt)



Source:

VATech Hydro, Austria

Ring synchronous generator with high pole count for river hydro power plant (bulb type generators)

Rotor with spider, rotor poles with field winding and damper cage

At plant site *Freudenau/Vienna, Austria*

River *Danube*

Mounting of rotor to turbine shaft

32 MVA, 50 Hz
92 poles
rotor diameter 7.45 m
rated speed 65.2/min
over-speed 219/min

circumference velocity at over-speed:
$\boldsymbol{v_{u,max}}$ **= 85 m/s**

centrifugal acceleration at over-speed: a/g = 200

Source:

VATech Hydro, Austria

Rotor spider during milling before mounting of rotor yoke

Manufacturing of bulb type hydro generator for *Freudenau* power plant

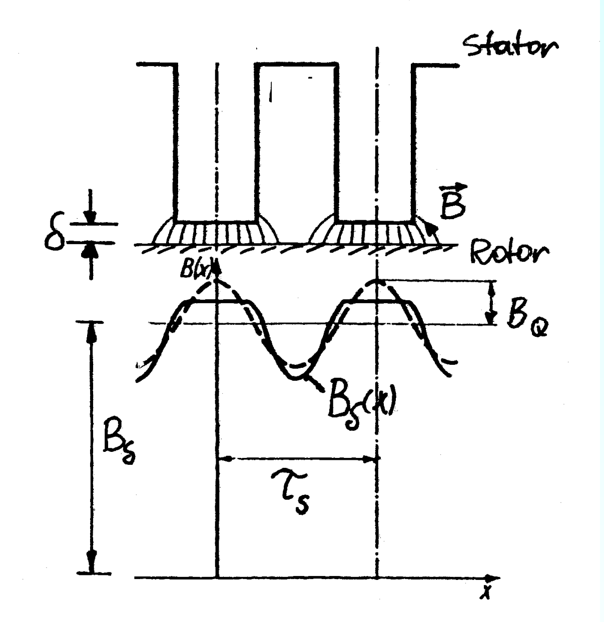
Source:

VATech Hydro, Austria

Manufacturing of poles for high pole count low speed ring generator

Pole shoes, built as laminated iron stack to suppress eddy currents, which are induced by slot ripple magnetic air gap field due to stator slot openings

Slots for damper bars



Source: VATech Hydro, Austria

Massive rotor pole shaft welded to laminated pole shoes

Source:

VATech Hydro, Austria

Drilling holes into massive pole shaft to fix them to rotor yoke ring with screws

Welding machine

Welding of massive pole shaft o laminated pole shoes

Source:

VATech Hydro, Austria