Large Generators and High Power Drives

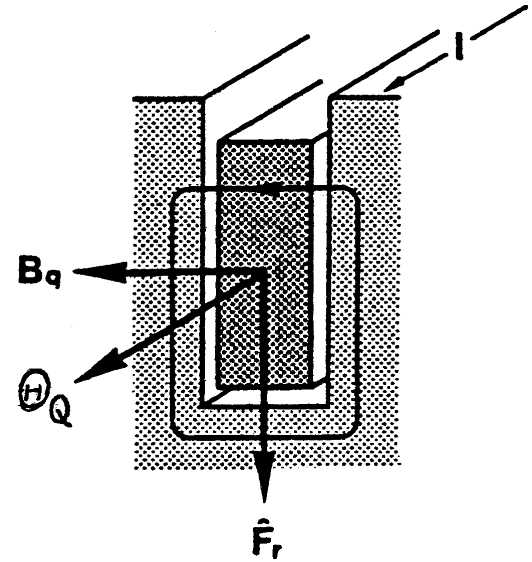
Contents of lectures

1. Manufacturing of Large Electrical Machines
2. Heating and cooling of electrical machines
3. Eddy current losses in winding systems
4. Excitation of synchronous machines
5. Design of large synchronous machines
6. Wind generators and high power drives
7. Forces in big synchronous machines

Source:

Siemens AG, Germany

7. Forces in big synchronous machines



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7.3 Single sided magnetic pull at eccentric rotor position

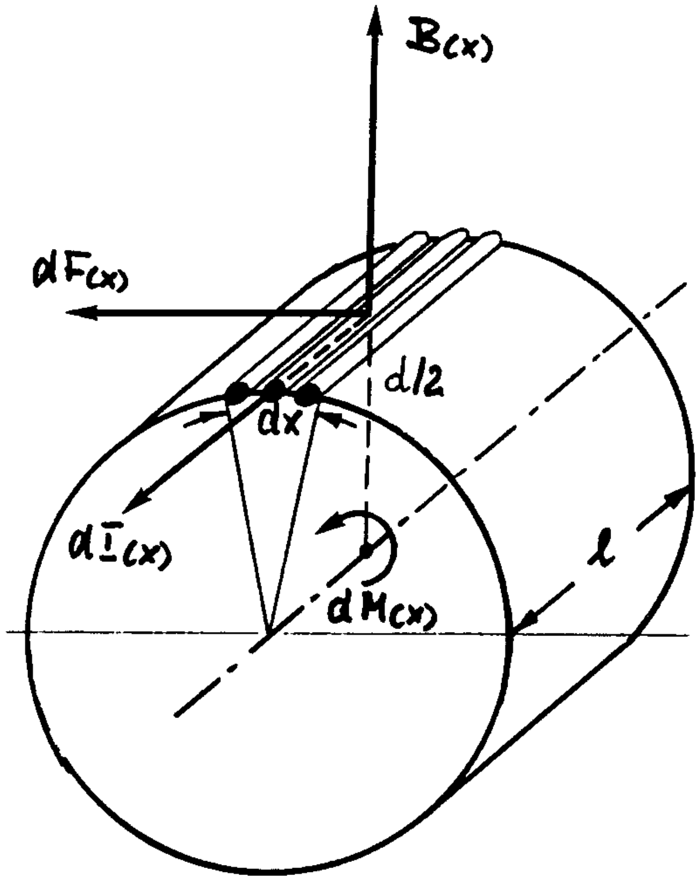
7.4 *LORENTZ* forces on slot conductors

7.5 LORENTZ forces on winding overhang conductors

7.6 Rotor pole fixation in large synchronous machines

Source: Neidhöfer, G.; BBC, Switzerland

7.1 Torque generation



Source: Neidhöfer, G.; BBC, Switzerland

$$dF(x) = dI(x)\cdot B_\delta(x)\cdot l = l\cdot A(x)\cdot B_\delta(x)\cdot dx$$

$$dM(x) = \frac{d}{2}\cdot dF(x) = \frac{d}{2}\cdot l\cdot A(x)\cdot B_\delta(x)\cdot dx$$

$$M = 2p\int_0^{\tau_p} dM = p\cdot d\cdot l\cdot \int_0^{\tau_p} A(x)\cdot B_\delta(x)\cdot dx$$

$$A(x) = \hat{A}\cdot\sin\left(\frac{x\pi}{\tau_p} - \varphi_i\right) \qquad \hat{A} = k_{w1}\cdot\sqrt{2}\cdot A$$

$$B_\delta(x) = B_{\delta 1}\sin\left(\frac{x\pi}{\tau_p}\right)$$

$$M = l\cdot(p\tau_p)^2\cdot\hat{A}\cdot\hat{B}_{\delta 1}\cdot\cos\varphi_i\,/\,\pi$$

Tangential thrust

$$M = l \cdot (p\tau_p)^2 \cdot \hat{A} \cdot \hat{B}_{\delta 1} \cdot \cos\varphi_i / \pi$$

$$S_e = \frac{M \cdot \Omega_{syn}}{\cos\varphi_i}$$

ESSON: $$S_e = \frac{\pi^2}{\sqrt{2}} \cdot k_{w1} \cdot A \cdot B_{\delta 1} \cdot d^2 \cdot l \cdot n = C_e \cdot d^2 \cdot l \cdot n$$

Air gap thrust: **Force per surface:** $\tau = F/(d_{si} \cdot \pi \cdot l)$ $\quad \tau = \hat{A} \cdot \hat{B}_\delta \cdot \cos\varphi_i / 2$

Example:

AC-machines: $k_{w1} \approx 0.95$, A = 700 A/cm, maximum thrust at:

$\tau = \hat{A} \cdot \hat{B}_\delta \cdot \cos\varphi_i / 2 = 94000 \cdot 1 \cdot 1 / 2 = 47000$ **N/m²** $\cong$ **0.5 bar**

In reality: $\cos\varphi_i$ ~ 0.9, so thrust for AC lower by 10%: 0.45 bar.

Summary:

Torque generation

- Calculation via *LORENTZ*-Force on single conductors, integration over one pole pitch, and multiplication with the pole number:

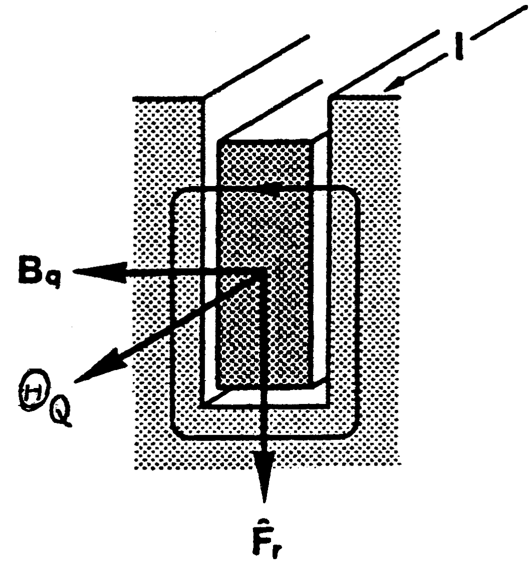
$$M = 2p \int_0^{\tau_p} dM = p \cdot d \cdot l \cdot \int_0^{\tau_p} A(x) \cdot B_\delta(x) \cdot dx$$

- Rotating-field machines:

$$M = l \cdot (p\tau_p)^2 \cdot \hat{A} \cdot \hat{B}_{\delta 1} \cdot \cos\varphi_i / \pi$$

- Tangential air gap thrust = Tangential force per rotor surface

7. Forces in big synchronous machines



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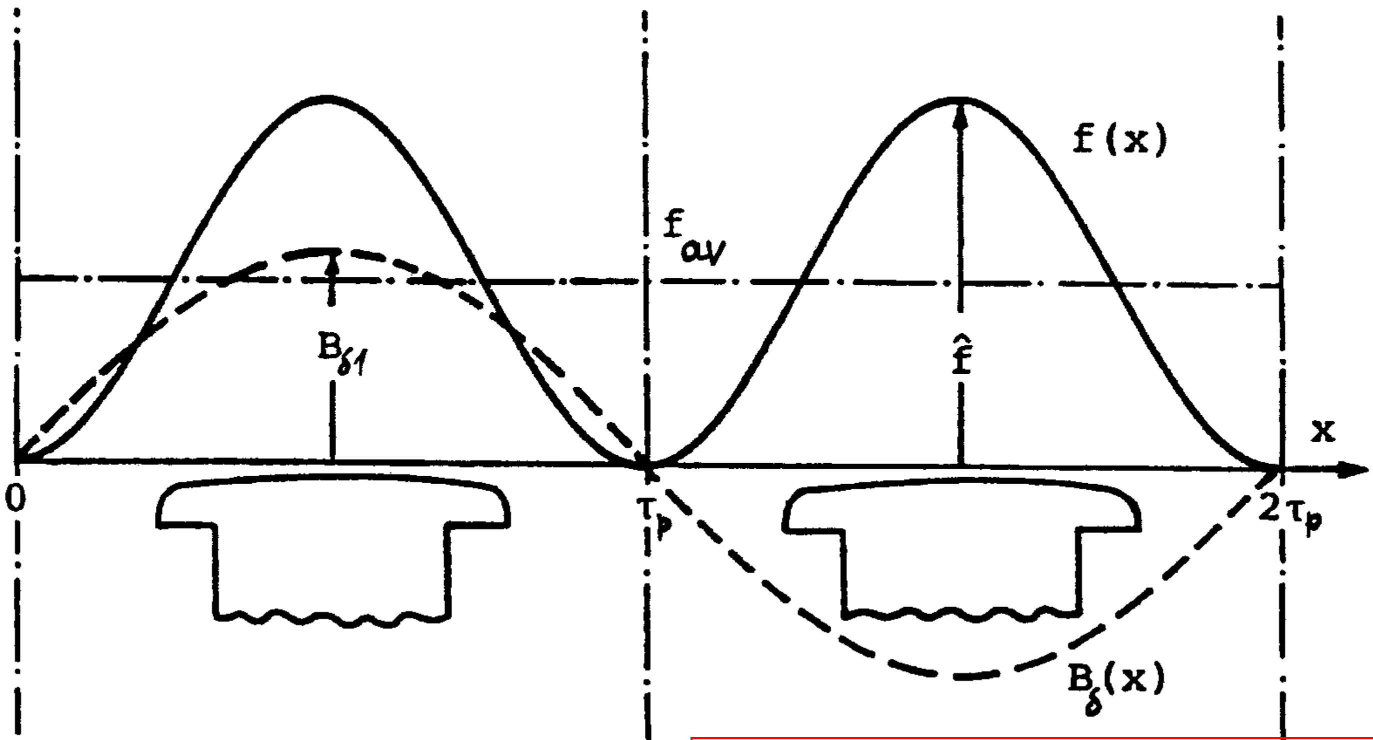
Source: Neidhöfer, G.; BBC, Switzerland

7.2 Radial forces at centric rotor position



$B_{\delta 1}$ = 1 T:

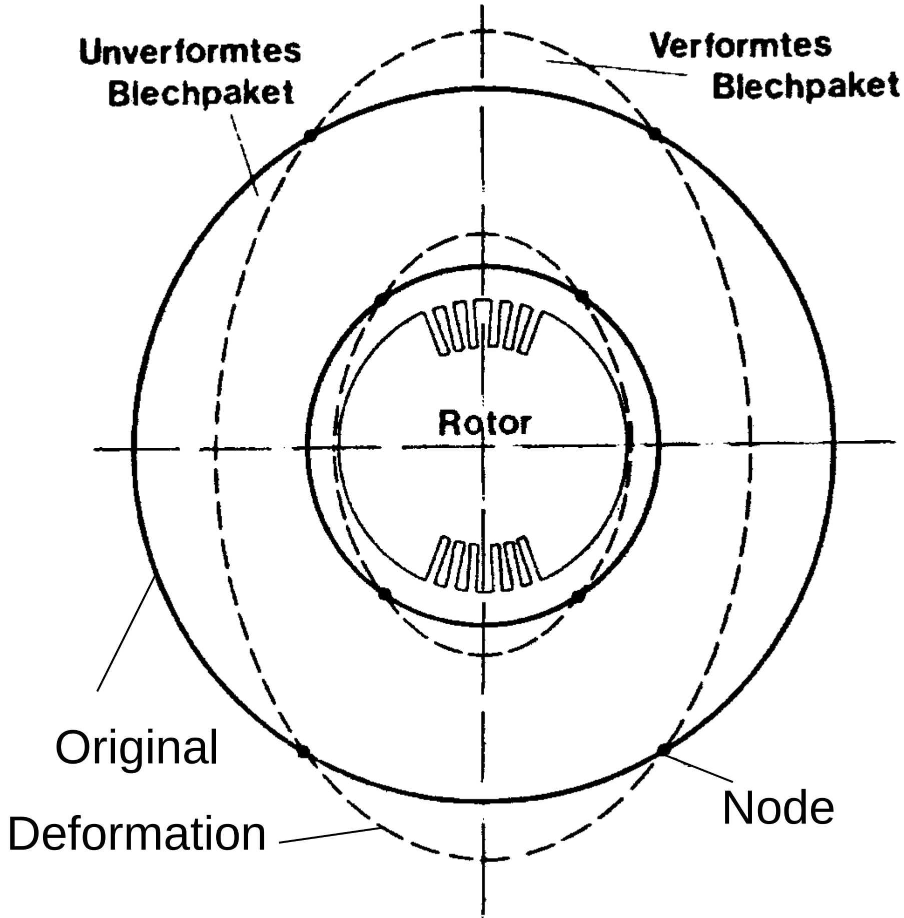
$$\hat{f} = \frac{B_{\delta 1}^2}{2\mu_0} = \frac{1^2}{2 \cdot 4\pi \cdot 10^{-7}} = 400 \cdot 10^3 \,\mathrm{N/m^2}$$

$$B_\delta(x) = B_{\delta 1} \sin\left(\frac{x\pi}{\tau_p}\right)$$

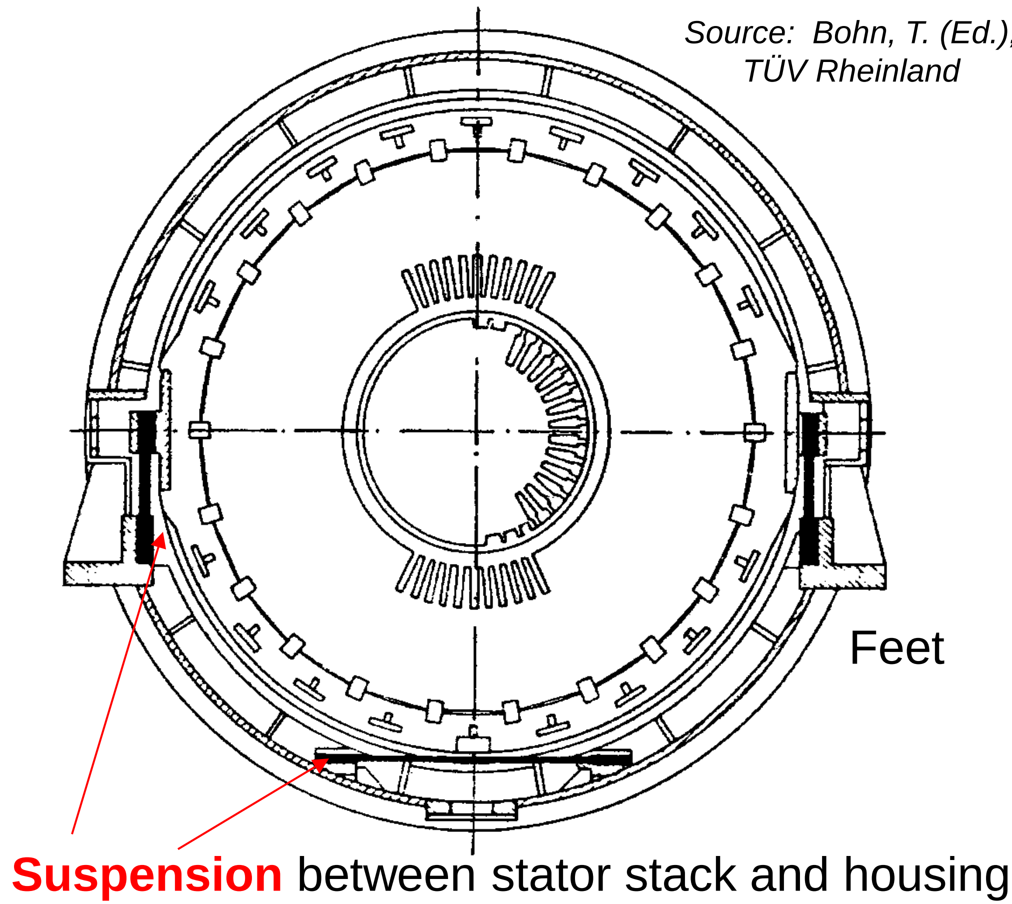
$$f(x) = \frac{B_\delta^2(x)}{2\mu_0} = \frac{B_{\delta 1}^2}{4\mu_0} \cdot \left(1 - \cos\left(\frac{2\pi x}{\tau_p}\right)\right)$$

Source: Neidhöfer, G.; BBC, Switzerland

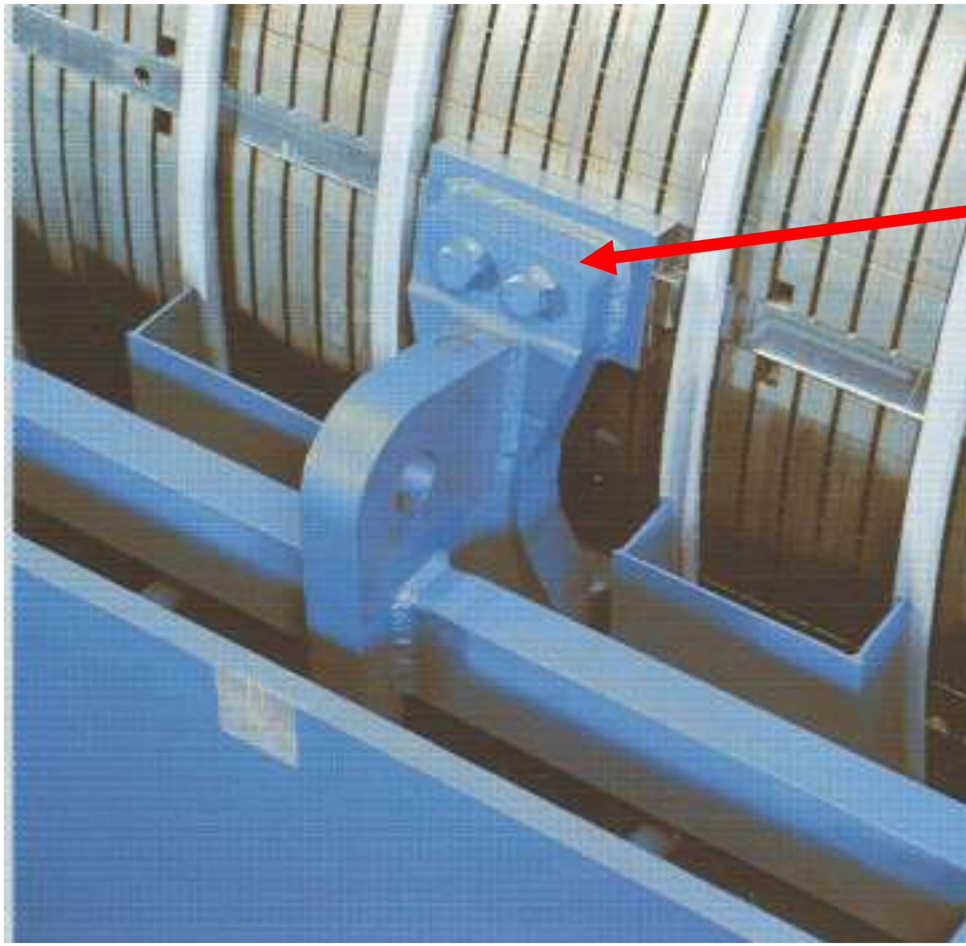
Double-frequent stator vibrations in 2-pole synchronous machines (“100 Hz” or “120 Hz”)



Source: Bohn, T. (Ed.), TÜV Rheinland



Core spring mounting

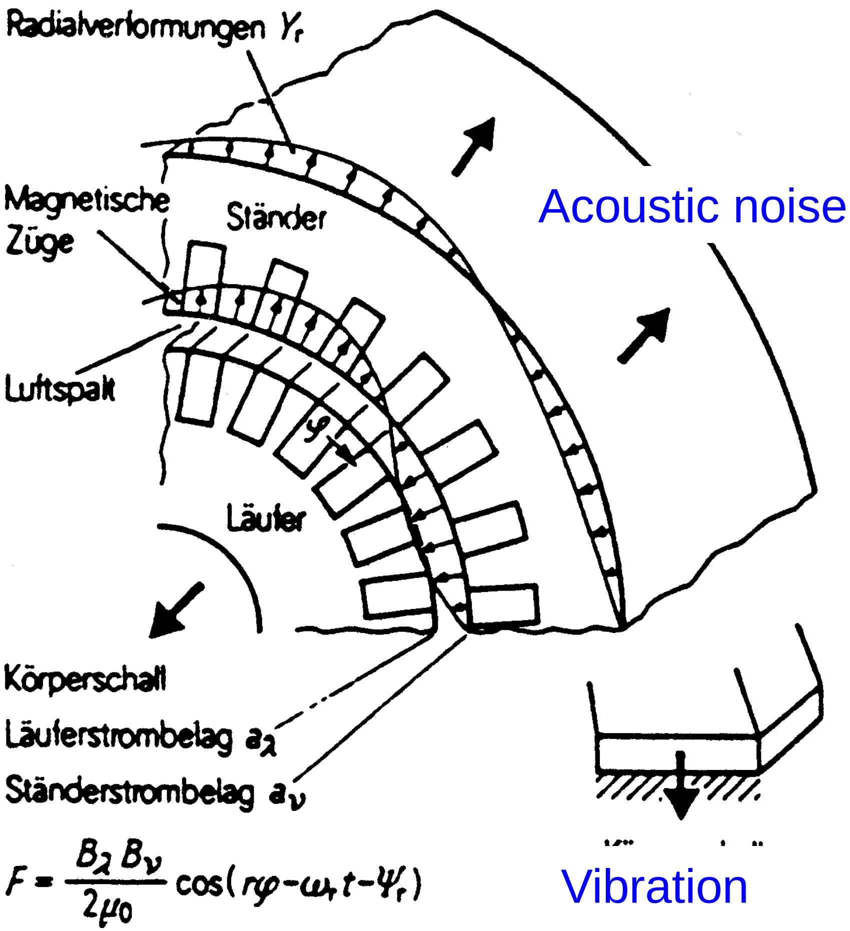


Suspension between stator stack and housing

Source:

Siemens AG, Mülheim/Ruhr, Germany

Electromagnetic acoustic noise and vibration



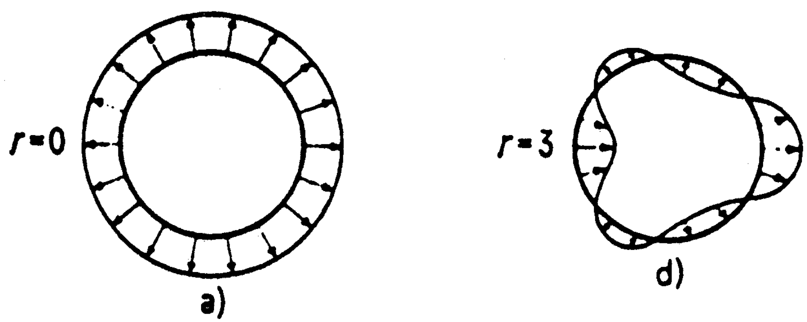
- The stator iron may be regarded as a steel ring, whereas the rotor is a steel cylinder.

- Therefore the stator is less stiff than the rotor and is bent by the force waves.

- As the iron surface is shaken with this frequency, the surrounding air is compressed and de-compressed with frequency f_{Ton}. So acoustic sound waves are generated with that tonal frequency f_{Ton} to be heard by e.g. humans.

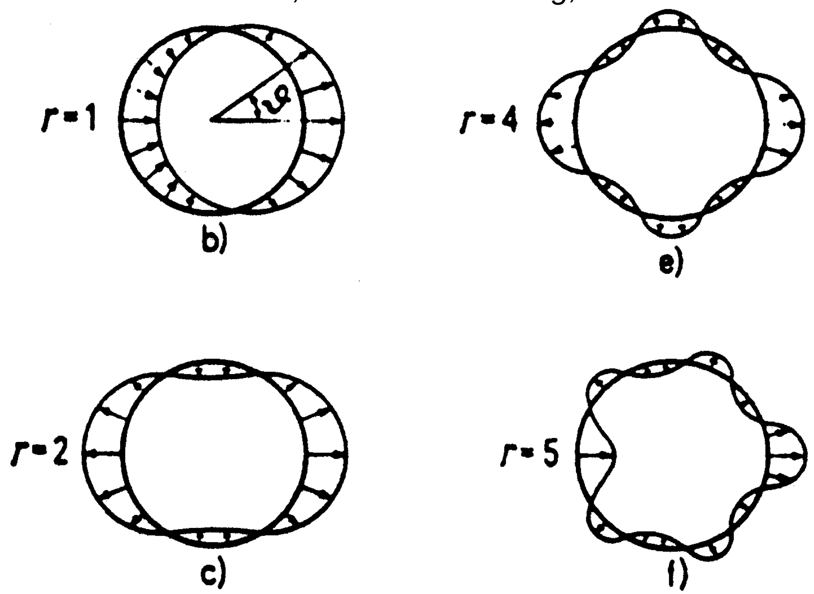
Source: Seinsch, H.-O., Teubner-Verlag

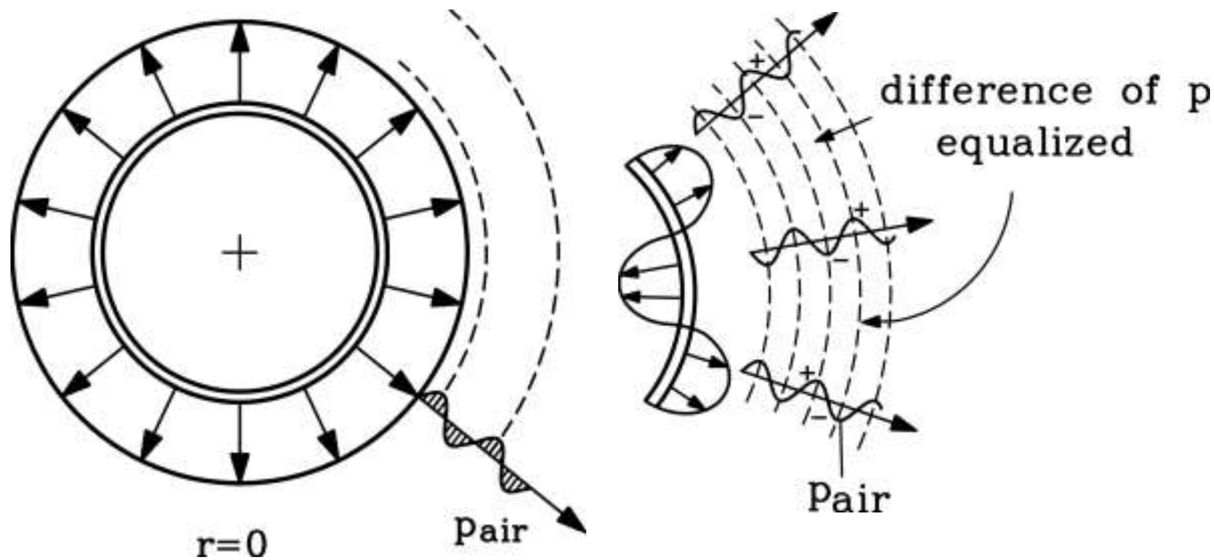
Deformation of stator yoke



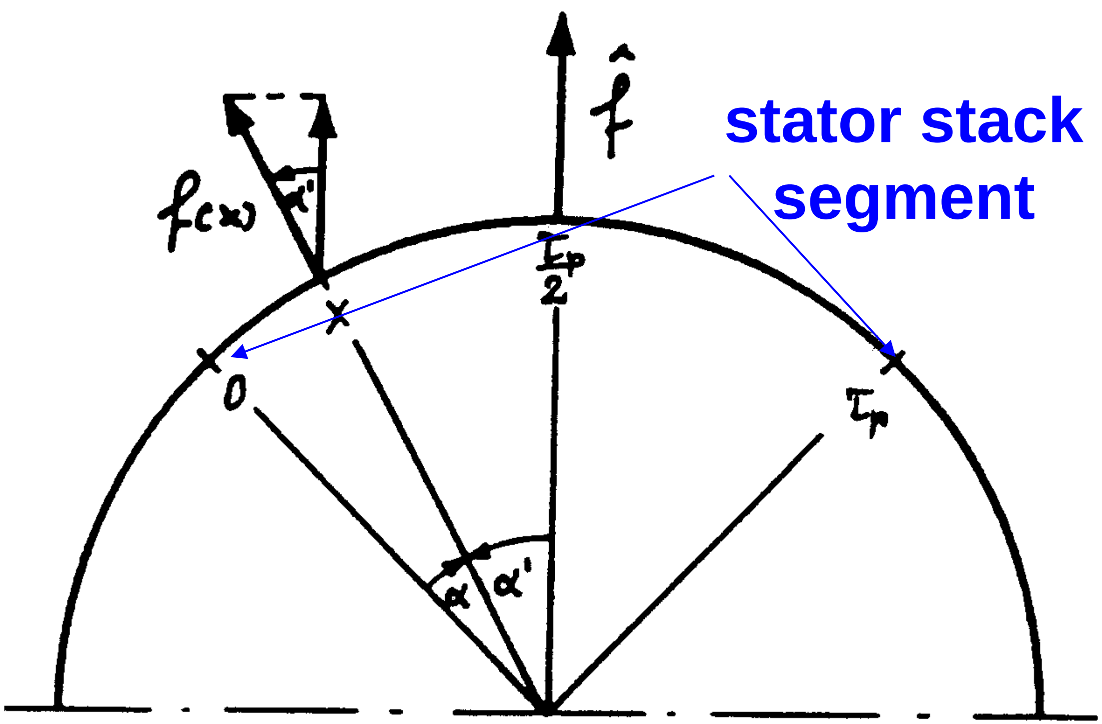
- 2r = 0 : Stator surface oscillates in phase along stator circumference, so far reaching sound wave is generated.
- With increased node number sound pressure is equalized easier.

Source: Jordan, H. Girardet-Verlag, Essen





Resulting radial force on a stator stack segment



- Force per pole sector :

$$F_\tau = d \cdot l \cdot f_{av} \cdot \frac{p^2}{p^2 - \frac{1}{4}} \cdot \sin(\frac{\pi}{2p})$$

- With increasing pole count the force per pole sector decreases !

Source: Neidhöfer, G.; BBC, Switzerland

Example: Two-pole single phase turbine generator for *German* railways

50 MVA, 16 2/3 Hz, 1000/min. The stator iron stack is made of two halves.

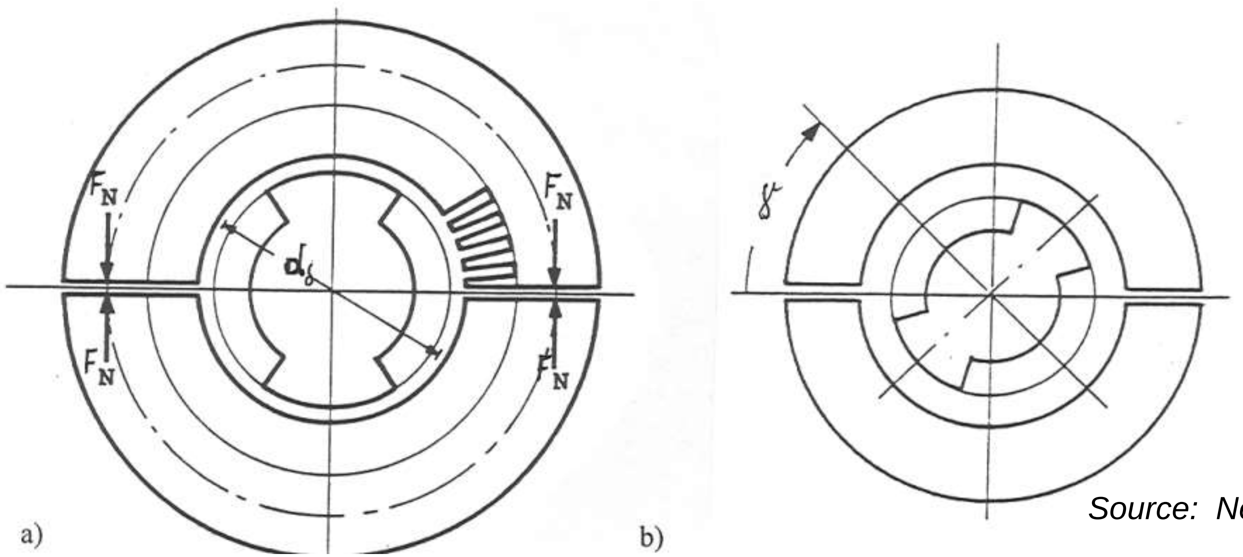
Mass per stator halve: m = 150 tons

Stack length: l = 5.0 m, stator bore (in the middle of air gap): $d_\delta = 1.6$ m

Yoke cross section: $A_{ys,tot} = 3.0\ \mathrm{m}^2$

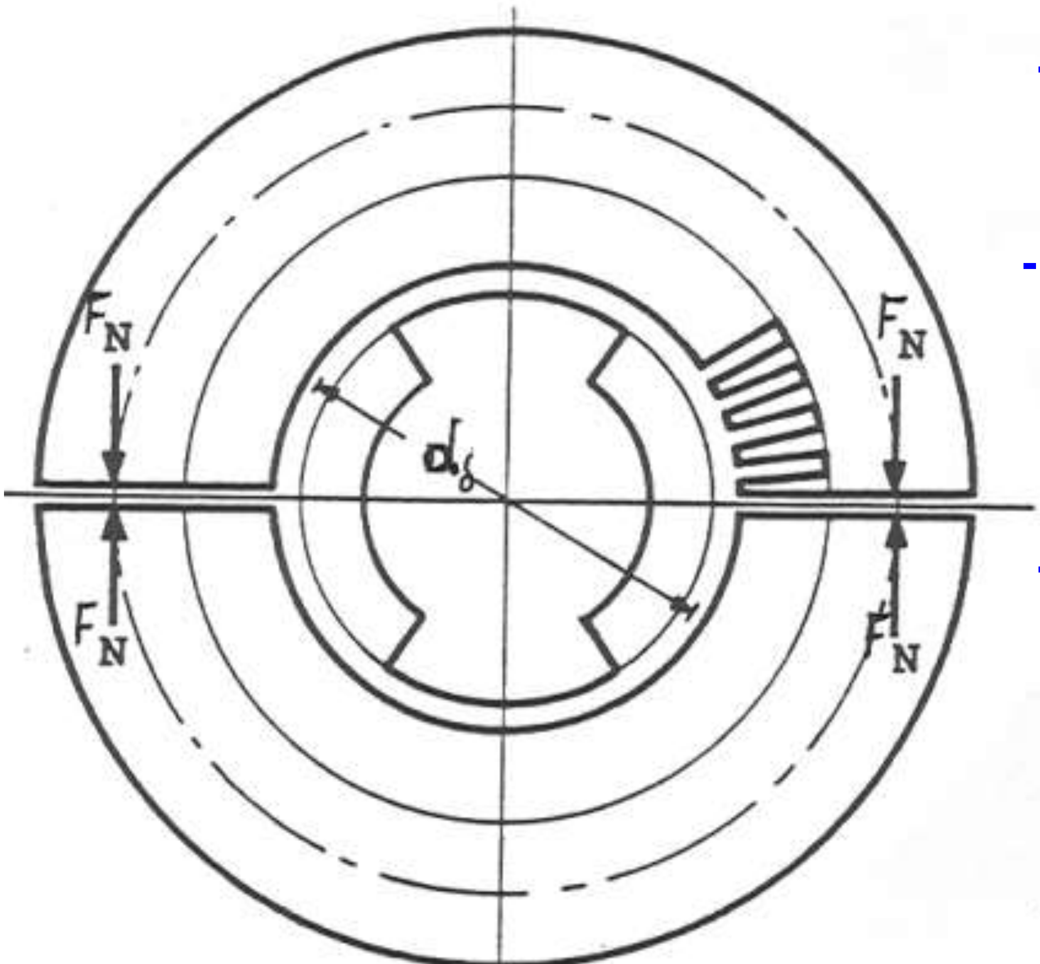
magnetic yoke cross section (without cooling ducts): $A_{ys} = 2.4\ \mathrm{m}^2$

Fundamental amplitude of air gap and yoke flux density: $B_{\delta 1} = 1.0$ T, $B_{ys} = 1.67$ T



Source: Neidhöfer, G.; BBC, Switzerland

Forces at the separation line in the yoke



Source: *Neidhöfer, G.; BBC, Switzerland*

- **Gravitation force:**

$$F_m = \frac{mg}{2} = \frac{150000}{2} \cdot 9.81 = \underline{\underline{736}}\,\mathrm{kN}$$

- **Magnetic pull:** Pulsation with 2x16.7 = 33.3 Hz between 0 and:

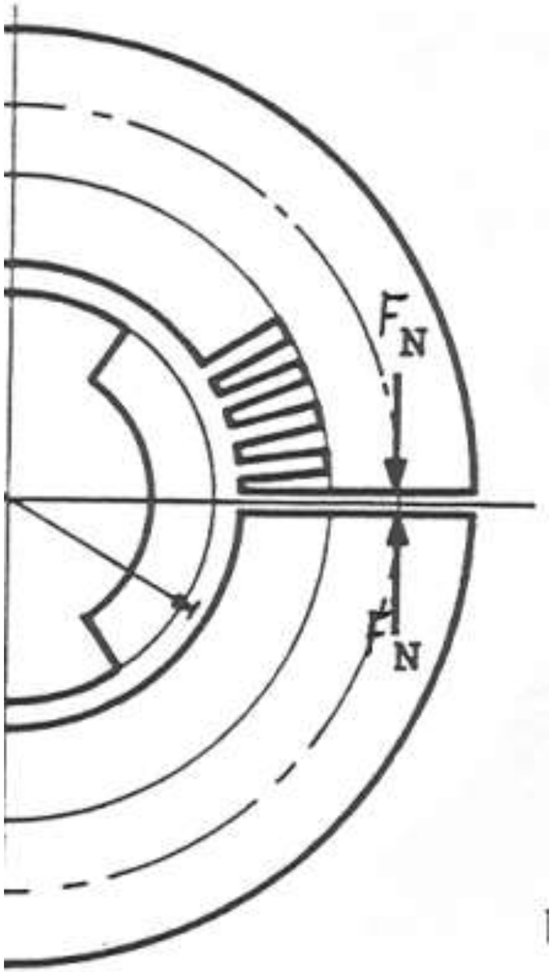
$$F_y = \frac{B_{ys}^2}{2\mu_0} \cdot A_{ys} = \frac{1.67^2}{2 \cdot 4\pi \cdot 10^{-7}} \cdot 2.4 = \underline{\underline{2663}}\,\mathrm{kN}$$

- **Magnetic pull of the rotor:** depending on rotor position. Pulsating with $2n = 2f$ = 33.3 Hz.

$$F_\tau = d_\delta \cdot l \cdot f_{av} \cdot \frac{p^2}{p^2 - \frac{1}{4}} \cdot \sin\left(\frac{\pi}{2p}\right) =$$

$$= 1.6 \cdot 5 \cdot 199 \cdot 10^3 \cdot \frac{1^2}{1^2 - 0.25} \cdot \sin(\pi/2) = \underline{\underline{2122}}\,\mathrm{kN}$$

Resulting force at the separation line in the yoke



$$F_N = F_m + F_{ys} + F_r = 736 + 2663 + 1061 = \underline{\underline{4460}}\,\text{kN}$$

The resulting force is 6-times (!) of the gravitational force.

Pressure on the insulation foil in the separation:

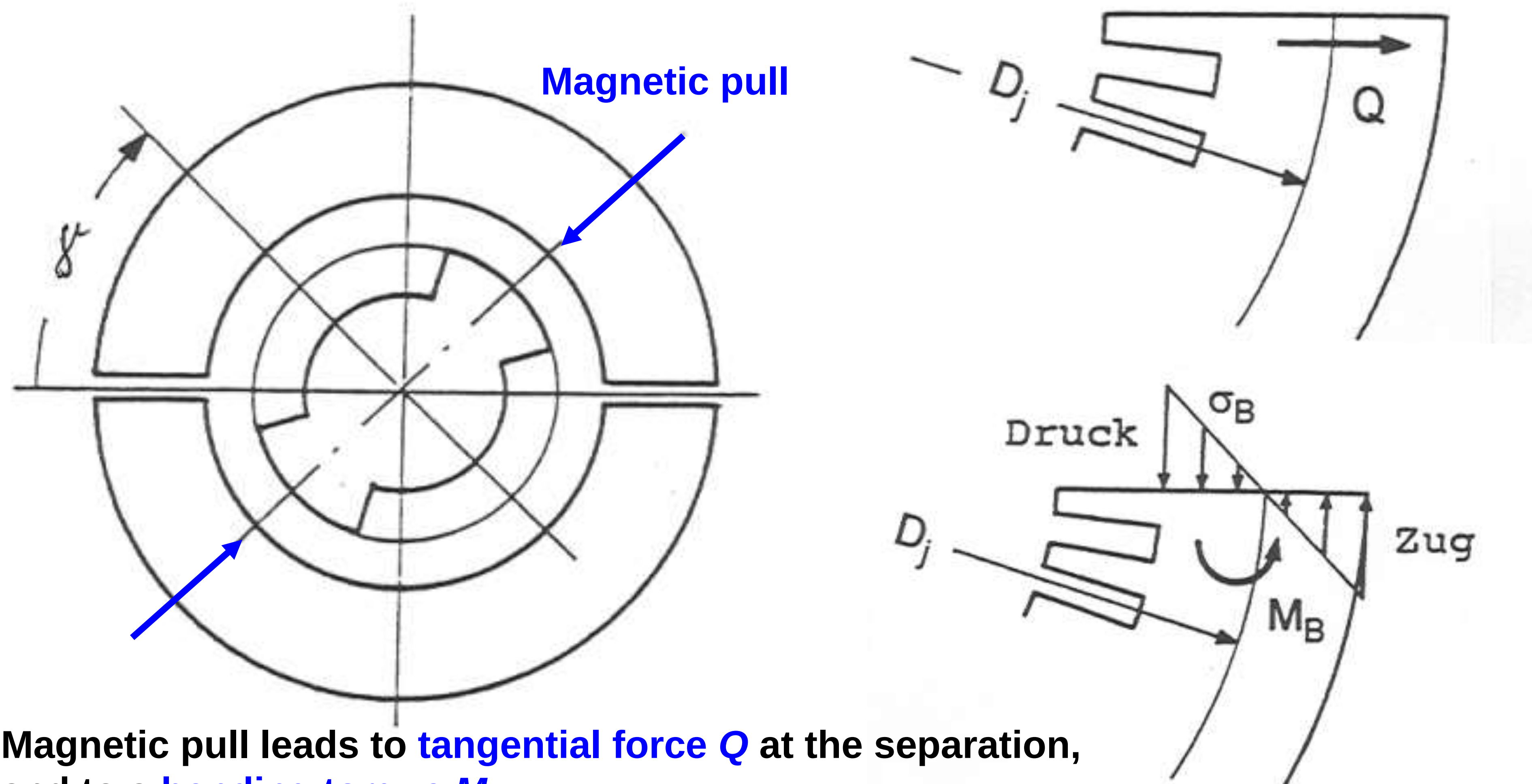
$$p = \frac{F_N}{A_{ys,tot}} = \frac{4460}{3} \cdot 10^3 = \underline{\underline{1487}}\,\text{kN/m}^2$$

Note:

Tensile strength of steel St37: 3.7 MPa = 3700 kN/m².

Source: Neidhöfer, G.; BBC, Switzerland

Resulting force at 45° rotor position



Magnetic pull leads to tangential force *Q* at the separation, and to a bending torque M_B.

Source: Neidhöfer, G.; BBC, Switzerland

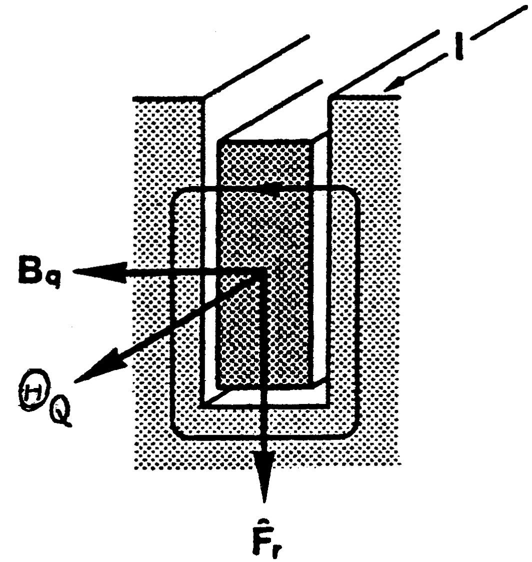
Summary:

Radial forces at centric rotor position

- Radial component of air gap field leads to magnetic pull between stator & rotor
- Equalization of radial forces along circumference for symmetrical machines = no resulting stator or rotor radial force,

  BUT:
  - Local resulting forces on stator stack segments
  - Deformation of flexible stator yoke
    → Electromagnetic acoustic noise and vibration
    → Periodical force oscillation with double stator frequency

7. Forces in big synchronous machines



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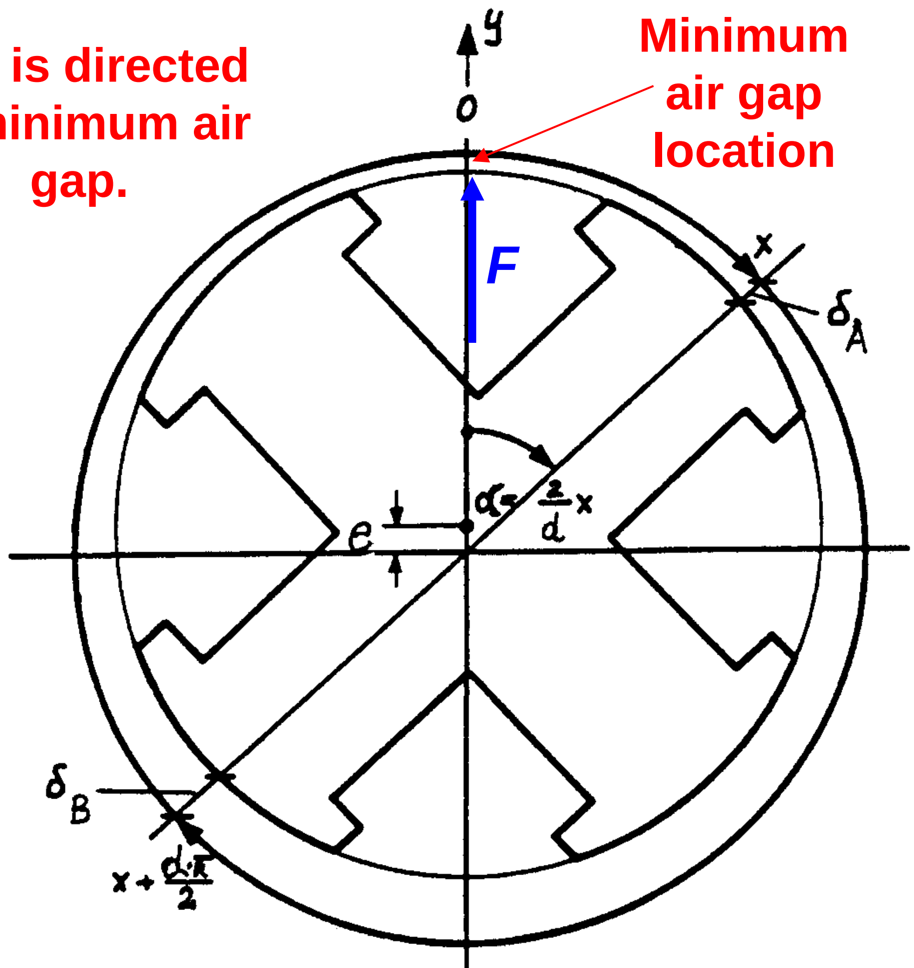
Source: Neidhöfer, G.; BBC, Switzerland

7.3 Single sided magnetic pull *F* at eccentric rotor position

Pull is directed to minimum air gap.



Source: *Neidhöfer, G.; BBC, Switzerland*

$2p \geq 4$:

$$F = \frac{\pi}{4\mu_0} \cdot d \cdot l \cdot \frac{e}{\delta} \cdot B_{\delta 1}^2$$

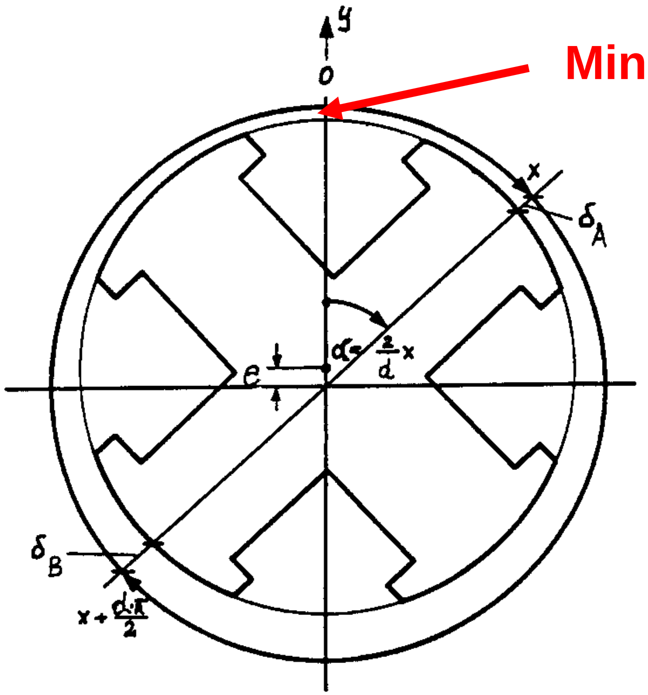
$2p = 2$:

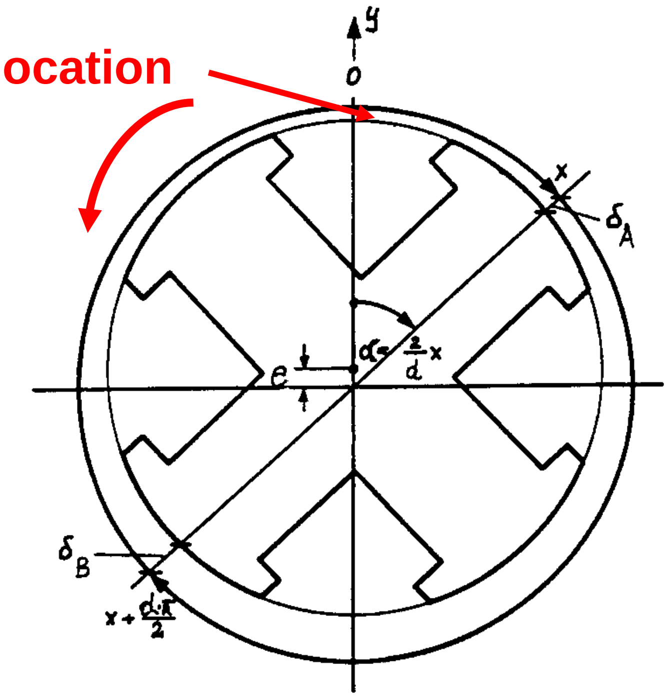
$$F = \frac{\pi}{8\mu_0} \cdot d \cdot l \cdot \frac{e}{\delta} \cdot B_{\delta 1}^2$$

For two-pole machines the single sided pull due to rotor eccentricity is only 50% of the value for machines with higher pole count.

Static and dynamic eccentricity

Minimum air gap location





Static eccentricity:	**Dynamic eccentricity:**
Minimum air gap location is fixed.	Minimum air gap location rotates with *n.*
Rotor rotates around displaced rotor axis.	Displaced rotor axis rotates with *n*.

Source: Neidhöfer, G.; BBC, Switzerland

Dependence of single-sided magnetic pull on field position

For higher pole counts $2p > 2$:

- Single sided radial force does not depend on the position of fundamental field wave amplitude relative to the position of minimum air gap.

For two-pole machines $2p = 2$:

- Single sided radial force depends on the position of fundamental field wave amplitude relative to the position of minimum air gap.

Therefore:

At static eccentricity: Single sided pull is pulsating between zero and F with $f = 2n$.

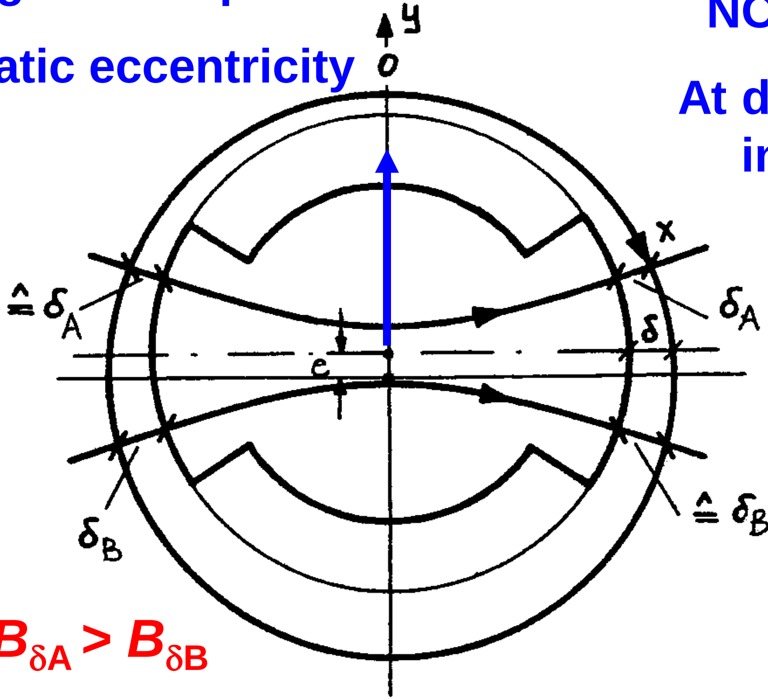
At dynamic eccentricity: Single sided pull is constant and rotates with minimum air-gap location, BUT its amplitude varies with the field position between 0 and F.

Example:
In case of dynamic eccentricity in d-axis direction the radial eccentricity force **vanishes.**

Two-pole machines: Pulsation of single sided magnetic pull

Single-sided pull:

At static eccentricity



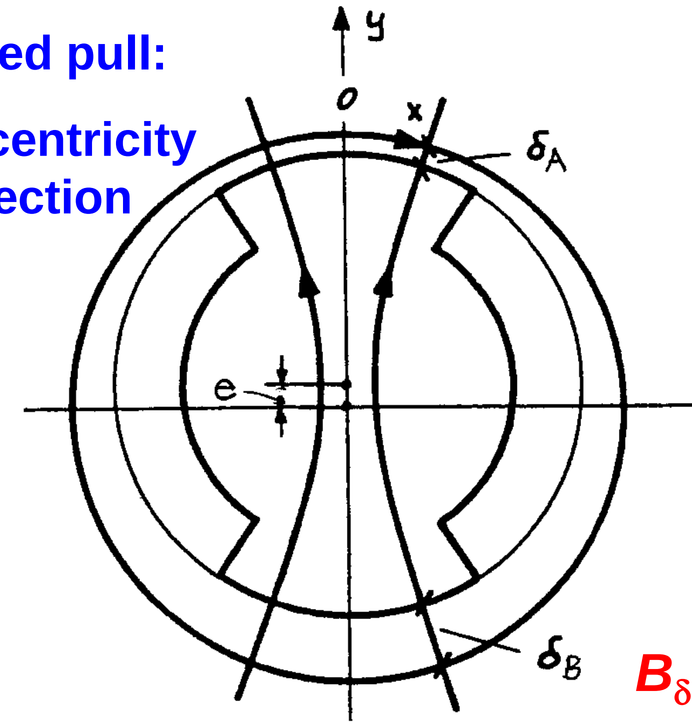
$B_{\delta A} > B_{\delta B}$

Radial force is pulsating between zero and F with $f = 2n$.

Source: Neidhöfer, G.; BBC, Switzerland

NO single-sided pull:

At dynamic eccentricity in d-axis direction



$B_{\delta A} = B_{\delta B}$

Radial force is constant and rotates with n.
Force amplitude depends on field position relative to minimum air-gap.

In case of dynamic eccentricity in *d*-axis direction the radial eccentricity force vanishes.

Example: Single sided magnetic pull for a salient pole synchronous machine

Four-pole hydro generator 1.12 MVA, rotor mass 1350 kg.

$$d_{si} = 0.555m, \quad l = 0.49\text{m}, \quad B_{\delta 1} = 0.90\text{T}, \quad \delta = 7.5\text{mm}, \quad e = 0.6\text{mm}$$

Eccentricity : $\boxed{e/\delta = 0.6/7.5 = 0.08}$

- Single sided radial pull in direction of the minimum air gap:

$$F = \frac{\pi}{4\mu_0} \cdot d_{si} \cdot l \cdot \frac{e}{\delta} \cdot B_{\delta 1}^2 = \frac{\pi}{4 \cdot 4\pi \cdot 10^{-7}} \cdot 0.555 \cdot 0.49 \cdot 0.08 \cdot 0.9^2 = \underline{\underline{11013}}\text{N}$$

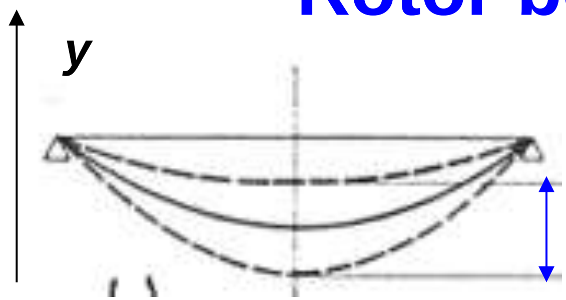
- Influence of iron saturation leads to reduction: here typically - 40 %:

F = 6 600 N

- <u>Conclusion:</u> Single sided magnetic pull: ca. 50% of rotor gravitational force:

6 600 N = ca. 0.5 x 1350xg = 0.5 x 13 240 N.

Rotor bending natural frequencies



Source: Wiedemann, E.; Kellenberger, W.; Springer, 1968

Vertical part of rotational bending oscillation:

-Lumped mass model: Rotor mass *m*, elasticity *c*:

$$m_r \cdot \ddot{y} - c \cdot y = 0$$

Natural bending frequency:

$$f_b = \frac{1}{2\pi} \cdot \sqrt{\frac{c}{m_r}}$$

Exciting centrifugal force due to static imbalance e_S:

$$F_U = m_r \cdot (2\pi n)^2 \cdot e_S$$

Vertical (*y*-)component: $F_{U,y} = F_U \cdot \sin(2\pi n \cdot t) = F_U \cdot \sin(\Omega_m \cdot t)$

Additional magnetic pull *F* due to dynamic eccentricity, caused by F_U:

- Equivalent magnetic spring constant: $k = F / e = \frac{\pi}{4\mu_0} \cdot \frac{d \cdot l}{\delta} \cdot B_{\delta 1}^2$

The single sided pull reduces the natural bending frequency:

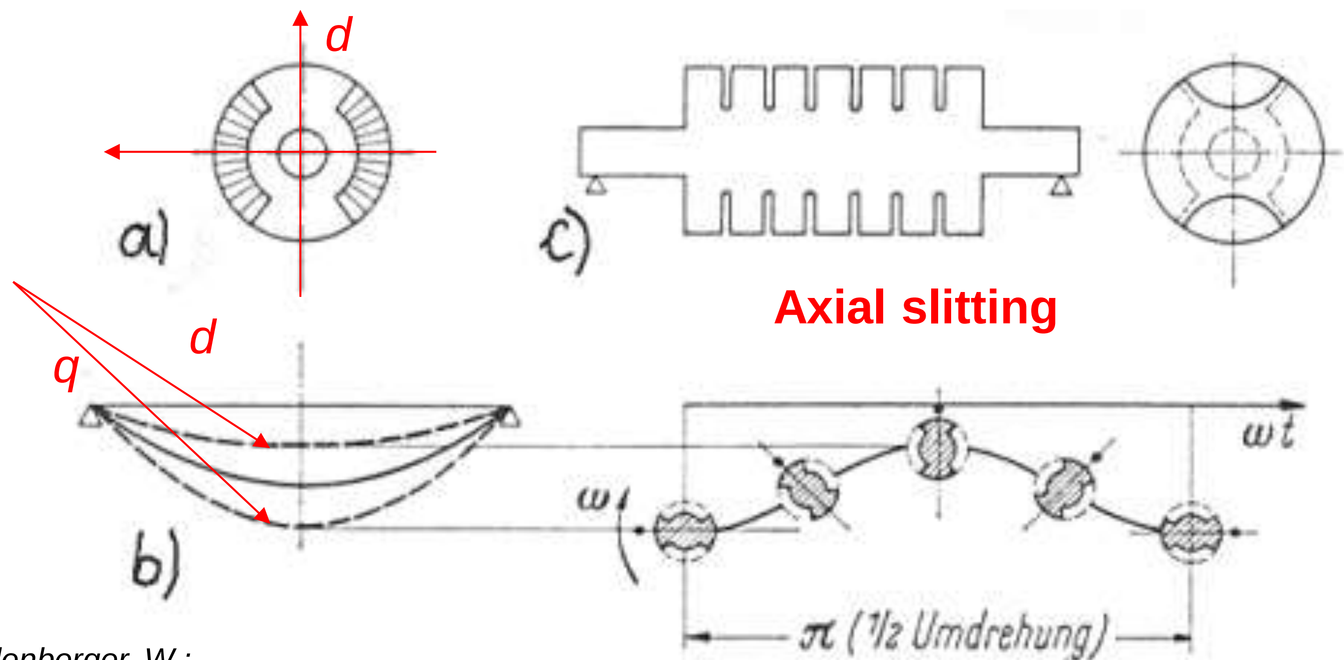
$$f_b^* = \frac{1}{2\pi} \cdot \sqrt{\frac{c-k}{m_r}}$$

7. Forces in big synchronous machines

	Salient pole generator	Turbine generator
Data:	1.12 MVA, 50 Hz, $2p$ = 4, 1500 / min	125 MVA, 50 Hz, $2p$ = 2, 3000 / min
$B_{\delta 1}$ / T	0.7	0.8
d / l	0.555 m / 0.49 m	1.06 m / 5.6 m
δ / mm	7.5	52.5
Rotor mass m_r	1350 kg	47140 kg
Bending natural frequency f_b	36.67 Hz (⇔ 2200 /min)	18.17 Hz (⇔ 1090 /min)
Calculations:		
c / N/mm	71666	615088
k / N/mm	11105	22613
k/c	0.155	0.0368
Reduction of frequency	0.92	0.981
Static bending y	0.185 mm	0.75 mm
Static bending with pull y^*	0.22 mm	0.78 mm
y^*/δ	3 %	1.5 %

Influence of slotting on rotor bending in two pole machines

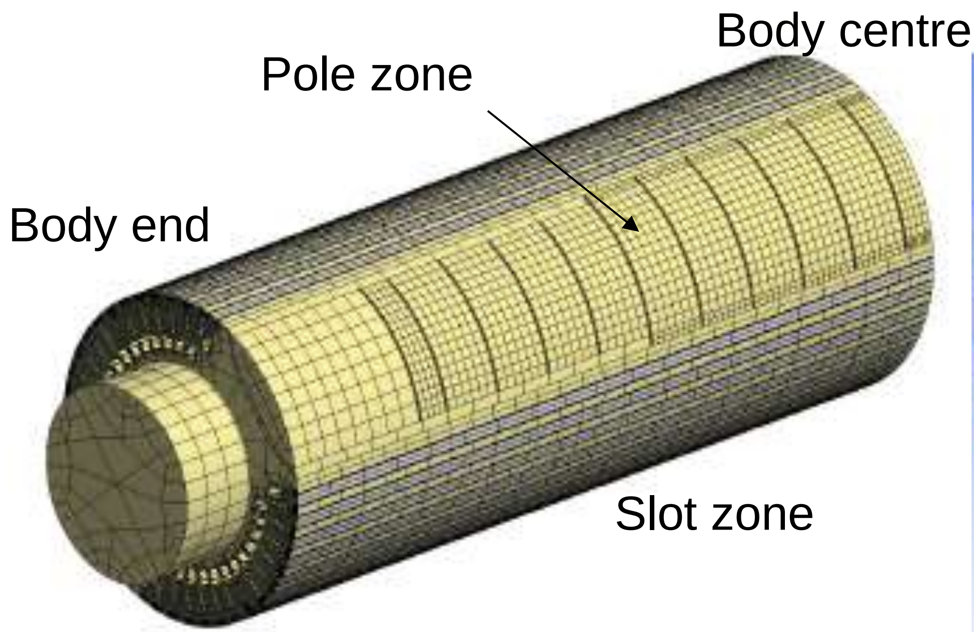
- Rotor stiffness in *d*-axis bigger than in *q*-axis due to rotor slotting.



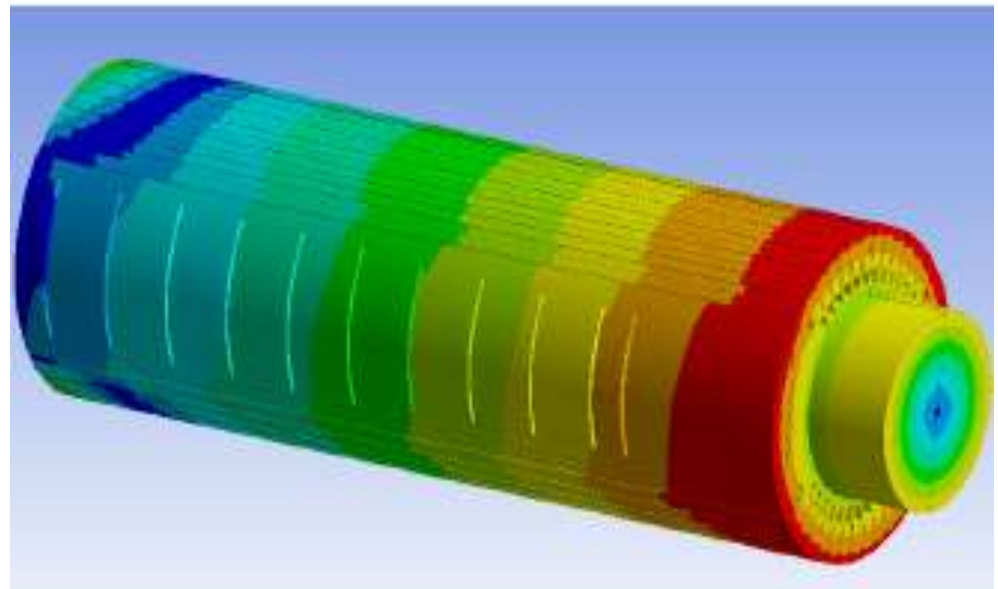
Source: Wiedemann, E.; Kellenberger, W.; Springer-Verlag, 1968

- **Rotor stiffness in *y*-direction varies with rotor position, hence with 2*n*.**
- **This leads to mechanical excitation of bending oscillation with 2*n*.**
- **Axial slitting of poles reduces *d*-axis stiffness; to be equal to *q*-axis stiffness.**

Finite element calculation of a two-pole rotor: Bending and torsional deformations



Finite element three-dimensional model of ONE HALF of a two-pole turbine generator rotor



Calculated **torsional** deformation:

Yellow/Red: Big torsion deformation
Blue: Small torsion deformation

Source: Alstom, Switzerland

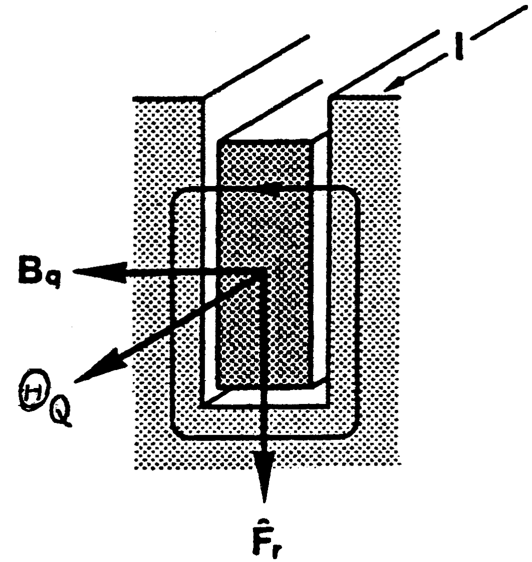
Summary:

Single sided magnetic pull at eccentric rotor position

- Static and dynamic rotor eccentric position: Magnetic pull is directed to minimum air gap location
- Constant magnetic force
- At 2-pole machines: Pulsating radial force with $f = 2n$
- Dynamic eccentricity in d-axis direction: Radial force is zero

- Influence on rotor natural bending frequency: Reduction of elasticity due to negative „magnetic“ spring
- Axial slitting of poles to equalize q-axis and d-axis stiffness

7. Forces in big synchronous machines



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Source: Neidhöfer, G.; BBC, Switzerland

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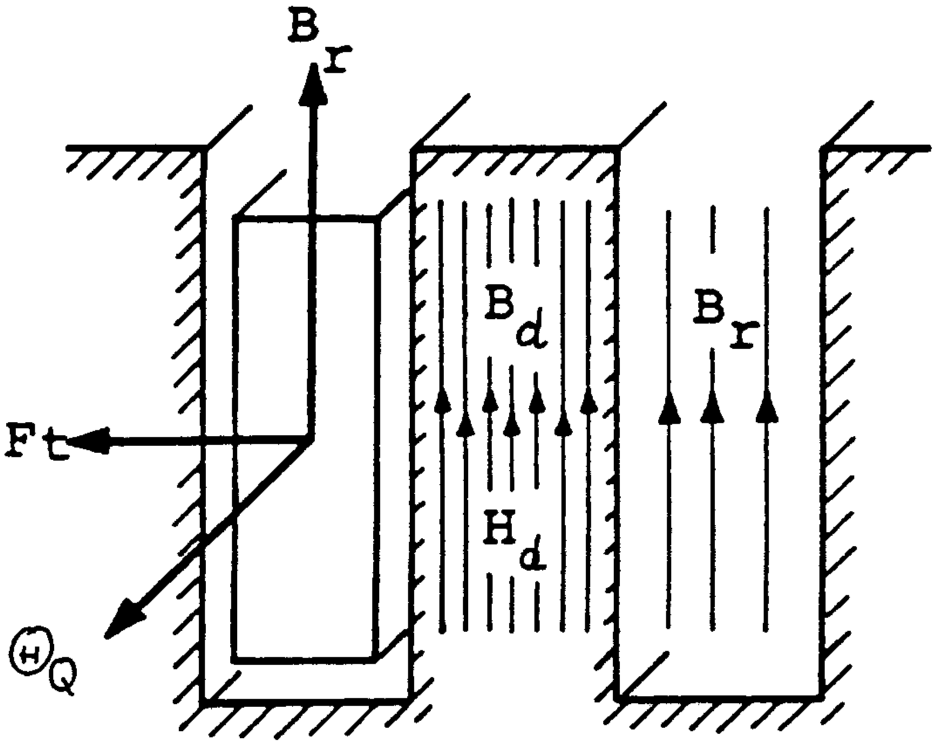
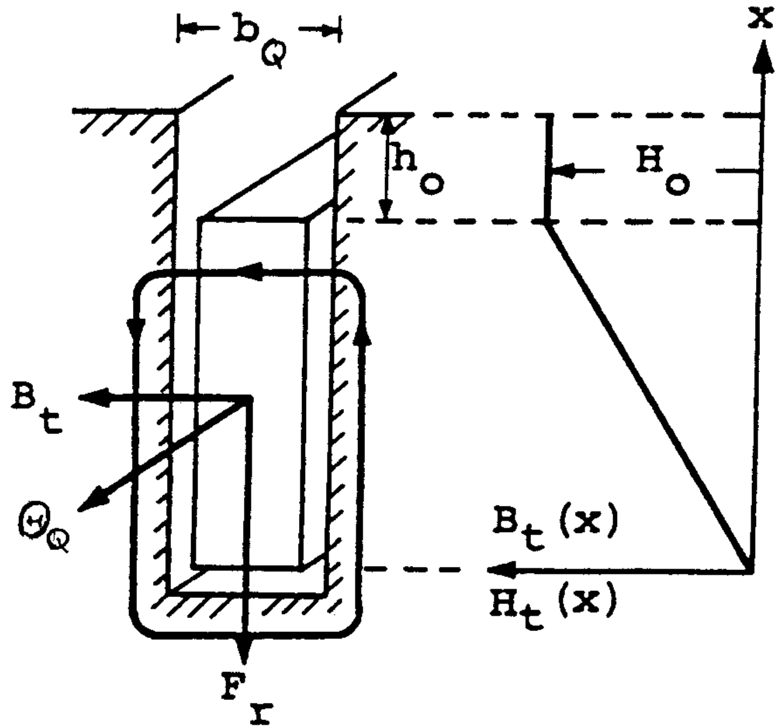


Tangential force due to radial field of rotor



Radial force due to slot leakage self field

Source: Neidhöfer, G.; BBC, Switzerland

Where is the tangential force localized ?

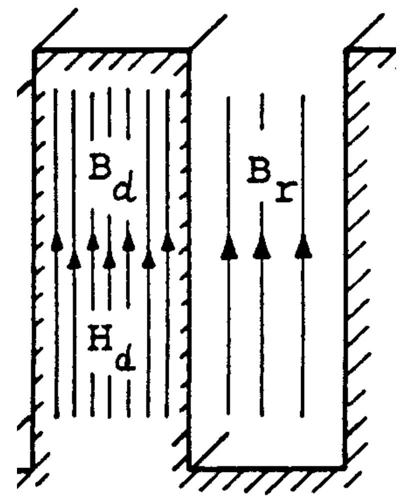
NOT at the conductor, <u>but</u> AT the tooth!

Tangential force per slot pitch: $F_\tau = l \cdot \Theta_Q B_\delta$

Radial flux density in the slot: $B_r \approx \mu_0 H_d$

Tangential force at the slot conductor: $F_t = l \cdot \Theta_Q \cdot B_r$

$$F_t / F_\tau = B_{r,Q} / B_\delta$$

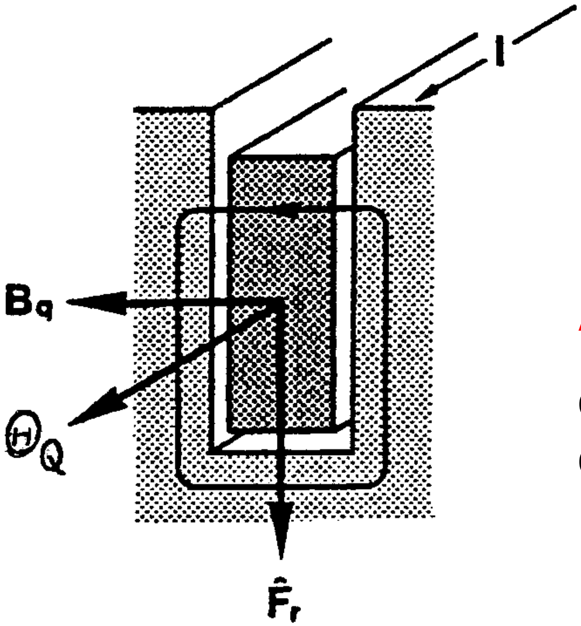


Example: **The force on the slot conductor is only 2% of the total force per slot pitch, which mainly acts as tangential magnetic pull on the tooth side.**

$$F_t / F_\tau = B_{r,Q} / B_\delta = 0.016 / 0.9 = 0.018 \simeq \underline{\underline{1/50}}$$

Source: Neidhöfer, G.; BBC, Switzerland

Radial conductor forces hammer with 50 Hz on the slot insulation



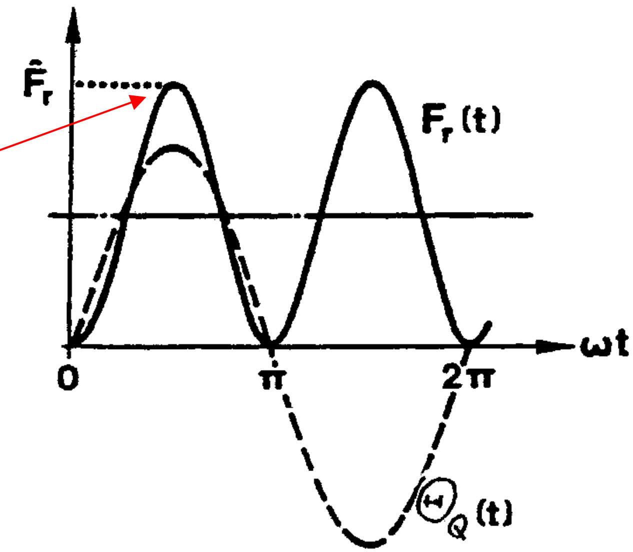
Peak pressure:

$$\hat{f}_r = \hat{F}_r / (b_Q \cdot l) = \frac{\mu_0}{2} \cdot \frac{\hat{\Theta}_Q^2}{b_Q^2}$$

At sudden short circuit:

e.g. current is 12-times rated current: **38 MPa !**

Source: Neidhöfer, G.; BBC, Switzerland

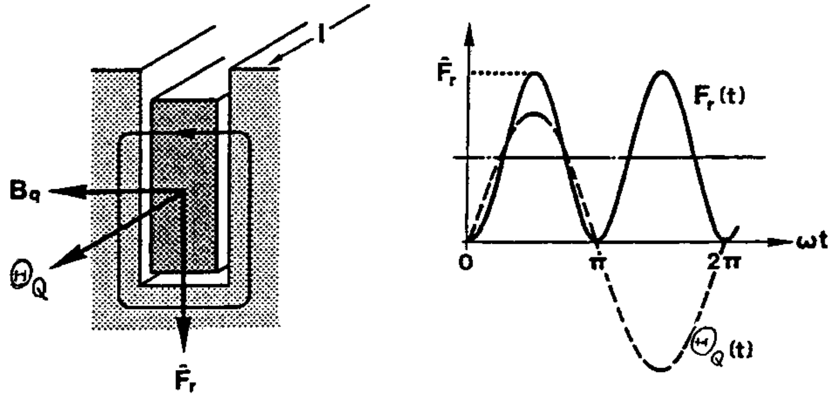


- Single layer winding, AC current: $Q_Q(t) = \hat{\Theta}_Q \sin(\omega t)$ $\quad B_Q(t) = \mu_0 \dfrac{\Theta_Q(t)}{b_Q}$

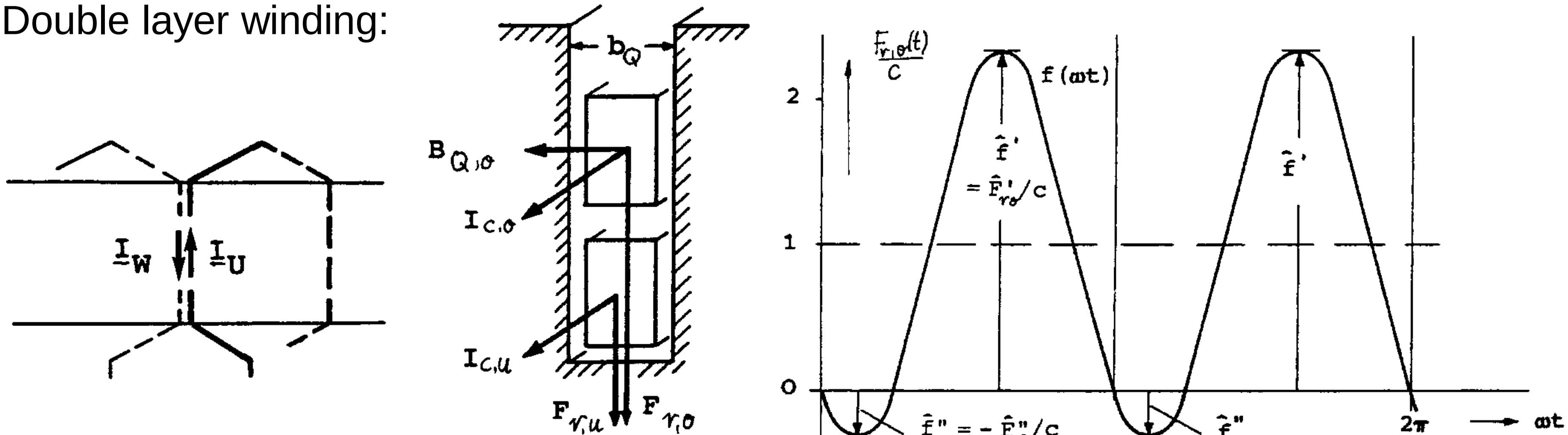
$$F_r(t) = l \cdot \Theta_Q(t) \cdot B_Q(t) = \frac{\mu_0}{2} \cdot \frac{l}{b_Q} \cdot \hat{\Theta}_Q^2 \cdot \sin^2(\omega t)$$

Double-layer winding: Radial hammering force is reduced

Single layer winding:

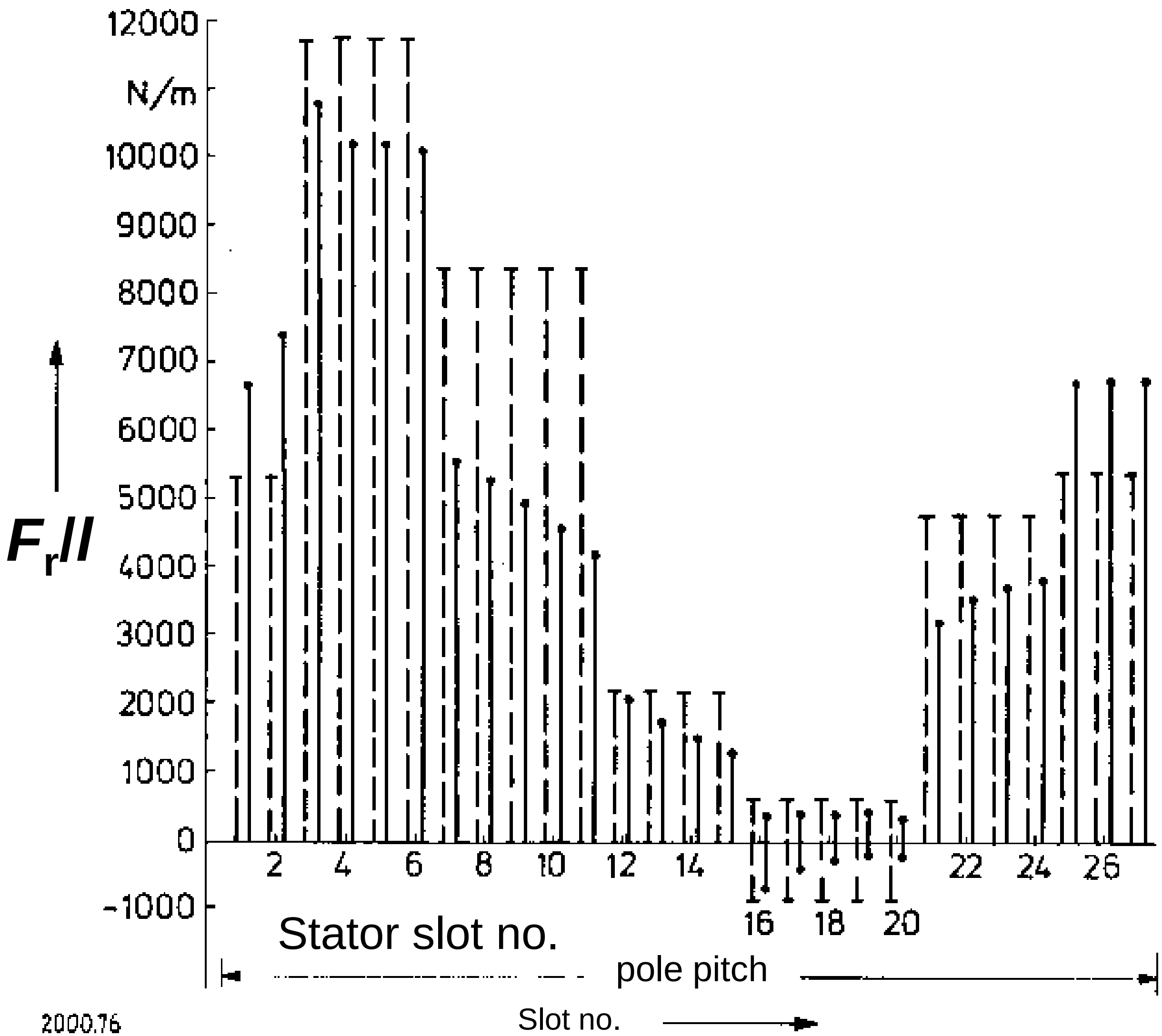


Double layer winding:



Source: Neidhöfer, G.; BBC, Switzerland

7. Forces in big synchronous machines



1500 MVA, 4-pole turbine generator, *Biblis/Germany*

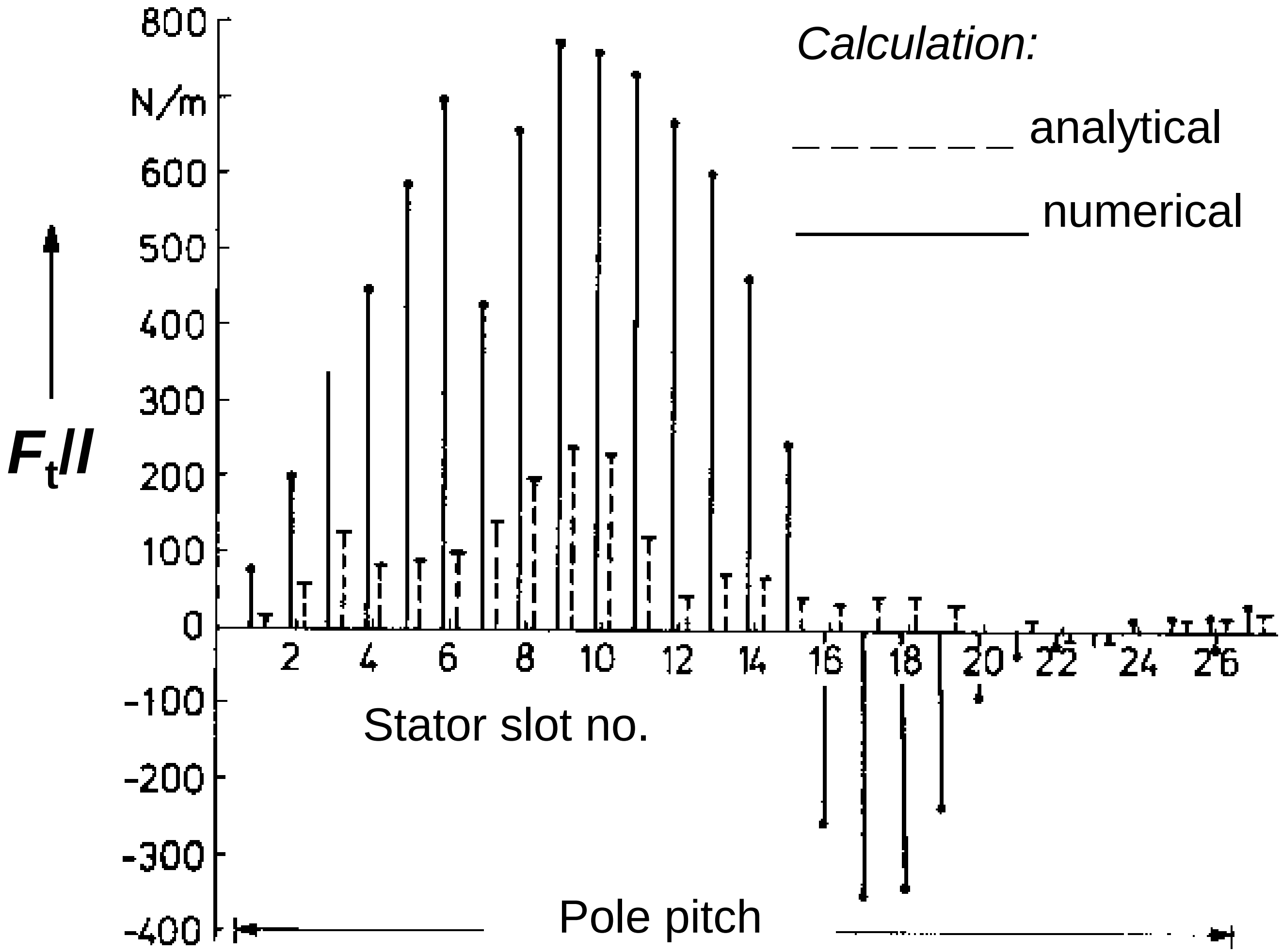
Calculated amplitudes of radial forces per axial length on stator slot conductors, 27 slots per pole,
$q_s = 9$, $m_s = 3$,
pitching $W/\tau_p = 22/27$

_ _ _ _ _ _ _ analytical calculation

__________ numerical calculation

Source: AEG, Germany

7. Forces in big synchronous machines

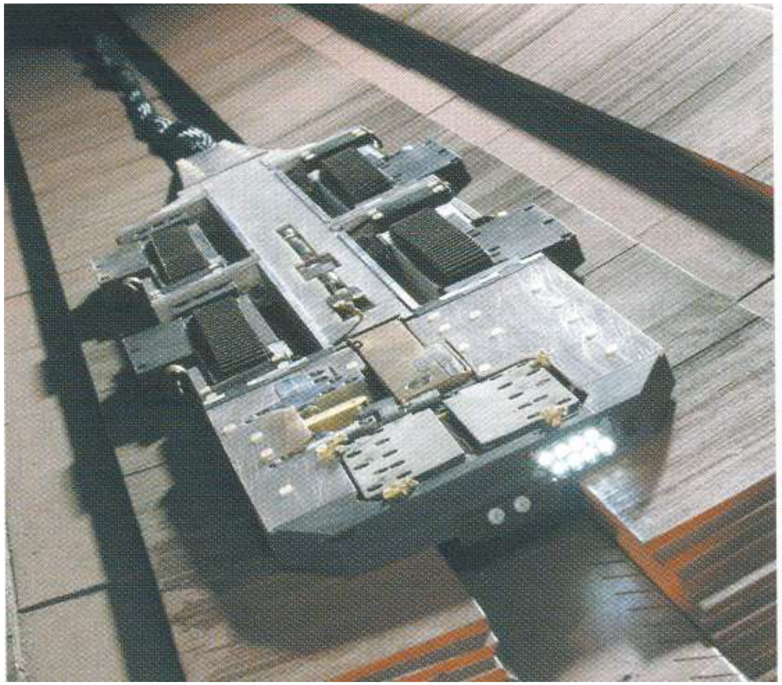


1500 MVA, 4-pole turbine generator, *Biblis/Germany*

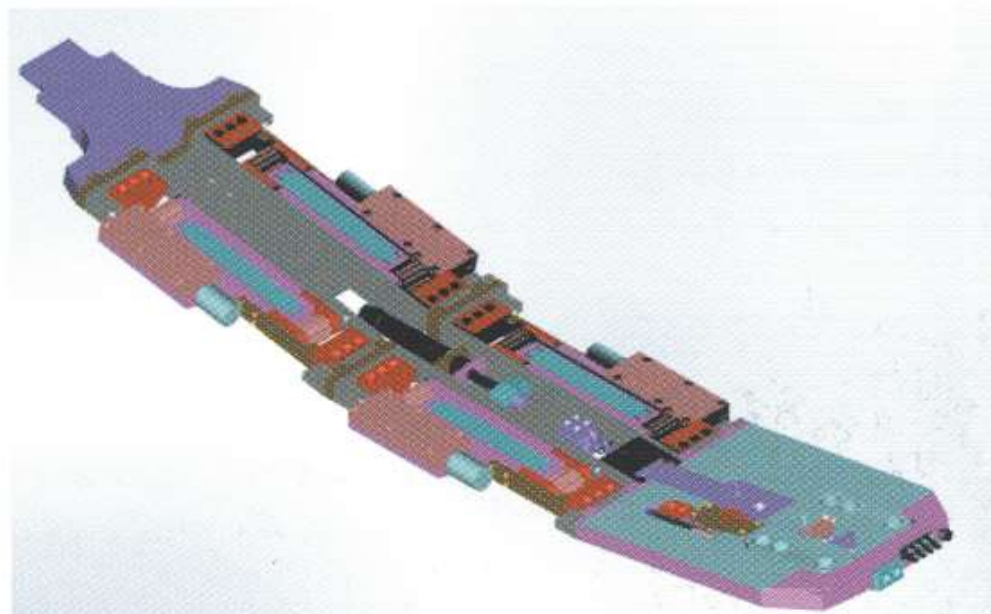
Calculated amplitudes of tangential forces per axial length on stator slot conductors, 27 slots per pole, $q_s = 9$, $m_s = 3$, pitching $W/\tau_p = 22/27$

Source: AEG, Germany

Monitoring of turbine generator stator wedges on-site



Wedge Tightness Carriage inspects tightness of stator wedge; rotor is removed (may also be in-situ).



3D view of Carriage: Flexible articulation of robotic carriage helps access also in machines with narrow axial clearances

Source:

Siemens AG, Mülheim/Ruhr, Germany

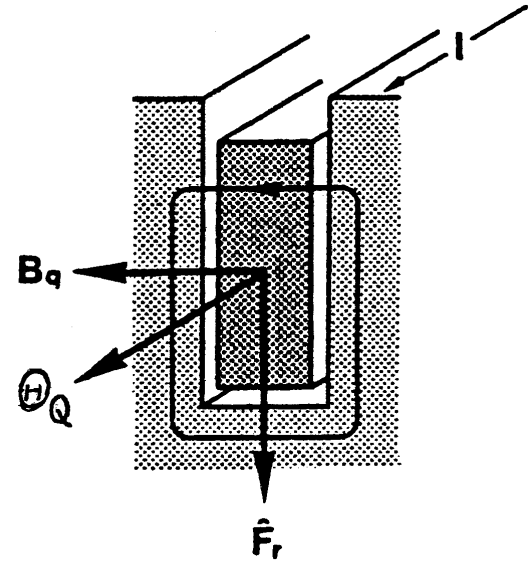
Summary:

LORENTZ forces on slot conductors

- Tangential conductor force due to radial field of rotor
  - Rather small, since total force mainly acts as tangential magnetic pull on the teeth

- Radial force due to slot leakage field
  - Strong stator-frequent pressure inward against the slot insulation
  - Double layer winding reduces hammering force due to pitching of coils

7. Forces in big synchronous machines



7.1 Torque generation

7.2 Radial forces at centric rotor position

7.3 Single sided magnetic pull at eccentric rotor position

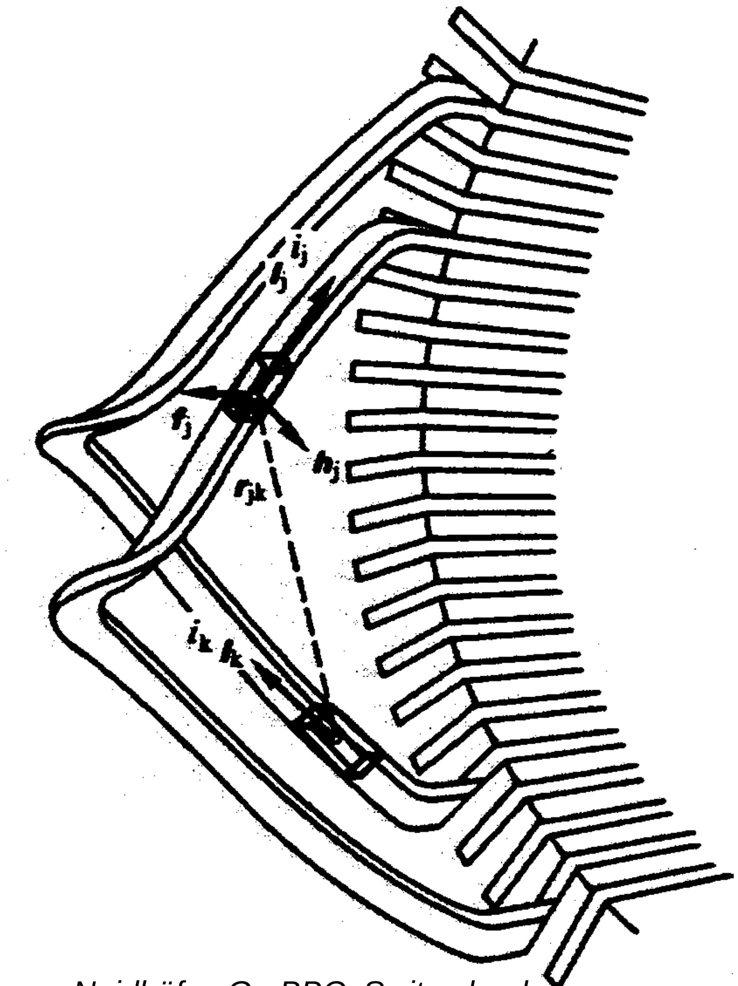
7.4 *LORENTZ* forces on slot conductors

7.5 LORENTZ forces on winding overhang conductors

7.6 Rotor pole fixation in large synchronous machines

Source: Neidhöfer, G.; BBC, Switzerland

7.5 *LORENTZ* forces on winding overhang conductors



Source: Neidhöfer, G.; BBC, Switzerland

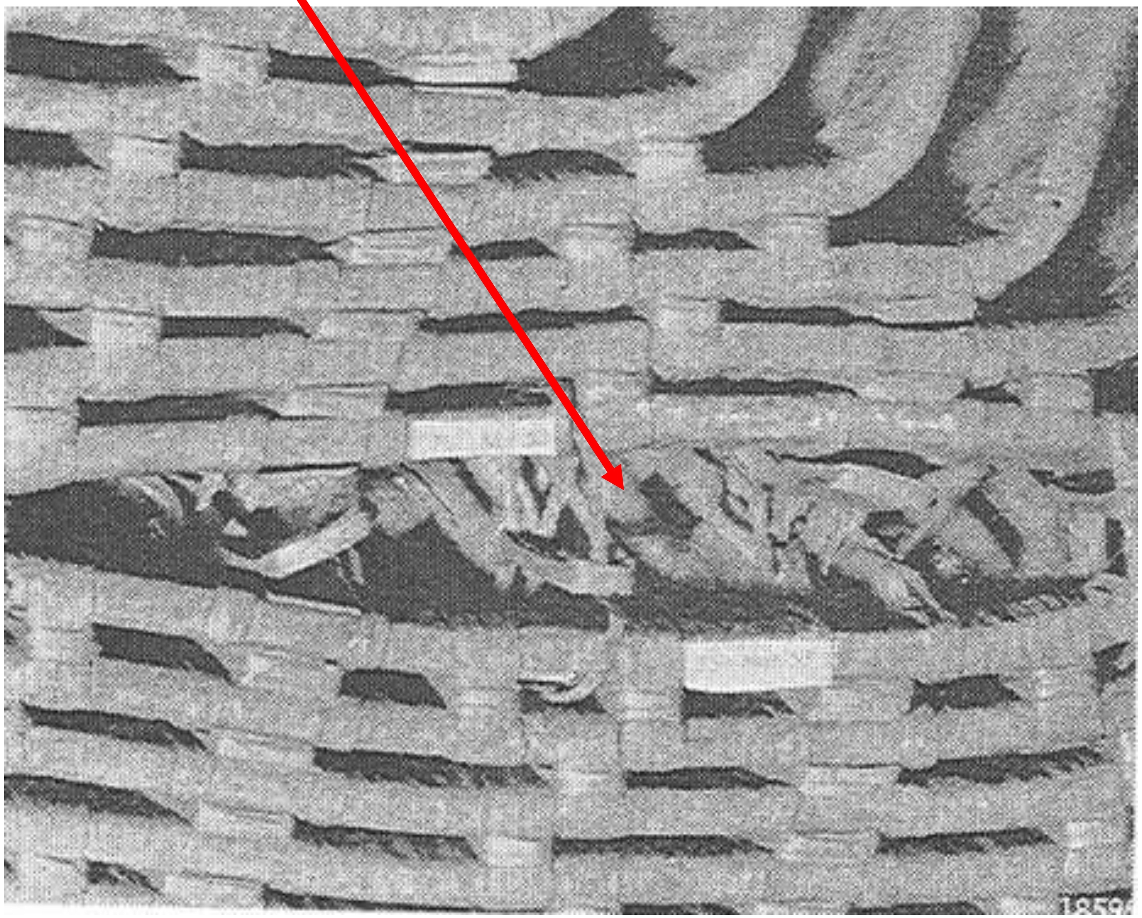
- ***LORENTZ* forces between adjacent coil sides**
- **Attraction of coils sides of the same phase.**
- **Repulsion of coil sides of different phases.**

- **Extreme forces at sudden short circuit:**
- **e.g. 12 times rated current: 144-times of rated forces.**

$$F(t) = \frac{\mu_0}{2\pi} \cdot \frac{L}{a} \cdot i_1(t) \cdot i_2(t)$$

- ***L:* length of conductor section**
- ***a:* distance between conductor centre lines**

Damage of winding overhang at phase separation after sudden short circuit



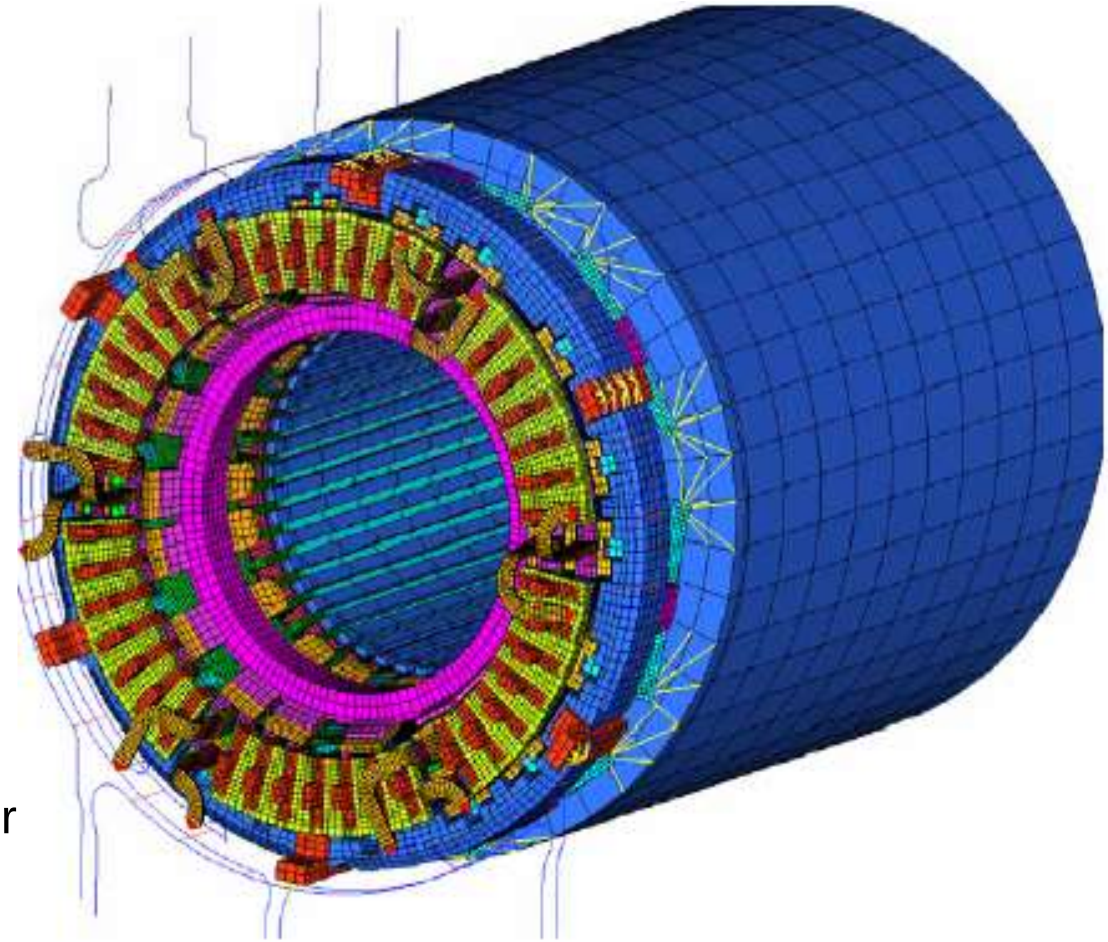
Source:

BBC, Switzerland

Special fixations of the winding overhang are needed, especially in large, two-pole machines !

Source: Andritz Hydro, Austria

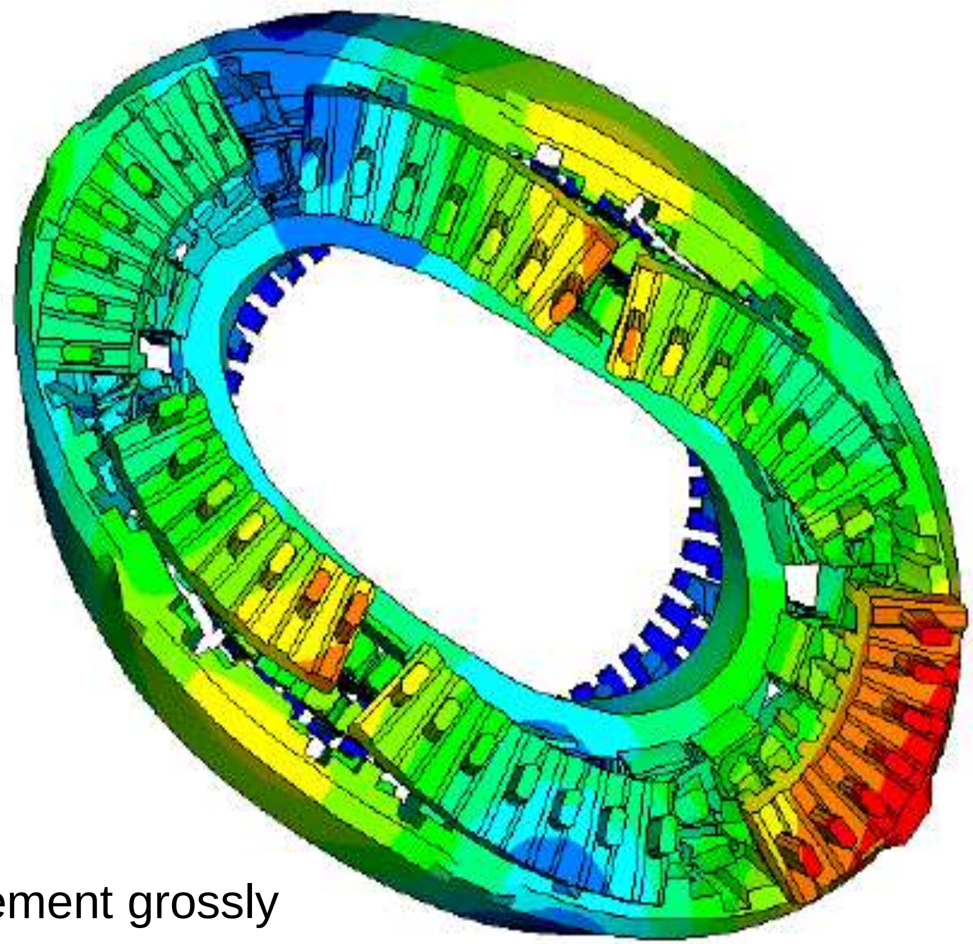
3D finite element model of stator end winding zone



Turbine generator

Source: Alstom, Switzerland

Calculated four-node vibration mode of the stator end winding

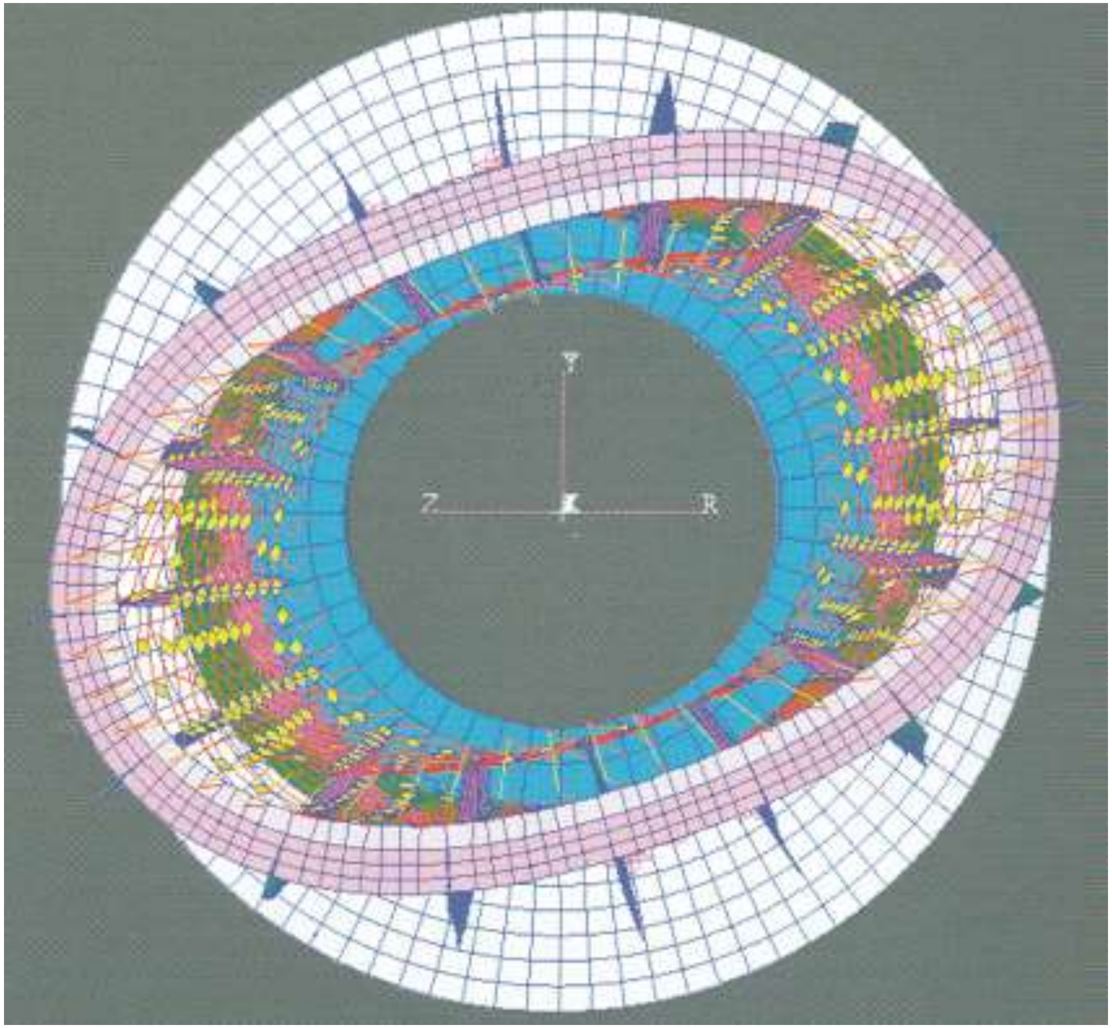


Turbo generator

Calculated displacement grossly exaggerated

Source: Alstom, Switzerland

7. Forces in big synchronous machines



Generator end winding modelling

3D finite element calculation of end winding elliptical vibration mode (4-node vibration mode)

Calculated displacement grossly exaggerated

Source:

Siemens AG, Mülheim/Ruhr, Germany

Large Generators and High Power Drives

Summary:

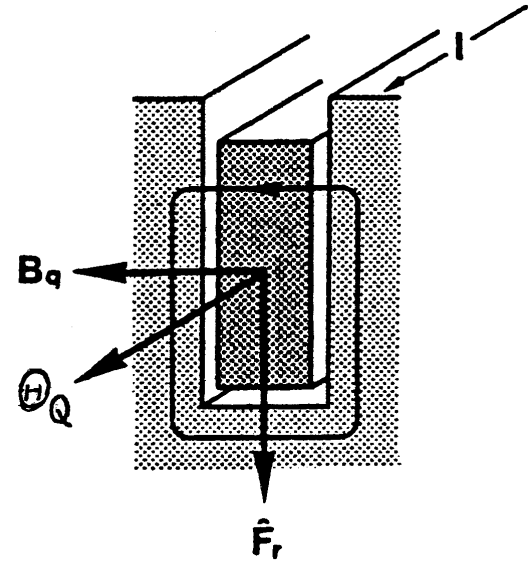
LORENTZ forces on winding overhang conductors

-Attracting and repulsing forces between coil sides of the same phase, depending on the phase shift of neighbouring currents of different phases

$$F \sim I_1 \cdot I_2$$

- Big critical pulsating forces in case of sudden short circuit
- Special fixations of the winding overhang necessary

7. Forces in big synchronous machines



7.1 Torque generation

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7.4 *LORENTZ* forces on slot conductors

7.5 LORENTZ forces on winding overhang conductors

7.6 Rotor pole fixation in large synchronous machines

Source: Neidhöfer, G.; BBC, Switzerland

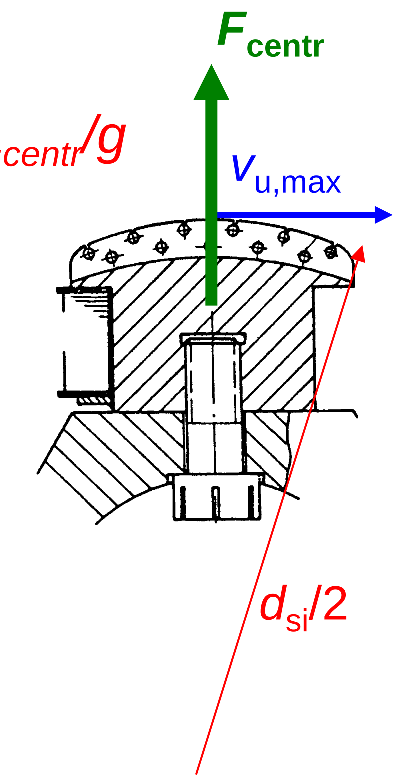
7.6 Rotor pole fixation in large synchronous machines

Rotor surface velocity (at over-speed): $v_{u,\max} = d_{si} \cdot \pi \cdot n_{\max}$ $\sigma_t = \rho \cdot v_{u,\max}^2 < \sigma_{zul}$

Centrifugal acceleration: $a_{centr} = \dfrac{v_{u,\max}^2}{d_{si}/2}$

"specific centrifugal force *f*" = centrifugal force F_{centr}/gravity: a_{centr}/g

$$F_{centr} = m \cdot \frac{v_{u,\max}^2}{d_{si}/2} \qquad f = \frac{F_{centr}}{m \cdot g} = \frac{v_{u,\max}^2}{g \cdot d_{si}/2} = \frac{a_{centr}}{g}$$



Source: Gregori, F.; TU Wien

A) Screwed poles

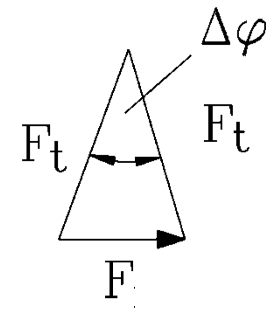
B) Dove-tail fixation

C) Double-dove tail / Hammer fixation

D) Double hammer fixation (or three hammers)

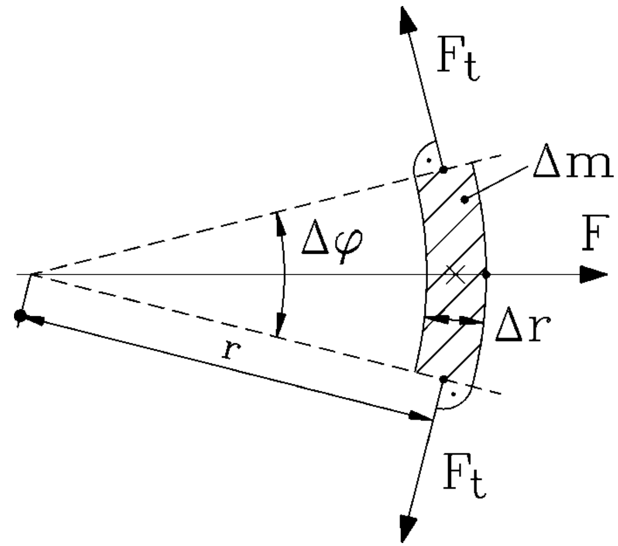
E) "Bolted comb" (nowadays not any longer used, too expensive)

Tangential mechanical stress due to radial centrifugal force



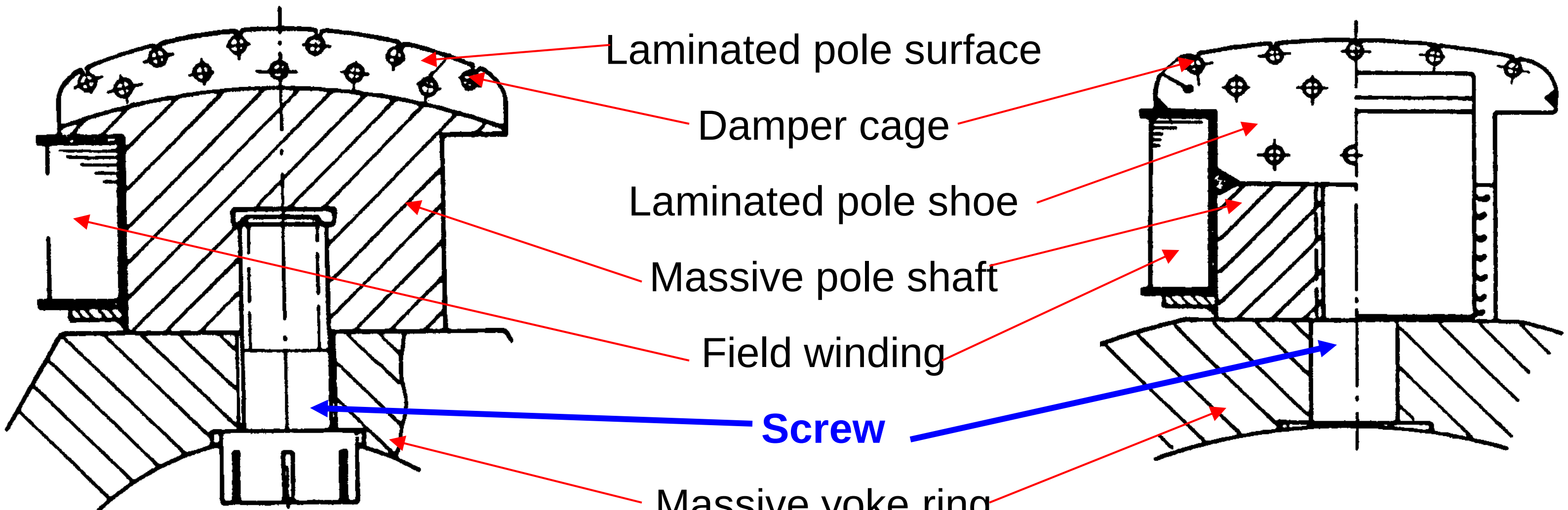
Example: Steel cylinder fixation of rotor winding overhang

- Mass element of rotor (angle $\varphi << 1$) :
  $dm = \rho \cdot r \cdot \varphi \cdot dr \cdot l$
- Centrifugal force per mass element:
  $dF = dm \cdot r \cdot \Omega_m^2, \quad \Omega_m = 2\pi n$
- mechanical tangential forces:
  $$2 \cdot dF_t \cdot \sin(\varphi/2) = dF \quad \rightarrow \quad dF_t = \frac{dF}{2\sin(\varphi/2)} \approx \frac{dF}{\varphi}$$
- **tangential tensile stress :**
  $$\sigma_t = \frac{dF_t}{l \cdot dr} \approx \frac{dF}{l \cdot dr \cdot \varphi} = \rho \cdot (r\Omega_m)^2 = \rho \cdot v_u^2 < \sigma_{zul}$$



$$\sigma_t = \rho \cdot v_u^2 < \sigma_{zul}$$

A) Screwed poles: $v_{u,max}$ = 110...120 m/s



Massive pole, laminated pole surface

Massive pole shaft, laminated pole shoe

$$a_{centr} / g \leq 600..800$$

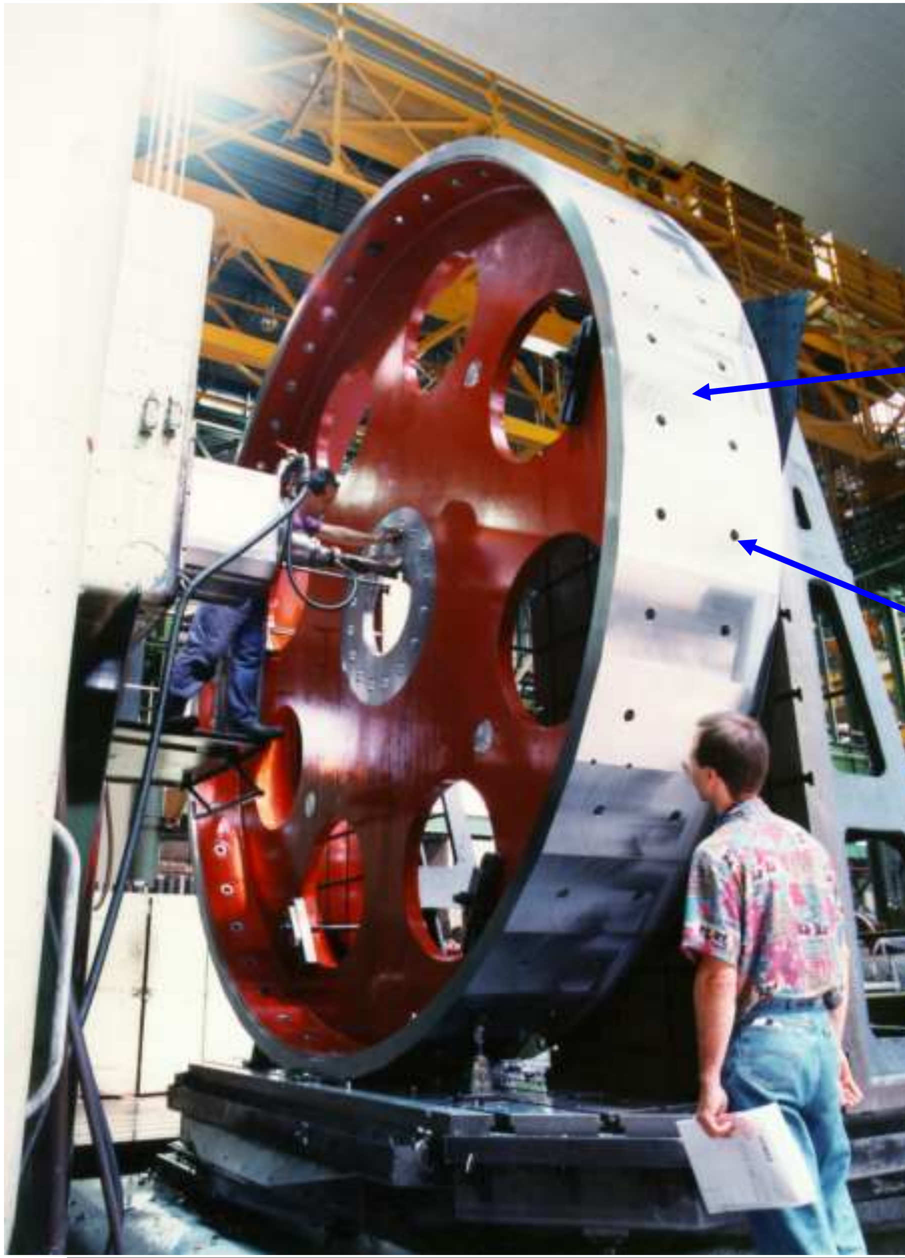
Source: Gregori, F., TU Wien

Example:

River hydro plant, *Kaplan* turbine, *Friesach* (River *Drau)/Austria*, Bulb turbine generators, 48 poles, 8.5 MVA, 50Hz, d_{si} = 4.34 m, n_N/n_{max} = 125/395/min,

$v_{u,max}$ = 90m/s, a_{centr}/g = 380.

Screwed rotor poles



Massive rotor yoke ring of a bulb type hydro power generator for low speed, high pole count

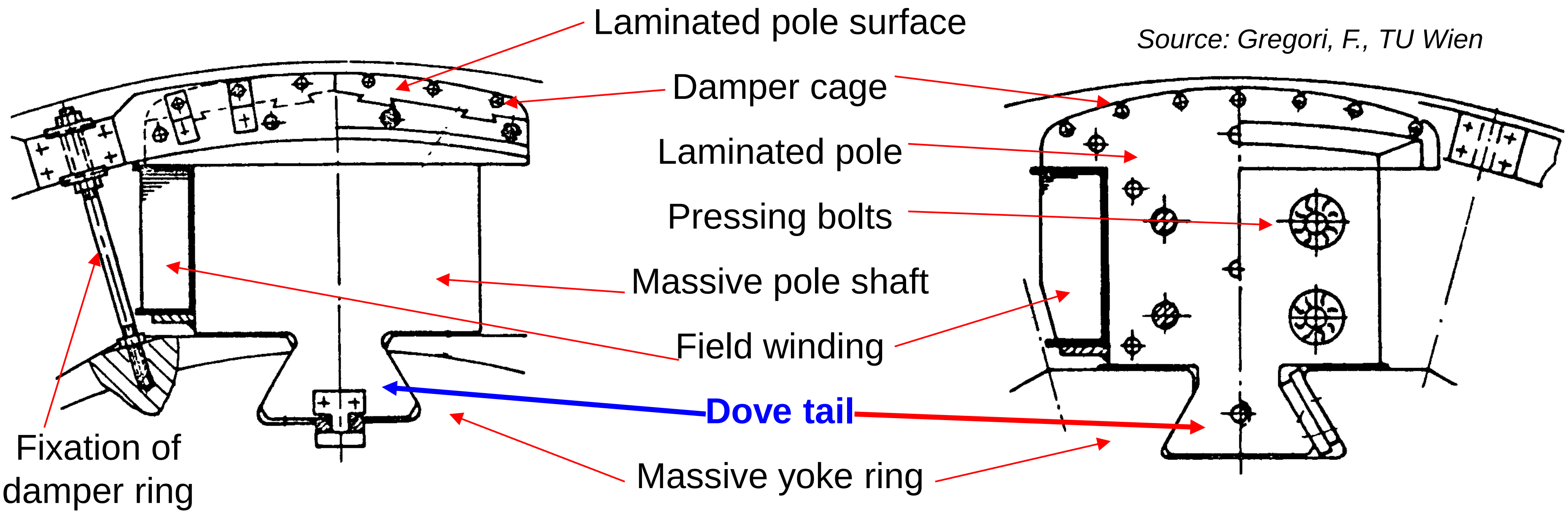
River power plant, *Kaplan* turbine drive

Holes to screw the poles

Source:

Andritz Hydro, Austria

B) Dove-tail fixation $v_{u,max}$ = 130...180 m/s



Massive pole, laminated pole surface

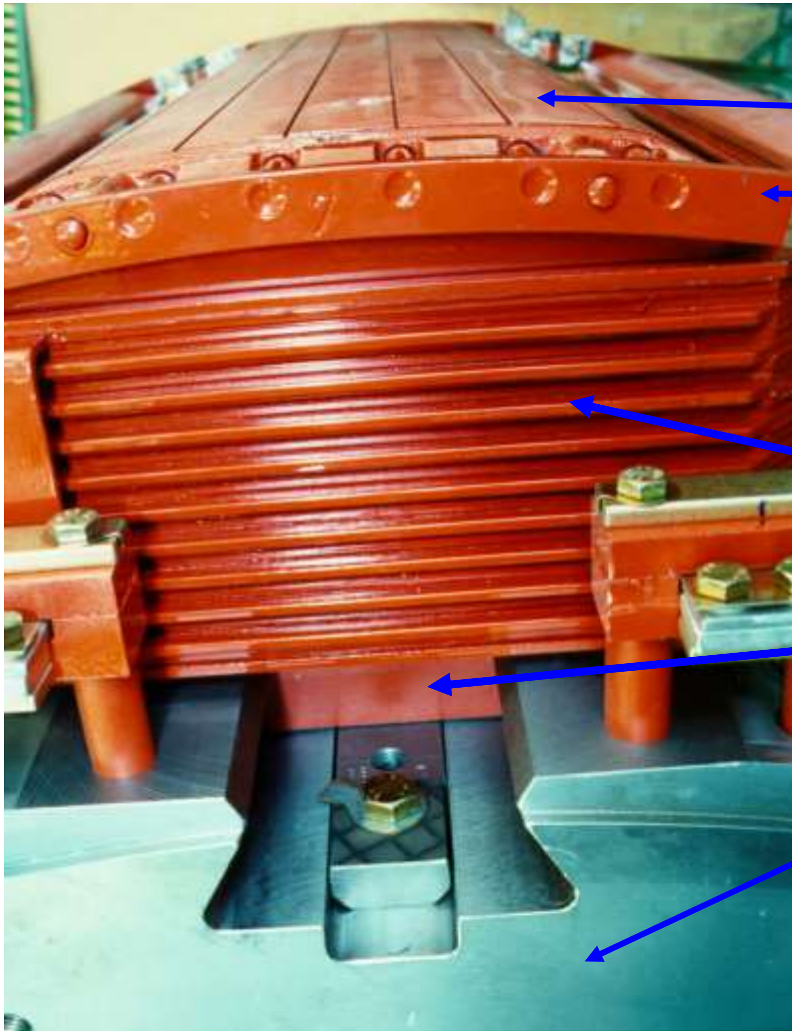
Laminated pole, pressed with bolts

Massive poles: $a_{centr} / g \leq 1850$ Laminated poles: $a_{centr} / g \leq 1300..1500$

Example:

Double dove tail fixation, laminated poles: Hydro power plant *Shi San Ling/China*, 12 poles, 222 MVA, 50 Hz, d_{si} = 4.5 m, n_N/n_{max} = 500/725/min, $\boldsymbol{v_{u,max}}$ **= 170 m/s,** $\boldsymbol{a_{centr}/g}$ **= 1322**

Dove-tail fixation



Laminated pole surface

Damper cage (bars and ring)

Field winding

Dove tail fixation

Massive yoke ring

Source:

Andritz Hydro, Austria

Dove-tail fixation

Damper cage (bars and ring)

Field winding

Dove tail fixation

Massive yoke ring

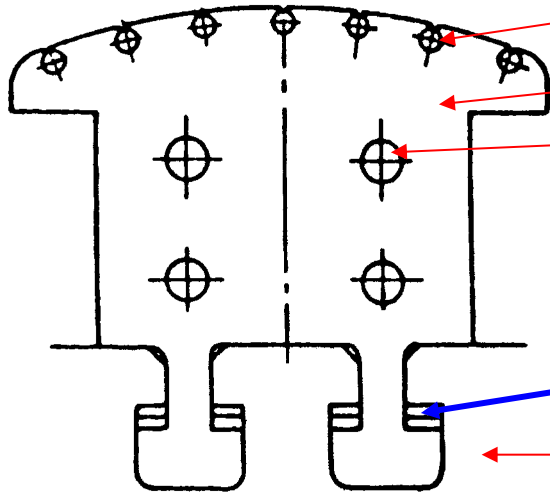
Source:

Andritz Hydro, Austria

D) Hammer fixation: $v_{u,max}$ = 180 ... 200 m/s

$a_{centr}/g \sim 2000$

Source: Gregori, F., TU Wien



Laminated pole, pressed with bolts, double hammer fixation

Examples:

Double hammer fixation: Storage plant *Kühtai/Austria*, 10 poles, n_N = 600/min, 167 MVA, 50 Hz, d_{si} = 3.4 m, n_{max}/n_N = ca. 1.7, **$v_{u,max}$ = ca. 180 m/s, a_{centr}/g = ca. 2000**

Four-fold hammer fixation: Single phase hydro power plant (German railways): *Langenprozelten (river Main)/Deutschland*, 4 poles, 16.7 Hz, n_N/n_{max} = 500/757/min, 94 MVA, d_{si} = 3.5 m, **$v_{u,max}$ = 139 m/s, a_{centr}/g = 1121,** Pole mass 31 t (!)

7. Forces in big synchronous machines

Triple hammer fixation of rotor poles

Triple hammer fixation of rotor poles

Pump storage power plant *Vianden /Luxembourg*

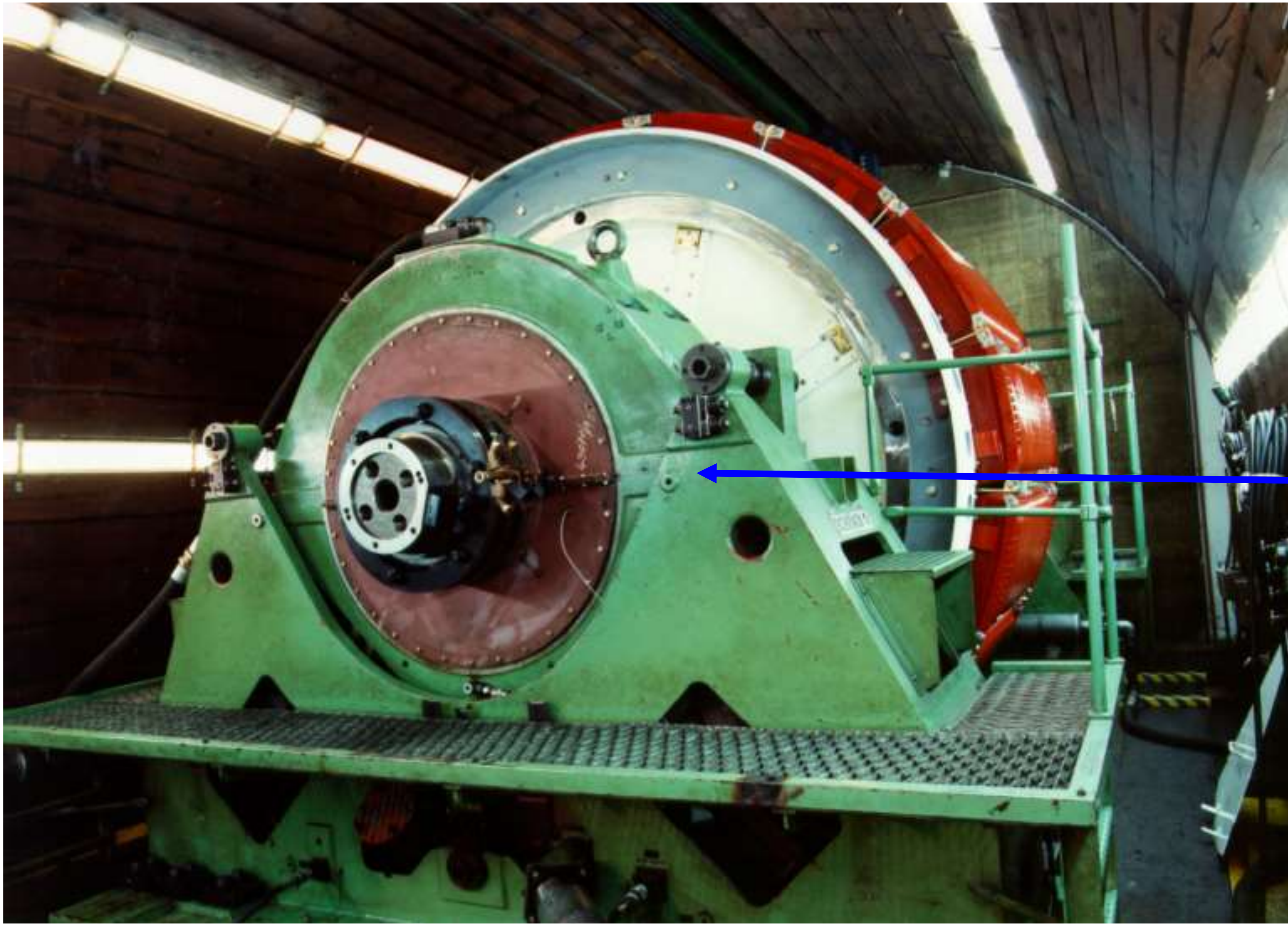
Refurbishment of rotor winding

Laminated pole, massive pressure plates at the pole ends

Source:

Andritz Hydro, Austria

7. Forces in big synchronous machines



Balancing and over-speed test of salient pole rotor

Special bearings to measure unbalance, manufactured by *Schenck/Darmstadt*

Source:

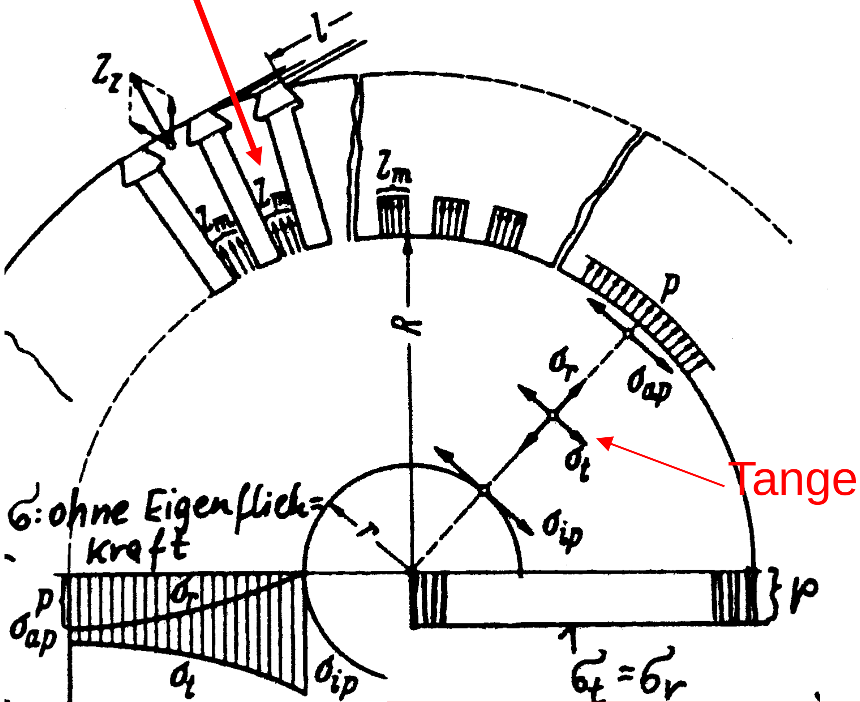
Andritz Hydro, Austria

7. Forces in big synchronous machines

Cylindrical rotor synchronous machines: $v_{u,max}$ = 215 ... 235 m/s

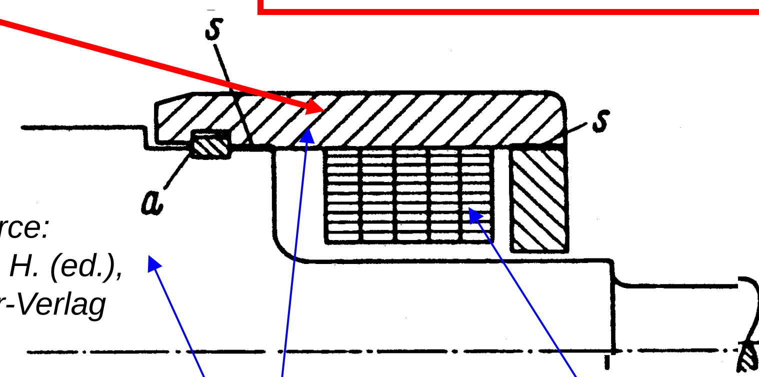
- Tangential mechanical stress in steel cylinder fixation of rotor winding overhang
- Radial stress in rotor teeth

a_{centr}/g up to 10000



Tangential stress

Source: Wiedemann, E.; Kellenberger, W.; Springer-Verlag, 1968



Source: Sequenz, H. (ed.), Springer-Verlag

Winding fixation

End winding overhang

Massive rotor body

Max. diameter d_{si} = 1.25 m, n_N = 3000/min, 50 Hz, n_{sch}/n_N = 1.2,
$v_{u,max}$ = 236 m/s, a_{centr}/g = 9050

7. Forces in big synchronous machines

Cylindrical rotor synchronous machines

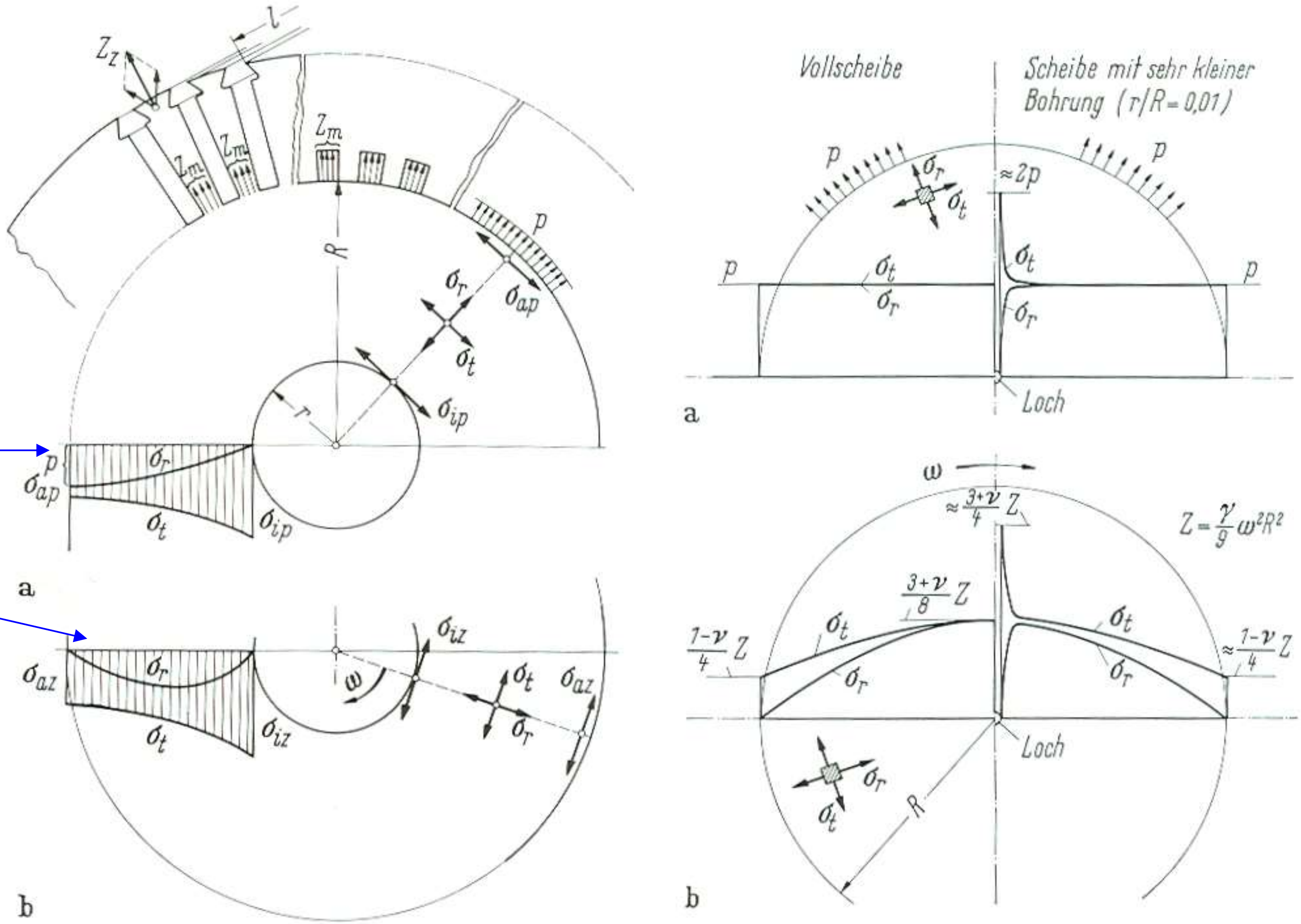
Tangential and radial mechanical stress

a) due to rotor teeth and winding

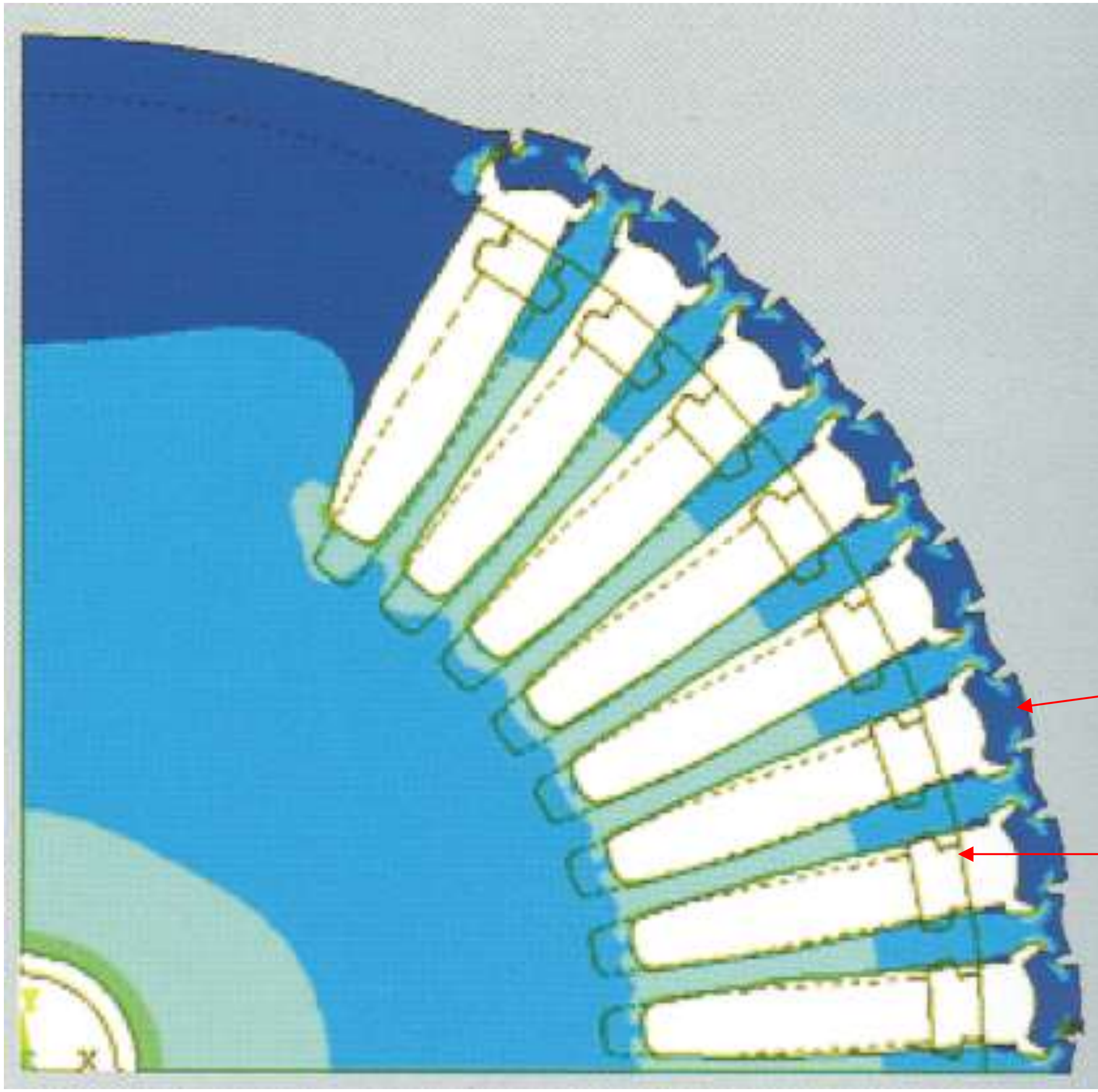
b) due to rotor yoke mass

Rotor body without central hole **has 50% lower stress!**

Source: Wiedemann, E.; Kellenberger, W.; Springer-Verlag



7. Forces in big synchronous machines



Finite element simulation of rotor deformation (exaggerated) at over-speed test

Two-pole turbine generator,
125 % over-speed

Deformation
(exaggerated)

Original geometry

Source:

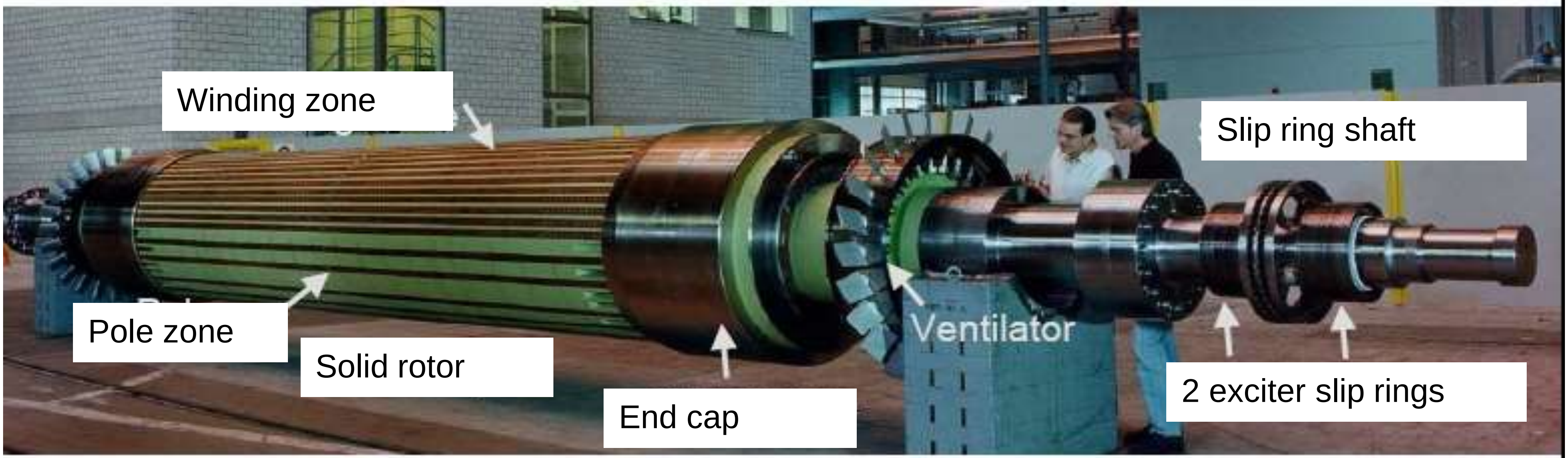
Siemens AG, Mülheim/Ruhr, Germany

7. Forces in big synchronous machines

Largest mechanical stress in Two-Pole Turbine Generators

Example: f_s = 50 Hz: Largest possible power: 1 GW at 50 Hz, n = 3000/min
Rotor diameter: d = 1.25 m: v = 188 m/s = 676 km/h at $2p$ = 2, l_{Fe} = 8 m
- Bigger rotor diameters not possible due to limited strength of steel
- Longer rotors not possible due to strong rotor bending

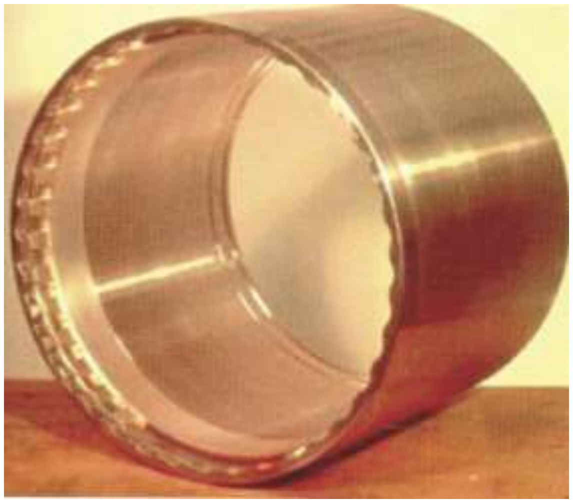
Source: Alstom Power Generation, Mannheim



Manufacturing of Hydrogen gas-cooled Two-pole Rotor, 1 GW, *Lippendorf/Germany*

7. Forces in big synchronous machines

Two-Pole Generator Rotor End Winding Retaining Cap



Modern stainless steel end caps: resistant to stress corrosion cracking due to Cr content e.g.: Fe-18Mn-18Cr-0.05C-07N steel ("18:18 steel")

2-pole generator: End cap failure (ca. 1975): non-magnetic austenitic manganese steel, sensible to stress corrosion cracking in moisture or aggressive halogen atmosphere

Source: Electra, April 2012

Summary:

Rotor pole fixation in large synchronous machines
- Fixation of the poles against centrifugal forces
- Increased mechanical requirements with rising circumferential speed
- Fixation types for salient rotor machines:
    - Screwed poles
    - (Double) Dove-tail fixation
    - (Double/triple) Hammer fixation
- Extreme mechanical stress in cylindrical rotor machines especially at two-pole machines: centrifugal acceleration up to 10000-times gravitational acceleration
- Retaining rings as end winding fixation

That´s all, folks !