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

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. Forces in big synchronous machines

7.1 Torque generation

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

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

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

\[
A(x) = \hat{A} \cdot \sin\left(\frac{x\pi}{\tau_p} - \phi_i\right) \quad \hat{A} = k_{w1} \cdot \sqrt{2} \cdot A
\]

\[
B_\delta(x) = B_{\delta_1} \sin\left(\frac{x\pi}{\tau_p}\right)
\]

\[
M = l \cdot (p \tau_p)^2 \cdot \hat{A} \cdot B_{\delta_1} \cdot \cos \phi_i / \pi
\]

Source: Neidhöfer, G.; BBC, Switzerland
7. Forces in big synchronous machines

**Tangential thrust**

\[ M = l \cdot (p \tau_p)^2 \cdot \hat{A} \cdot \hat{B} \delta_1 \cdot \cos \varphi_i / \pi \]

\[ S_e = \frac{M \cdot \Omega_{\text{syn}}}{\cos \varphi_i} \]

**ESSON:**

\[ S_e = \frac{\pi^2}{\sqrt{2}} \cdot k_w \cdot A \cdot B \delta_1 \cdot d^2 \cdot l \cdot n = C_e \cdot d^2 \cdot l \cdot n \]

**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: \( k_w \approx 0.95, A = 700 \text{ A/cm}, \) maximum thrust at:

\[ \tau = \hat{A} \cdot \hat{B} \delta \cdot \cos \varphi_i / 2 = 94000 \cdot 1 \cdot 1 / 2 = 47000 \text{ N/m}^2 \approx 0.5 \text{ bar} \]

**In reality:** \( \cos \varphi_i \sim 0.9, \) so thrust for AC lower by 10%: 0.45 bar.
Large Generators and High Power Drives

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:

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

- Tangential air gap thrust = Tangential force per rotor surface
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. Forces in big synchronous machines

7.2 Radial forces at centric rotor position

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

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

Source: Neidhöfer, G.; BBC, Switzerland

\[ B_{\delta 1} = 1 \, \text{T:} \]

\[ \hat{f} = \frac{B_{\delta 1}^2}{2\mu_0} = \frac{1^2}{2 \cdot 4\pi \cdot 10^{-7}} = 400 \cdot 10^3 \, \text{N/m}^2 \]
7. Forces in big synchronous machines

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

Source: Bohn, T. (Ed.), TÜV Rheinland
7. Forces in big synchronous machines

Core spring mounting

Suspension between stator stack and housing

Source:
Siemens AG, Mülheim/Ruhr, Germany
7. Forces in big synchronous machines

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 $f_{\text{Ton}}$. So acoustic sound waves are generated with that tonal frequency $f_{\text{Ton}}$ to be heard by e.g. humans.

Source: Seinsch, H.-O., Teubner-Verlag
7. Forces in big synchronous machines

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
7. Forces in big synchronous machines

Resulting radial force on a stator stack segment

- Force per pole sector:

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

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

Source: Neidhöfer, G.; BBC, Switzerland
7. Forces in big synchronous machines

**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: $A_{ys,\text{tot}} = 3.0$ m$^2$

magnetic yoke cross section (without cooling ducts): $A_{ys} = 2.4$ 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
7. Forces in big synchronous machines

Forces at the separation line in the yoke

- **Gravitation force:**

\[ F_m = \frac{mg}{2} = \frac{150000}{2} \cdot 9.81 = 736 \text{kN} \]

- **Magnetic pull:** Pulsation with \(2 \times 16.7 = 33.3\) Hz between 0 and:

\[ F_y = \frac{B_{ys}^2}{2\mu_0} \cdot A_{ys} = \frac{1.67^2}{2 \cdot 4\pi \cdot 10^{-7}} \cdot 2.4 = 2663 \text{kN} \]

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

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

\[ = 1.6 \cdot 5 \cdot 199 \cdot 10^3 \cdot \frac{1^2}{1^2 - 0.25} \cdot \sin\left(\frac{\pi}{2}\right) = 2122 \text{kN} \]

*Source: Neidhöfer, G.; BBC, Switzerland*
7. Forces in big synchronous machines

Resulting force at the separation line in the yoke

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

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

Pressure on the insulation foil in the separation:

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

Note:

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

Source: Neidhöfer, G.; BBC, Switzerland
7. Forces in big synchronous machines

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

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. Forces in big synchronous machines

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

Pull is directed to minimum air gap.

Minimum air gap location

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

$$F = \frac{\pi}{4\mu_0} \cdot d \cdot l \cdot \frac{e}{\delta} \cdot B_{\delta_1}^2$$

$$2p \geq 4:$$

$$F = \frac{\pi}{8\mu_0} \cdot d \cdot l \cdot \frac{e}{\delta} \cdot B_{\delta_1}^2$$

Source: Neidhöfer, G.; BBC, Switzerland
7. Forces in big synchronous machines

Static and dynamic eccentricity

Static eccentricity:
Minimum air gap location is fixed.
Rotor rotates around displaced rotor axis.

Dynamic eccentricity:
Minimum air gap location rotates with $n$.
Displaced rotor axis rotates with $n$.

Source: Neidhöfer, G.; BBC, Switzerland
7. Forces in big synchronous machines

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.
7. Forces in big synchronous machines

**Two-pole machines:** Pulsation of single sided magnetic pull

**Single-sided pull:**

At static eccentricity

Radial force is *pulsating* between zero and \( F \) with \( f = 2n \).

\[ B_{\delta_A} > B_{\delta_B} \]

**NO single-sided pull:**

At dynamic eccentricity in *d-axis* direction

Radial force is constant and rotates with \( n \).

Force amplitude depends on field position relative to minimum air-gap.

\[ B_{\delta_A} = B_{\delta_B} \]

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

Source: Neidhöfer, G.; BBC, Switzerland
7. Forces in big synchronous machines

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

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

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

Eccentricity: \[\frac{e}{\delta} = 0.6 / 7.5 = 0.08\]

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

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

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

\[F = 6600 \text{ N}\]

- **Conclusion:** Single sided magnetic pull: ca. 50% of rotor gravitational force:

\[6600 \text{ N} = \text{ca.} \, 0.5 \times 1350 \times g = 0.5 \times 13240 \text{ N.}\]
7. Forces in big synchronous machines

Rotor bending natural frequencies

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:

$$ k = \frac{\pi \cdot d \cdot l}{4 \mu_0 \cdot \delta} \cdot B_{\delta_1}^2 $$

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

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

Influence of slotting on rotor bending in two pole machines

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

- Rotor stiffness in $y$-direction varies with rotor position, hence with $2n$.

- This leads to mechanical excitation of bending oscillation with $2n$.

- Axial slitting of poles reduces $d$-axis stiffness; to be equal to $q$-axis stiffness.

7. Forces in big synchronous machines

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

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. Forces in big synchronous machines

7.4 Lorentz forces on slot conductors

Tangential force due to radial field of rotor  
Radial force due to slot leakage self field

Source: Neidhöfer, G.; BBC, Switzerland
7. Forces in big synchronous machines

Where is the tangential force localized?

**NOT at the conductor, **but 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: \( F_t = l \cdot \Theta_Q \cdot B_r \)

\[
\frac{F_t}{F_\tau} = \frac{B_{r,Q}}{B_\delta}
\]

**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.

\[
\frac{F_t}{F_\tau} = \frac{B_{r,Q}}{B_\delta} = 0.016/0.9 = 0.018 \approx \frac{1}{50}
\]

Source: Neidhöfer, G.; BBC, Switzerland
7. Forces in big synchronous machines

**Radial conductor forces hammer with 50 Hz on the slot insulation**

Peak pressure:

\[ \hat{f}_r = \frac{\hat{F}_r}{b_Q \cdot l} = \frac{\mu_0}{2} \cdot \frac{\hat{\Theta}_Q^2}{b_Q^2} \]

At sudden short circuit:

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

Source: Neidhöfer, G.; BBC, Switzerland

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

\[ F_r(t) = l \cdot \Theta_Q(t) \cdot B_Q(t) = \frac{\mu_0}{2} \cdot \frac{l}{b_Q} \cdot \hat{\Theta}_Q^2 \cdot \sin^2(\omega t) \]
7. Forces in big synchronous machines

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

Source: AEG, Germany
7. Forces in big synchronous machines

**Calculation:**
- analytical
- numerical

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
7. Forces in big synchronous machines

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. Forces in big synchronous machines

7.5 **LORENTZ** forces on winding overhang conductors

- **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

*Source: Neidhöfer, G.; BBC, Switzerland*
7. Forces in big synchronous machines

Damage of winding overhang at phase separation after sudden short circuit

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

Source: BBC, Switzerland

Source: Andritz Hydro, Austria

Source:
BBC, Switzerland
7. Forces in big synchronous machines

3D finite element model of stator end winding zone

Source: Alstom, Switzerland
7. Forces in big synchronous machines

Calculated four-node vibration mode of the stator end winding

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
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

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. Forces in big synchronous machines

7.6 Rotor pole fixation in large synchronous machines

Rotor surface velocity (at over-speed): \( v_{u,\text{max}} = d_{si} \cdot \pi \cdot n_{\text{max}} \)

Centrifugal acceleration: \( a_{\text{centr}} = \frac{v_{u,\text{max}}^2}{d_{si} / 2} \)

“specific centrifugal force \( f’ \) = centrifugal force \( F_{\text{centr}} \)/gravity: \( a_{\text{centr}}/g \)

\[
F_{\text{centr}} = m \cdot \frac{v_{u,\text{max}}^2}{d_{si} / 2} \quad f = \frac{F_{\text{centr}}}{m \cdot g} = \frac{v_{u,\text{max}}^2}{g \cdot d_{si} / 2} = \frac{a_{\text{centr}}}{g}
\]

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)

Source: Gregori, F.; TU Wien
7. Forces in big synchronous machines

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: $v_{u,\text{max}} = 110...120 \text{ m/s}$

Example:
River hydro plant, Kaplan turbine, Friesach (River Drau)/Austria, Bulb turbine generators, 48 poles, 8.5 MVA, 50Hz, $d_{si} = 4.34 \text{ m}$, $n_{N}/n_{\text{max}} = 125/395/\text{min}$, $v_{u,\text{max}} = 90\text{ m/s}$, $a_{\text{centr}}/g = 380$. 

Source: Gregori, F., TU Wien
7. Forces in big synchronous machines

**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 surface
- Damper cage
- Laminated pole
- Pressing bolts
- Massive pole shaft
- Field winding
- Massive yoke ring
- Dove tail

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, $v_{u,max} = 170$ m/s, $a_{centr}/g = 1322$
7. Forces in big synchronous machines

**Dove-tail fixation**

- Laminated pole surface
- Damper cage (bars and ring)
- Field winding
- **Dove tail fixation**
- Massive yoke ring

Source: Andritz Hydro, Austria
7. Forces in big synchronous machines

Dove-tail fixation

- Damper cage (bars and ring)
- Field winding
- Dove tail fixation
- Massive yoke ring

Source:
Andritz Hydro, Austria
7. Forces in big synchronous machines

D) Hammer fixation: \( v_{u,\text{max}} = 180 \ldots 200 \text{ m/s} \)

![Diagram of hammer fixation with labels](image)

\( a_{\text{centr}}/g \sim 2000 \)

*Source: Gregori, F., TU Wien*

**Examples:**

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

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

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: \( v_{u,\text{max}} = 215 \ldots 235 \text{ m/s} \)

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

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


Source: Sequenz, H. (ed.), Springer-Verlag
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:** \( f_s = 50 \text{ Hz} \): Largest possible power: 1 GW at 50 Hz, \( n = 3000/\text{min} \)

Rotor diameter: \( d = 1.25 \text{ m} \): \( v = 188 \text{ m/s} = 676 \text{ km/h} \) at \( 2p = 2 \), \( I_{\text{Fe}} = 8 \text{ m} \)

- 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
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
Large Generators and High Power drives

That’s all, folks!