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 $I_A$"
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

- **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 $f_s = n/p$. Stator current due to this voltage excites stator field, which rotates *synchronously with 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 with round rotor: Turbine generator for thermal power plant

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

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
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 ($\mu = 1$):

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

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

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

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

- 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 $U_p$:

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

with frequency $f_s = np \Rightarrow$ 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:

\[
U_s = U_p + jX_h I_s + jX_{s\sigma} I_s + R_s I_s
\]

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

\[
\begin{align*}
U_p & & \quad \text{\textbf{Up}} \\
\text{Us} & & \quad \text{\textbf{Us}} \\
\end{align*}
\]
Alternative “current-source” equivalent circuit

\[ U_s = U_p + jX_d I_s + R_s I_s \]

Current source equivalent circuit, where voltage drop of \( I'_f \) at \( jX_h \) gives \( U_p \)!

\[ U_p = jX_h I'_f \]

Amplitude and phase shift of \( U_p \) may be described in equivalent circuit by fictive AC stator current \( I'_f \)!
Transfer ratio for rotor field current

- **Stator self-induced voltage:**
  \[ U_{s,s} = jX_h I_s \]
  by stator air-gap field

- **Back EMF \( U_p \):** 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 \( U_p \) is determined via \( I_f \).
  
  b) Phase shift of \( U_p \) with respect to stator voltage \( U_s \) 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 \( \vartheta \).

- **Amplitude and phase shift of \( U_p \):** may be described in equivalent circuit by fictive AC stator current \( \hat{I}_f \):
  \[ U_p = jX_h \hat{I}_f \]

- **This defines transfer ratio of field current \( \bar{u}_f \):**
  \[
  I'_f = \bar{u}_f I_f = \frac{1}{\bar{u}_f} I_f
  \]

  \[
  I'_f = \frac{U_p}{U_{s,s}} I_s = \frac{B_p}{B_{s,\delta}} I_s = \hat{V}_f \cdot I_s \quad \text{shall be} \quad \frac{1}{\bar{u}_f} I_f
  \]

  With \( \hat{V}_f = \frac{2}{\pi} \cdot \frac{N_f}{p} \cdot k_{wf} \cdot I_f \), \( \hat{V}_s = \frac{\sqrt{2}}{\pi} \cdot m_s N_s \cdot k_{ws} \cdot I_s \)

  we get:
  \[ \bar{u}_f = \frac{m_s N_s k_{ws} \sqrt{2}}{2N_f k_{wf}} \]
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 \( \varphi \) between -90° and -180°:
    Hence \( \cos \varphi \) negative: \( P_e \) is negative = power delivered to the grid (GENERATOR).
    \[ P_e < 0: \text{Generator}, \quad P_e > 0: \text{Motor}. \]
  - b) electrical reactive power:
    \[ Q = m_s U_s I_s \sin \varphi \]
    Phase angle \( \varphi \) negative = stator current LEADS ahead stator voltage:
    \( \sin \varphi \) negative: \( Q \) is negative = capacitive reactive power: Machine is capacitive consumer.
    \[ Q < 0: \text{over-excited}, \text{capacitive consumer.} \]
    \[ Q > 0: \text{under-excited}, \text{inductive consumer.} \]
Load angle $\vartheta$, internal voltage $U_h$, magnetising current $I_m$

- **Load angle** $\vartheta$ between stator phase voltage $U_s$ and back EMF phasor $U_p$. 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):

  $$U_h = U_p + jX_h I_s$$

- **Magnetising current** $I_m$:
  Fictitious stator current to excite resulting air gap field (rotor and stator field):

  $$I_m = I'_f + I_s$$

- Voltage triangle $U_p, jX_h I_s, U_h$ and current triangle $I'_f, I_s, I_m$ are of the same shape, but shifted by $90^\circ$. 
### Over-/under-excitation, generator/motor-mode

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<tr>
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<th>Generator: rotor leading</th>
<th>Motor: rotor lagging</th>
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<tbody>
<tr>
<td>Over-excitation</td>
<td>$\vartheta &gt; 0$: Rotor LEADS ahead of resulting rotating magnetic field = Phasor $U_p$ LEADS ahead of $U_h$.</td>
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- **Facit:**

  Stator- and rotor field rotate always synchronously. Generator- and motor mode are only defined by sign of load angle $\vartheta$. 
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 \((I_s = 0, I_r > 0)\):
- 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 \( U_p \), resulting field axis = Direction of \( U_h \)
- 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 \( U_s = \text{const.} \) & \( R_s = 0 \)

- **Machine operates at RIGID grid:** \( U_s = \text{constant} = U_s \) (= phasor put in real axis of complex plane):
  \[
  U_p = U_p (\cos \vartheta + j \cdot \sin \vartheta) \quad \text{and} \quad I_s = (U_s - U_p)/(jX_d) \Rightarrow I_s^* = (U_s - U_p^*)/(-jX_d)
  \]

- **Active power** \( P_e \):
  \[
  P_e = m_s U_s I_s \cos \varphi = m_s \Re \left\{ \frac{U_s I_s^*}{U_p} \right\}
  \]
  \[
  P_e = m_s \Re \left\{ U_s \cdot \frac{U_s - U_p (\cos \vartheta - j \cdot \sin \vartheta)}{-jX_d} \right\} = -m_s \frac{U_s U_p}{X_d} \sin \vartheta
  \]

- **Electromagnetic torque:**
  \[
  M_e = \frac{P_m}{\Omega_{\text{syn}}} = \frac{P_e}{\Omega_{\text{syn}}} = -m_s \frac{U_s U_p}{X_d} \sin \vartheta = -M_{p0} \sin \vartheta
  \]

**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 $M(\varphi)$: 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 $\vartheta_0$: *Tangent* as linearization: 
  
  $$M_e(\vartheta) \approx M_e(\vartheta_0) + \partial M_e / \partial \vartheta \Delta \vartheta \quad \text{with} \quad \Delta \vartheta = \vartheta - \vartheta_0$$

  $$c_\vartheta(\vartheta_0) = \partial M_e / \partial \vartheta \bigg|_{\vartheta_0}$$

  : Equivalent spring constant  \iff \[ \Delta M_e = c_\vartheta \cdot \Delta \vartheta \]

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

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

- **NEWTON’s law of motion**

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

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

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

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

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

  \[ \Rightarrow \Delta \vartheta(t) \sim \sinh(\omega_e t) \]

  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:

\[ \Delta \dot{\theta} + \left( p \cdot \left| c_\theta \right| / J \right) \Delta \theta = 0 \Rightarrow \Delta \ddot{\theta} + \omega_e^2 \Delta \theta = 0 \Rightarrow \Delta \theta(t) \sim \sin(\omega_e t) \]

leads to differential equation with oscillation as solution. Rotor oscillates around steady state point of operation \( \theta_0 \), which is defined by the stator field, that is generated by the “rigid” grid.

Natural frequency of oscillation (eigen-frequency):

\[ f_e = \frac{\omega_e}{2\pi} = \frac{1}{2\pi} \sqrt{\frac{p |c_\theta|}{J}} \]

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

**Example:** Operation at no-load \( (M_e = 0, \theta_0 = 0) \):

\[ |c_\theta| = -M_{p0} \cdot \cos(0) = M_{p0} \]

With \( p \Omega_{\text{syn}} = \omega_N \) and rated acceleration time \( T_J = J \cdot \Omega_{\text{syn}} / M_N \), we get:

\[ f_e = \frac{1}{2\pi} \sqrt{\frac{\omega_N \cdot M_{p0}}{T_J \cdot M_N}} \]

Synchronous motor driving a fan blower for a wind tunnel:

\( P_N = 50 \text{ MW}, f_N = 50 \text{ Hz}, T_J = 10 \text{ s}, M_{p0}/M_N = 1.5, \)

\[ f_e = \frac{1}{2\pi} \sqrt{\frac{2\pi 50}{10 \cdot 1.5}} = 1.09 \text{ Hz} \]
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 $U_p$

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

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 $\delta_0$: $c_d = \hat{B}_{d1} / \hat{B}_s < 1$ \textbf{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 $\delta_0$: $c_q = \hat{B}_{q1} / \hat{B}_s << 1$ \textbf{ca. 0.4 ... 0.5, thus} $L_{qh} = c_q \cdot L_h$
Stator current \( I_s \): \( d \)- and \( q \)-component

**Stator current phasor** \( I_s \) decomposed into \( d \)- and \( q \)-component:

\[
I_s = I_{sd} + I_{sq}
\]

\( I_{sd} \) is in phase or opposite phase with fictitious current \( I_{\hat{f}} \). 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 \( \Phi_{dh} \).

\( I_{sq} \) is phase-shifted by \( 90^\circ \) to \( I_{sd} \) and excites therefore a stator air gap field in \( q \)-axis (inter-pole gap). The corresponding air gap flux is \( \Phi_{qh} \).

**Stator self-induced voltage** consists of two, by \( 90^\circ \) phase shifted components:

\[
j \omega_s L_{dh} I_{sd} + j \omega_s L_{qh} I_{sq}
\]

and of self-induced voltage of stator leakage flux:

\[
j \omega_s L_{s\sigma} I_s
\]
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:

$$U_s = R_s I_s + j\omega_s L_{s\sigma} I_s + j\omega_s L_{qh} I_{sq} + j\omega_s L_{dh} I_{sd} + U_p$$

or

$$U_s = R_s I_s + j\omega_s L_{s\sigma} (I_{sd} + I_{sq}) + j\omega_s (L_{qh} I_{sq} + L_{dh} I_{sd}) + U_p$$

- $X_d$: "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: $X_q = (0.5 \ldots 0.6) \cdot X_d$) e.g. salient pole hydro-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: $X_q = (0.8 \ldots 0.9) \cdot X_d$)
Torque of salient pole machine at $U_s =$ const. & $R_s =$0

- **OPERATION at ” rigid” grid:** $U_s =$ constant

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

  \[
  \underline{U}_s = U_{sd} + jU_{sq} \quad \underline{I}_s = I_{sd} + jI_{sq} \quad \underline{U}_p = j\underline{U}_p
  \]

  \[R_s = 0: \quad \underline{U}_s = jX_d \underline{I}_{sd} + jX_q \underline{I}_{sq} + \underline{U}_p\]

- **Active power $P_e$:**

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

  \[P_e = m_s (-X_q I_{sq} I_{sd} + X_d I_{sd} I_{sq} + U_p I_{sq})\]

- **Electromagnetical torque:**

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

  - **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 $U_s, \vartheta$:

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

Absolute value of pull-out load angle is $< 90^\circ$, as pull-out torque of reluctance torque occurs at load angle $\pm 45^\circ$.

Pull-out torque is increased by reluctance torque.

Equivalent spring constant $c_\vartheta$ 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

- 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** \( M_{\text{Dä}} \), 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: $A (-M_e, \vartheta_0)$:

\[ f_e = \frac{1}{2\pi} \sqrt{\frac{p \cdot c_3}{J}} \]

- Damping asynchronous torque (KLOSS): (linearized) $M_D(s) \approx \frac{2M_b}{s} = D \cdot s$

E.g.:

\[ \tau = 1/\alpha = 1/0.7 = 1.43 \text{s} \]

\[ f_e' = \frac{\sqrt{(2\pi f_e')^2 - \alpha^2}}{2\pi} = \frac{\sqrt{(2\pi \cdot 1.093)^2 - 0.7^2}}{2\pi} = 1.087 \text{Hz} \]
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", \( U_s \) is depending on load. E.g.: round rotor synchronous machine:
  - **No** \( M_e \sim \sin \vartheta \) - curve,
  - **No** rotor pull out at \( \vartheta = \pm 90^\circ \)

- **Example:** Mixed OHM’ic-inductive load \( Z_L \) (Load current \( I_L = -I_s \))

![Synchronous machine diagram](image)

Load impedance: \( Z_L \) (here: \( Z_L = R_L + jX_L \))
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·m²

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

Source: VATech Hydro, Austria
Mounting of sleeve bearing segments for vertical load

Bearing segments for vertical load

Bolts for segments

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)

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

Source:
VATEch Hydro,
Austria

Pump storage hydro power plant Vianden/Belgium

Refurbishment

Three-fold hammer head fixation

“Cooling fins” by increased copper width

Damper ring segments
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: \(v_{u,max} = 85 \text{ m/s}\)
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:
VA Tech Hydro, Austria
Drilling holes into massive pole shaft to fix them to rotor yoke ring with screws

Source: VATech Hydro, Austria