9. Electrically Excited and Permanent Magnet Synchronous Machines
High-speed excitation and de-excitation

- **High speed excitation**: Quick rotor field build-up: Applying of "ceiling voltage" $U_{f_{\text{max}}}$: Field current rises in minimum time $t_{12}$ from starting value $I_{f1}$ to set-point value $I_{f2}$. At stator no-load condition rotor electrical time constant $T$ is **Rotor open-circuit time constant** $T_f = L_f/R_f$.

- **Quick de-excitation**: Quick de-magnetization of rotor field: Applying an external field resistor $R_v$ (switch is in position 2) to reduce rotor winding time constant $T_f$.

\[
T_f^* = \frac{L_f}{R_f + R_v} = \frac{T_f}{1 + \frac{R_v}{R_f}}
\]

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

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

- **Brushless excitation**: Exciter generator is coupled to main synchronous machine rotor, being itself an **outer rotor synchronous machine**: Stator = ”DC excited” magnetic field. Rotor: Three-phase AC winding, in which voltage $U$ is induced. Rotating six-pulse B6-diode bridge rectifies $U$ to DC field voltage $U_f$, being applied to rotor **without any brushes or slip rings**. By variable stator DC field current the rotor field voltage is varied.
Measurement of equivalent circuit parameters \((n = \text{const.})\)

- **Open-circuit (= no-load) characteristic**: Generator operation, stator winding open circuit \((I_s = 0)\): Measured stator voltage is "back EMF": \(U_{s0}(I_f)\) or \(U_{s0}(I'_f)\). \(U_{s0} = U_p = U_h\) and \(I_f = I_m\).

  At high current \(I_f\) (high rotor flux): iron part saturate: \(U_{s0}(I_f)\) curbed characteristic.

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

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

- Synchronous reactance $x_d$ per unit of rated impedance $Z_N = U_{sN} / I_{sN}$:
  \[ x_d = \frac{X_d}{Z_N} = \frac{U_{sN}}{I_{sk0}} \cdot \frac{I_{sN}}{U_{sN}} = \frac{I_{sk0}}{I_{f0}} \]

- Synchronous reactance $x_d$ per unit of rated impedance $Z_N = U_{sN} / I_{sN}$:
No-load / short-circuit ratio \( k_K \)

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

\[
k_K = \frac{I_{f0}}{I_{fk}} = \frac{I_f(U_s = U_{SN}, I_s = 0)}{I_f(U_s = 0, I_s = I_{SN})} = \frac{1}{x_d}
\]

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

\[ x_{d, \text{sat}} < x_{d, \text{unsat}} \]

- Synchronous reactance \( X_d \sim \) Magnetizing inductance \( L_h \sim N_s^2 \tau_p / \delta \).

<table>
<thead>
<tr>
<th>Pole count ( 2p )</th>
<th>Synchronous reactance ( x_d )/p.u.</th>
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<tr>
<td>Turbo generators (round rotor)</td>
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<tr>
<td>Salient pole machines</td>
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<tr>
<td>PM-Machines with Surface magnet rotors</td>
<td>( \geq 4 )</td>
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</tbody>
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**Example:**
From no-load/short-circuit curve (previous slide) we get: \( k_K = 0.43 \), \( x_d = 1/0.43 = 2.32 \) p.u.
Permanent magnet materials

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

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

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

- Magnetic point of operation of PM: in 2. quadrant of $B(H)$-loop
Rare-earth magnets: Linear $B(H)$-Curve in 2. quadrant

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

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

- Rare-earth magnets are developed for high saturation polarization $J_s$.

- After turn-off of external field the remanence flux density $B_R = J_M(H_M = 0) = J_R$ remains.

- Two coercive field strengths $H_C$ defined:
  a) At $-H_{CB}$ the resulting magnetic flux density $B_M$ is zero.
  b) At $-H_{CJ}$ the magnetic polarization $J_M$ within the magnet is zero.

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

$$B_M = B_R + \mu_M H_M , \quad \mu_M = ca.1.05 \mu_0$$
PM synchronous machines: Air gap flux density $B_p$

PM rotor with surface mounted magnets

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

- No-load air gap flux-density $B_p$: Approximation $\mu_M = \mu_0$, $B_M \approx B_R + \mu_0 H_M$ and $\mu_{Fe} \to \infty$.
- AMPERE’s law gives: No-load ($I_s = 0$) = electrical Ampere turns $\Phi$ are zero;
  
  \[ 2(H_\delta \delta + H_M \delta) = \Phi = 0 \]

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

\[ B_p = B_\delta = \mu_0 H_\delta = -\mu_0 \frac{\delta}{\delta} H_M = B_M \]

magnetic operational line $B_M(H_M)$
PM synchronous machine: Magnetic point of operation $P$

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

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

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

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

- Depending on rotor position, the stator winding is fed with three-phase current system so, that stator field has always a fixed relative position to rotor field. Measurement of rotor position with e. g. incremental encoder or resolver. Rotor cannot be pulled out of synchronism, as stator field is always adjusted to rotor position.

- Often used control method with PM-drives: Stator current is fed as pure $q$-current:

\[ I_s = I_{sq}, \quad I_{sd} = 0 \]

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

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

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

\[
M_e = m_s \cdot U_p \cdot I_{sq} / \Omega_{syn} \quad \text{or with} \quad U_p = \omega_s \Psi_p / \sqrt{2} : \quad M_e = p \cdot m_s \cdot \Psi_p \cdot I_{sq} / \sqrt{2}
\]
PM synchronous machine as “Brushless-DC”-drive

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

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

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

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

“brushless DC”-drive: inverter + encoder   stator winding               rotor poles

No brushes: Low maintenance costs!
Example: “Brushless-DC” robot drive

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

PM-synchronous motors with position control

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

- Synchronous cylindrical rotor machine
- 12 poles, electrically excited
- Rated torque: 1.78 MNm, 0 … 58.5/min
- Rated power: 10.9 MW, 58.5 … 112.5/min
- Operated at cosØ = 1
- 2.5-times short time overload:
  - Max. torque: 4.3 MNm
  - Max. power: 26.5 MW
- 5.5m-heavy plate rolling-mill drive
- Dillinger Hüttenwerke AG

Source: Siemens AG, Germany
Damper cage in synchronous machines

- 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 $s$. $\Rightarrow$ 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 \((-M_e, \vartheta_0)\):

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

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

\[
\Delta \vartheta_0 = e^{-t/\tau} \quad \tau = 1/\alpha \quad T_e' = 1/f_e'
\]

\[
f_e' = \sqrt{\left(2\pi f_e\right)^2 - \alpha^2} \quad \frac{2\pi}{2\pi}
\]

E.g.: \(\tau = 1/\alpha = 1/0.7 = 1.43s\)

\[
f_e' = \sqrt{\left(2\pi \cdot 1.093\right)^2 - 0.7^2} / (2\pi) = 1.087Hz\]