Synchronous Motor

Actuators - IRO6

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Historical Development

1848 First **single-phase generator** by Nollet and Holmes (Alliance) for supply of lighting systems

1887-1888 Synchronous generators from Haselwander and Tesla (two-phase) or Bradley (three-phase): **salient pole machines**

1890 **Medium frequency machine** for 9..10 kHz with 384 poles from Tesla

1891 **Star and delta connection** patent from Dobrowolsky

1891 „Lauffen-Frankfurter power transmission“:
200 kW Three-phase alternator in claw pole design from Oerlikon

1901 Turbo rotor by Charles E.L. Brown (BBC): 250 kVA at 3000 min^{-1}

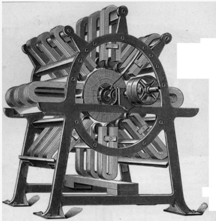
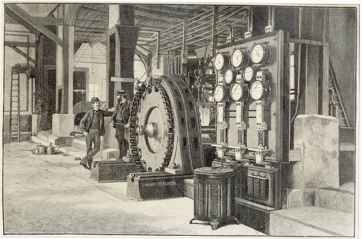


Fig. 3. Alliance-Maschine von Nollet.



Applications

Generators: Turbo generators ...1700MVA (steam/gas)
Salient pole generators ...800MVA (water, wind ...5MW)
Permanent magnet excitation (wind ...5MW)
Claw pole generator ...5kW (car)
Bicycle dynamo ...3W

Large drives: Converter motors for power > 5MW
Permanent magnet excitation (ship propulsion > 5MW)

Servo motors: permanent magnetic excitation, power 10W...50kW
(**robots**, machining tools)
Hi-Speed-Drives > $30\,000\,\mathrm{min}^{-1}$ (spindle drives, fly wheels)

Stepper motors: mostly permanent magnet excitation, Rotor diameter
0.5mm...25mm (data terminals, clocks, **small robots**)

Applications

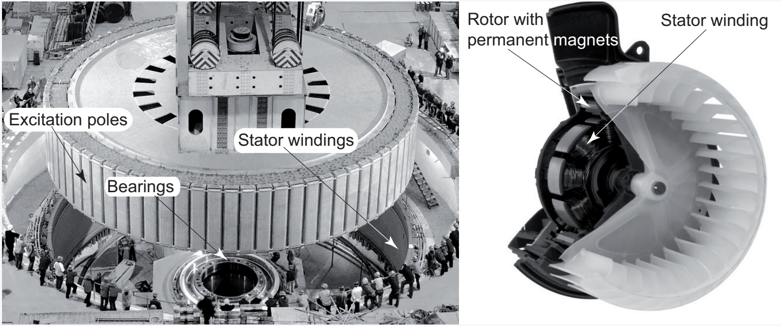


Figure 800 kVA hydropower generator and 300 W car interior fan with external rotor
(sources: left - Voith Hydro, right - Brose)

Electronically Commutated DC Motor

- DC motor with PM excitation ⇒ Synchronous motor with PM excitation
  - Excitation Poles: Stator ⇒ Rotor
  - Commutation: Commutator in Rotor ⇒ Inverter for the Stator
- Stator winding:
  - three-phase winding = 3 phases with an offset of 120°
- Excitation by permanent magnets
  - ⇒ Rectangular air gap field
  - ⇒ Rectangular induced voltage due to rotation
- Phase coils with an offset of 120°
  - ⇒ Phase shift of 120° between the induced voltage of the different phases

Induced voltage (German: "Polradspannung")

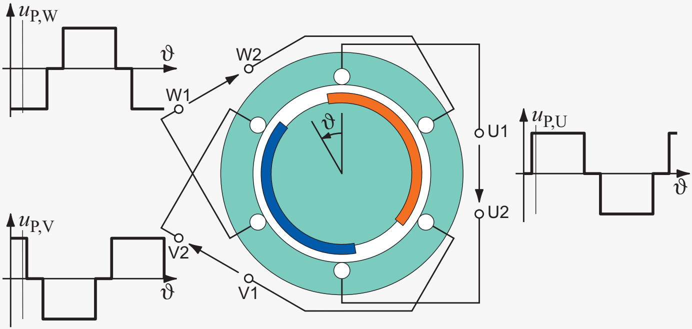


Figure Induced voltage at constant speed

- here: motor with two-poles ($p = 1$)
  $\Rightarrow$ block-shaped induced voltages with the frequency $f_S = p \cdot n$

Stator supply

Winding system and pole geometry rarely as simple as shown:

⇒ real $u_{P,U}$, $u_{P,V}$, $u_{P,W}$ often trapezoidal or sinusoidal

⇒ with block-shaped phase currents, constant power $p(t) = P$:

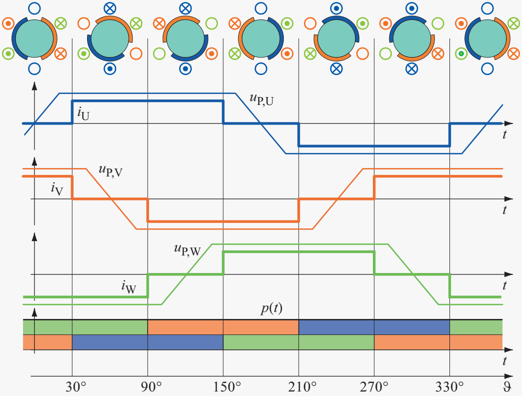


Figure Current and voltage curves EC motor

Hysteresis current controller

Simple control thanks to current blocks with width $\omega t = 120°$:

⇒ Switch current electronically from one strand to the next

⇒ Electronic commutation depending on rotor position

⇒ Resolution rotor position: $60°/p$ (light barriers, Hall elements)

Control currents via simple **hysteresis current controller**:

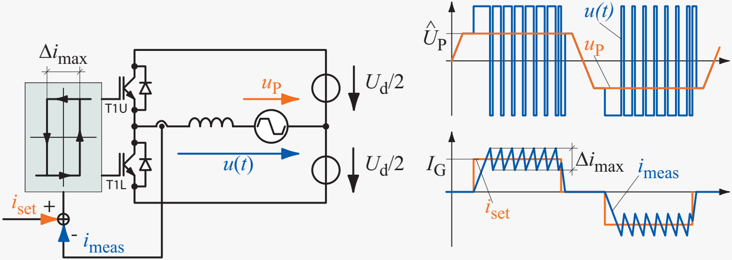


Figure Principle hysteresis current controller for single-phase inverter

Principle EC motor

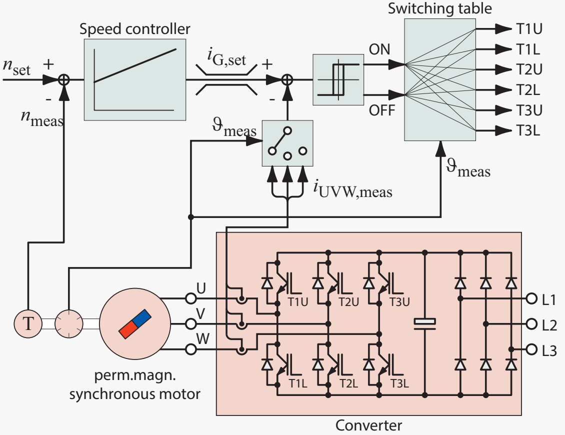


Figure Block diagram of an EC motor (electronically commutated DC motor or brushless DC motor)

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Induced voltage and Torque

Current I_G flows at any time in two phases:

$$P_\mathrm{i,mech} = 2 \cdot \hat{U}_\mathrm{P} \cdot I_\mathrm{G} \quad \Rightarrow \quad k_\mathrm{M,EC} = \frac{M_\mathrm{i}}{I_\mathrm{G}} = \frac{P_\mathrm{i,mech}/\Omega_\mathrm{m}}{I_\mathrm{G}} = \frac{2 \cdot \hat{U}_\mathrm{P} \cdot I_\mathrm{G}}{I_\mathrm{G} \cdot 2\pi n} = \frac{p}{\pi} \frac{\hat{U}_\mathrm{P}}{f_\mathrm{S}} \qquad (0.1)$$

⇒ **Torque constant** $k_\mathrm{M,EC}$

- each coil with N_S turns
- lamination length l_Fe
- the magnetic flux density in the air gap B_f
- rotor peripheral speed v_circ
- mean air gap diameter d_L

$$\hat{U}_\mathrm{P} = 2N_\mathrm{S} \cdot l_\mathrm{Fe} \cdot B_\mathrm{f} \cdot v_\mathrm{circ} = N_\mathrm{S} \cdot l_\mathrm{Fe} \cdot B_\mathrm{f} \cdot \underbrace{2\pi n}_{\Omega_\mathrm{m}} \cdot \frac{d_\mathrm{L}}{2} = \underbrace{N_\mathrm{S}\, l_\mathrm{Fe}\, d_\mathrm{L}\, B_\mathrm{f}}_{= k_\mathrm{M,EC}/2} \cdot \Omega_\mathrm{m} \qquad (0.2)$$

⇒ $k_\mathrm{M,EC}$ comparable to „torque constant“ $c\Phi_\mathrm{f}$ of the DC machine

Example 5-1: Drive for a car engine fan

The induced voltage of an EC motor was oscillographed as line-to-line voltage(!). The trapezoidal curve has a peak value of $8\,V$ at a frequency of $80\,Hz$ and a speed of $1200\,\mathrm{min}^{-1}$. How big is at this speed the current I_{G} at a power of $450\,W$? What internal torque M_{i} does the motor then generate? How many pole pairs p does the motor have and what is the torque constant $k_{\mathrm{M,EC}}$?

Example 5-1: Drive for a car engine fan

Alternating field

- EC-Motor with block-shaped currents ⇒ easy to control but with additional losses and vibrations
- Objective: generate an "ideal" rotating field with three sinusoidal currents

As first step, one phase excitation: ⇒ stationary alternating field

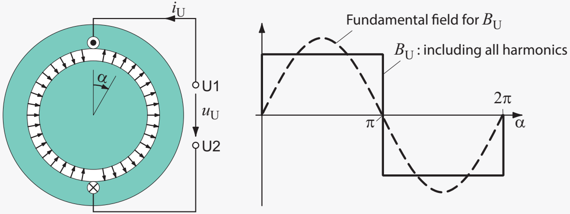

Figure Alternating field with one-phase excitation

⇒ Position of the zeros of $B_U(\alpha)$ constant

⇒ Amplitude of $B_U(\alpha)$ proportional to $i_U(t)$

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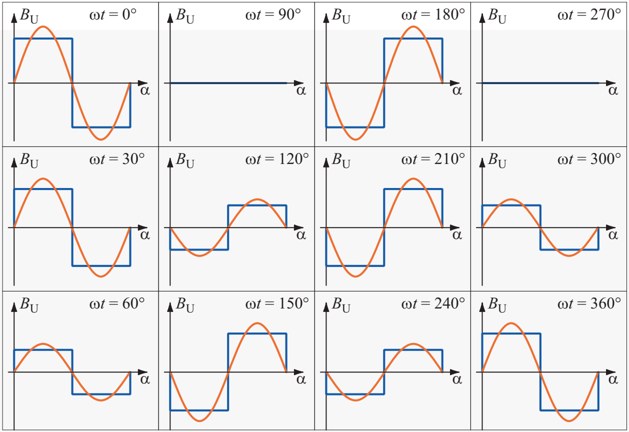


$$i_U(t) = \sqrt{2} I_U \cos \omega t = \quad \sqrt{2} I_U, \quad \sqrt{\frac{3}{2}} I_U, \quad \frac{\sqrt{2}}{2} I_U, \quad 0 \cdot I_U, \quad -\frac{\sqrt{2}}{2} I_U, \quad -\sqrt{\frac{3}{2}} I_U, \quad -\sqrt{2} I_U, \quad \ldots$$

$$\text{für } \omega t = \quad 0°, \quad 30°, \quad 60°, \quad 90°, \quad 120°, \quad 150°, \quad 180°, \quad \ldots$$

Figure alternating field with single-phase excitation

Space Vector

- Starting here: only the fundamental wave of the flux density $B_U(\alpha)$
- Fundamental wave represented as a vector („space vector“).

⇒ Length specifies the value

⇒ Direction indicates the position of the maximum

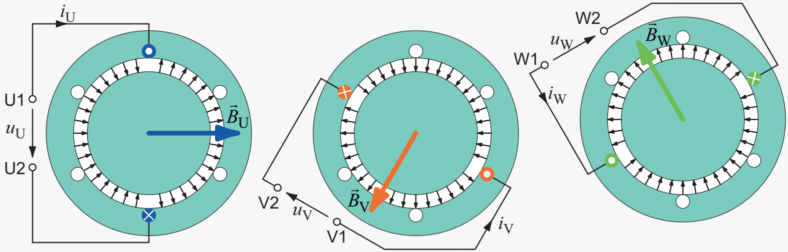


Figure Direction specifications for the space vectors

Overlay of 3 alternating fields to a rotating field

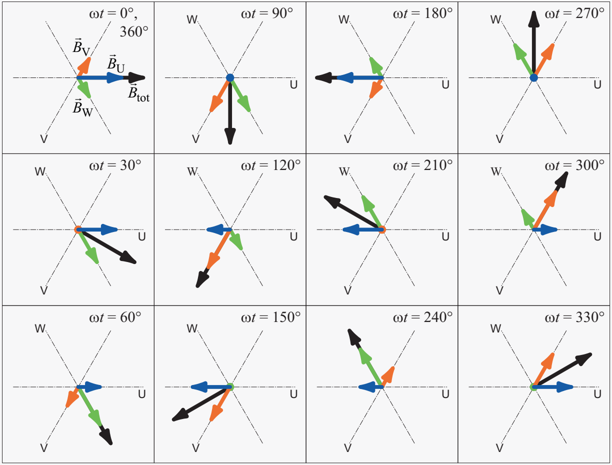


Figure Creation of a rotating field by overlaying 3 alternating fields

⇒ Sum of the three space vectors $\vec{B}_{\mathrm{U}}$, $\vec{B}_{\mathrm{V}}$ and $\vec{B}_{\mathrm{W}}$ results in total space vector $\vec{B}_{\mathrm{tot}}$

Equivalent circuit

- Consideration of strand U is sufficient (symmetrical system)
- Model behavior between U and neutral point
- Inductance / Reactance of the stator winding X_S needs to be considered

Voltage equation with the complex quantities:

$$\underline{U}_S = R_S \underline{I}_S + \mathrm{j} X_S \underline{I}_S + \underline{U}_P \tag{0.3}$$

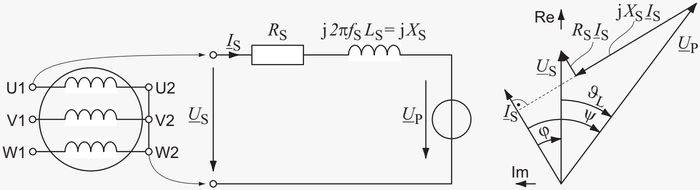
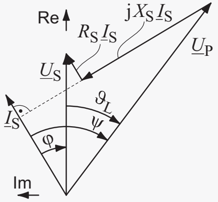


Figure Single-phase equivalent circuit and phasor diagram of the synchronous machine

Phasor Diagram



Phase angle φ
from current phasor $\underline{I}_S$ to voltage phasor $\underline{U}_S$

Load angle ϑ_L
from voltage phasor $\underline{U}_S$ to induced voltage phasor $\underline{U}_P$

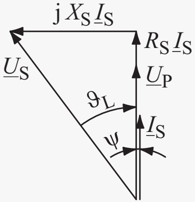
$\psi = \varphi + \vartheta_L$
from current phasor $\underline{I}_S$ to induced voltage phasor $\underline{U}_P$

- $\vartheta_L < 0$ Motor: Stator field leads the rotor field
- $\vartheta_L > 0$ Generator: Rotor field leads the stator field
- $\varphi < 0$ Overexcited: delivery of inductive reactive power
- $\varphi > 0$ Underexcited: consumption of inductive reactive power

Permanently excited synchronous motor

Motor consumes active power P_S:

$$P_S = 3U_S I_S \cos\varphi = P_{V,Cu,S} + P_\delta = \underbrace{3R_S I_S^2}_{P_{V,Cu,S}} + \underbrace{3U_P I_S \cos\psi}_{P_\delta}$$



$$M_i = \frac{P_\delta}{\omega_S/p} = \frac{3\,U_P I_S \cos\psi}{\omega_S/p}$$

$$= \frac{3\,U_P}{\omega_S/p} \cdot I_S, \text{ if } \psi = 0°$$

Figure Phasor diagram and torque in field-oriented operation

The excitation of the permanently excited synchronous machine is constant:

$$\frac{U_P}{\omega_S} = \text{const.} \quad \Rightarrow \quad \boxed{k_{M,PSM} = \frac{M_i}{I_S} = \frac{3\,U_P}{\omega_S/p} = \frac{3}{2}\frac{p}{\pi}\frac{U_P}{f_S}} \qquad (0.4)$$

Controller structure of permanent magnet synchronous motor

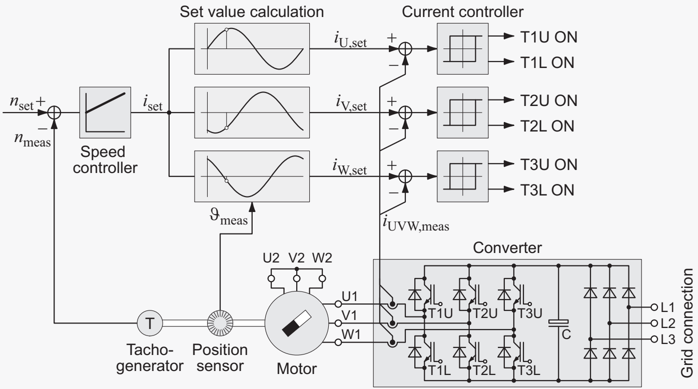


Figure Block diagram of a synchronous servo motor with sinusoidal currents

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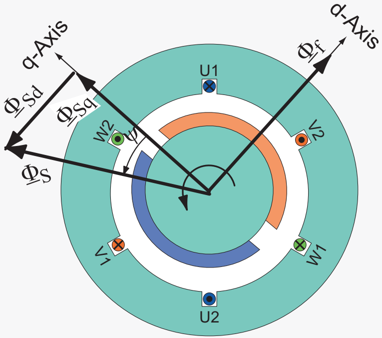
Example 5-2: Power Steering Motor

The induced voltage of a permanent magnet synchronous motor (drive for electric power steering) was oscillographed as line-to-line voltage(!). The sinusoidal curve has a peak value of $8\,V$ at a frequency of $80\,Hz$ and the nominal speed of $1200\,\mathrm{min}^{-1}$. What is the number of pole pairs p and the torque constant $k_{\mathrm{M,PSM}}$? What is the internal torque M_{i} and the phase current I_{S} at the nominal point with $750\,W$?

direct and quadrature axes

- Direct axis (d-axis):
  Parallel to rotor flow
- Quadrature axis (q-axis):
  Perpendicular to the rotor flux or parallel to the induced voltage



$$\Phi_{Sd} = \Phi_S \sin\psi$$
$$\Phi_{Sq} = \Phi_S \cos\psi$$
$$I_{Sd} = I_S \sin\psi$$
$$I_{Sq} = I_S \cos\psi$$

$$M_i = \frac{P_\delta}{\omega_S/p} = \frac{3\,U_P I_S \cos\psi}{\omega_S/p} = \frac{3\,U_P I_{Sq}}{\omega_S/p}$$

- q-current: generates torque
- d-current: enables field weakening

Field weakening for permanently excited synchronous motors

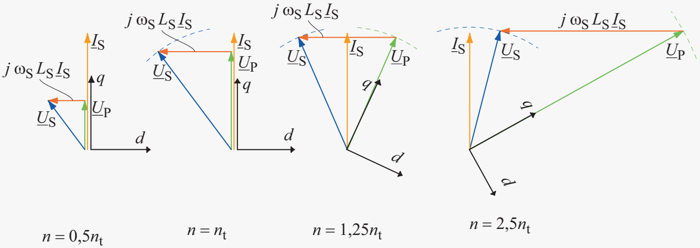
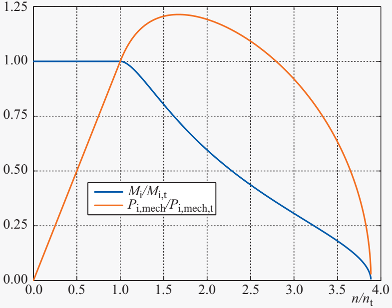
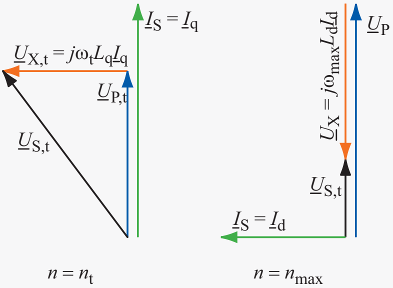


Figure Field weakening for permanently excited synchronous motors

- Base speed range: $U_S < U_{S,t}, n < n_t$
- „Lower“ field weakening area: $U_S = U_{S,t}, n > n_t, \cos\varphi \rightarrow 1$
  - ⇒ Power $3U_S I_S \cos\varphi$ may increase
  - ⇒ Torque is decreasing
- „Upper“ field weakening area: $U_S = U_{S,t}, n > n_t, \cos\varphi \rightarrow 0$
  - ⇒ Power $3U_S I_S \cos\varphi$ is getting smaller again
  - ⇒ Torque drops sharply

Field weakening at PSM - torque and max. speed





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Example 5-3: Synchronous servo drive on the converter

A six-pole, star connected, permanent magnet excited synchronous servo drive is given. At a speed of $3000\,\text{min}^{-1}$, a sinusoidal line-to-line voltage of $200\,V$ was measured in no-load operation. The measured winding resistance at operating temperature is $0.5\,\Omega$. The maximum continuous current is $12\,A$ and the maximum short-term current is $36\,A$.
At a speed of $100\,\text{min}^{-1}$, a winding current of $7.5\,A$ is measured for the three-phase short-circuited stator winding. Saturation effects and friction losses can be neglected for simplicity. Except in a. the stator copper losses can also be neglected. (Why?)

a. What is the synchronous inductance L_S?
b. The servo motor is driven by a converter on the 400 V three-phase mains (DC-voltage link $U_d \approx \sqrt{2} \cdot 400\,V$). What is the maximum continuous power at an angle of $\psi = 0°$ and at what speed does it occur? (all losses in the converter can be neglected and a practically infinite high switching frequency can be assumed) Explain the flow of reactive power! (Where is reactive power „generated“ and where is it „consumed“?)
c. Up to what maximum speed can the servo drive deliver three times the rated torque for a short time?
d. What is the maximum continuous power at rated current when the motor consumes pure active power? Up to what speed can the motor then be operated continuously and what is the torque compared to a?

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Example 5-4: Servo Motor Datasheet

The following servo motor (source: Siemens AG) is to be used in an industrial automation system. Except for the current heat losses in the stator winding, all losses can be neglected.

a. What are the efficiency and power factor at the rating point?
b. The servo drive is operated with q current up to the rated speed. Draw the phasor diagram with all relevant variables for the rating point.
c. Check the plausibility of the torque and voltage constants given in the data sheet using the previous calculations. What are the reasons for any deviation?
d. Up to what speed (at rated voltage and current) is active field weakening possible? (The stator resistance can be neglected).
e. Up to which speed is the maximum torque (at maximum current) possible? (Stator resistance can be neglected).

Example 5-4: Servo Motor Datasheet

a) + b) c) d) e)

Technical data and characteristics

7.2 1FK7 motors on SINAMICS S120 with 3 AC 400/480 V power supply

Table 7-5 1FK7034 CT

Technical data	Code	Unit	–5AK71	
Configuration data				
Rated speed	n_N	RPM	6000	
No. of poles	2p		6	
Rated torque (100 K)	$M_{N\ (100\ K)}$	Nm	1.0	
Rated current (100 K)	I_N	A	1.3	
Static torque (60 K)	$M_{0\ (60\ K)}$	Nm	1.35	
Static torque (100 K)	$M_{0\ (100\ K)}$	Nm	1.6	
Stall current (60 K)	$I_{0\ (60\ K)}$	A	1.6	
Stall current (100 K)	$I_{0\ (100\ K)}$	A	1.9	
Moment of inertia (with brake)	J_{MotBr}	10^{-4} kgm^2	0.98	
Moment of inertia (without brake)	J_{Mot}	10^{-4} kgm^2	0.9	
Optimum operating point				
Optimum speed	n_{opt}	RPM	6000	
Optimum power	P_{opt}	kW	0.63	
Limiting data				
Max. permissible speed (mech.)	$n_{max\ mech}$	RPM	10000	
Max. permissible speed (converter)	$n_{max\ Inv}$	RPM	10000	
Max. torque	M_{max}	Nm	6.5	
Max. current	I_{max}	A	8	
Physical constants				
Torque constant	k_T	Nm/A	0.86	
Voltage constant	k_E	V/1000 RPM	55	
Winding resistance at 20°C	R_{Str}	Ohm	4.5	
Cyclic inductance	L_D	mH	16.5	
Electrical time constant	T_{el}	ms	3.7	
Mechanical time constant	T_{mech}	ms	1.6	
Thermal time constant	T_{th}	min	30	
Shaft torsional stiffness	c_t	Nm/rad	5500	
Weight with brake	m_{MotBr}	kg	4.0	
Weight without brake	m_{Mot}	kg	3.7	
Recommended motor module 6SL312_-_TE13-0AA_				
Rated current converter	$I_{N\ Inv}$	A	3	
Max. current converter	$I_{max\ Inv}$	A	6	
Max. torque at $I_{max\ Inv}$	$M_{max\ Inv}$	Nm	4.9	

Figure Data sheet servo motor

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Exemple 5-5: Traction Drive

An eight-pole permanently excited drive for an electric car is specified on the rating plate:

$$75\,kW\ /\ 2100\,\mathrm{min}^{-1}\ /\ 320\,V\ /\ 170\,a$$

At nominal point, the induced voltage and phase current are in phase with each other.
Joule and friction losses can be neglected.

a. Qualitatively sketch the phasor diagram for the nominal point (recommended: approx. $50\,V/cm$)! What is the synchronous inductance L_S and the induced voltage?

b. What is the reactive power consumed and the torque at the nominal point?

c. What is the maximum power that can be delivered if the nominal voltage and current are not exceeded? At what speed and what torque does this operating point occur?

d. At three times the nominal speed, the motor is loaded with the nominal voltage in such a way that the nominal current flows. What is now the torque and power output?

Tip: it follows directly from the cosine theorem: $\cos\vartheta_\mathrm{L} = \dfrac{U_\mathrm{S}^2 + U_\mathrm{P}^2 - (X_\mathrm{S} I_\mathrm{S})^2}{2\,U_\mathrm{S} U_\mathrm{P}}$