5 Synchronous machine

5.1 History and areas of application

The first **single-phase generator** for generating electrical energy was presented in 1848 by Nollet and Holmes (Alliance). Generators of this design were primarily used to power lighting systems.

Three-phase synchronous generators were first built in 1887 by Haselwander and Tesla (two-phase) and Bradley (three-phase). These were **salient pole machines**, whose excitation poles are similar to the DC machine but in the rotor instead of in the stator. Today, salient-pole machines are mainly built as high-pole **hydroelectric power generators** for low speeds, sometimes with more than 60 poles and outputs up to around $800\,\mathrm{MVA}$.

In 1891 Dobrowolsky applied for a patent for the star and delta connection and as early as 1890 Tesla presented a medium-frequency machine for 9..10 kHz with 384 poles. The **first three-phase power transmission** from Lauffen to Frankfurt took place with a $200\,\mathrm{kW}$ three-phase generator in claw-pole design from Oerlikon. These first claw-pole generators are still being built in large numbers today as „alternators“ for combustion motor vehicles with outputs of up to $5\,\mathrm{kW}$.

The non-salient rotor was not invented until 1901 by Charles E.L. Brown (BBC). The excitation winding is distributed over several slots (similar to a three-phase winding) in the round rotor. This first **turbo generator** achieved at $3000\,\mathrm{min}^{-1}$ an output of $250\,\mathrm{kVA}$, which is modest by today's standards.

This design is used today with low numbers of poles for outputs of up to $1200\,\mathrm{MVA}$ ($p = 1,\ U_\mathrm{N} = 21\,\mathrm{kV}$) or $2200\,\mathrm{MVA}$ ($p = 2,\ U_\mathrm{N} = 27\,\mathrm{kV}$) as turbo generator to produce electricity from the output of gas and steam turbines.

Synchronous motors have long been of secondary importance in terms of number of machines compared to asynchronous motors. When operated on the converter, the **permanently excited synchronous motor** (excitation via permanent magnets instead of direct current excitation) is used for powers up to about $50\,\mathrm{kW}$ as **servo motor** for machine tools, handling devices and robotics. For outputs in the MW range, e.g. to drive large pumps with a regulated flow rate they are are often preferred to asynchronous machines because of the smaller converter (no need of reactive power).

Higher power DC motors are being replaced by synchronous motors for example in the automotive sector. (Starting at approx. $300\,\mathrm{W}$)

Synchronous motors are built in large numbers as small and very small motors (stepper motors), for example for precision engineering (e.g. clocks, printers, etc.).

In Figure 5.1 two synchronous machines are shown, which are also very different in terms of size: in the left figure, the installation of the rotor (rotor diameter approx. 8 m) for one of the 26 generators of the Hydroelectric power station Sanxia (Three Gorges Reservoir, China) and on the right a synchronous motor in a car interior fan (rotor inner diameter approx. 8 cm).

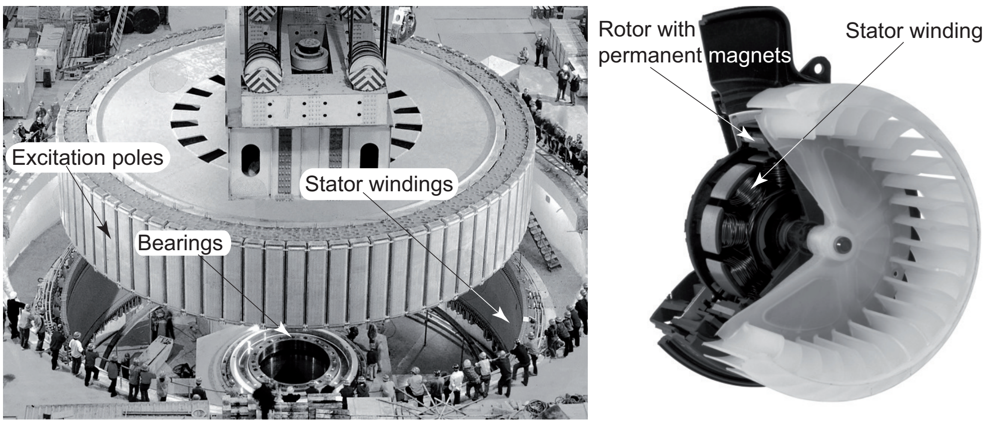


Figure 5.1: $800\,\mathrm{kVA}$ hydroelectric generator and $300\,\mathrm{W}$ car interior fan with external rotor (Sources - left: Voith Hydro, right: Brose)

In **Robotics** only the permanent magnet excited synchronous motor is used due to its dynamic advantages. It is therefore the focus of this chapter.

5.2 Synchronous motor as electronically commutated DC motor

The structure of a permanent magnet synchronous motor can be compared to a permanent magnet DC motor. In synchronous motors, the excitation poles are placed in the rotor instead of in the stator and the mechanical commutator, which in the DC-motor switches the direction of the armature currents, is replaced here by a **inverter**, i.e. by electronic switches feeding the stator.

The stator winding is designed as a three-phase winding, i.e. three windings offset by $120°$ are provided for the three phases. In the case of excitation by permanent magnets, an approximately square-wave form of the air gap induction can be assumed, so that the voltage induced in a stator winding must also have a square-wave form. In Figure 5.2 the development of the induced voltage (u_{P} due to "Polradspannung" in German) is shown for a two-pole configuration.

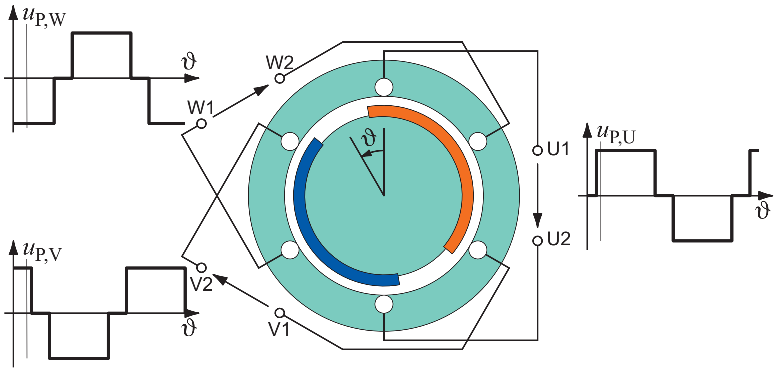


Figure 5.2: Induced voltage at constant speed

There are two magnetic shells on the rotor surface: a magnetic north and a magnetic south pole. There are three coils in the stator (U, V and W) whose forward and return conductors (U1/U2, V1/V2, W1/W2) are placed opposite to each other.

If a magnetic shell passes under the coil sides, a voltage is induced in the conductors, the sign of which depends on the direction of the magnetic field and the direction of rotation. If one of the two pole gaps lies under the conductors, the voltage is equal to zero. With this simple design, the voltage curves are a direct image of the induction in the air gap.

Since the coils in this three-phase winding are offset from each other by $120°$, the curves for the three induced voltages $u_{\mathrm{P,U}}$, $u_{\mathrm{P,V}}$ and $u_{\mathrm{P,W}}$ have a phase shift of $120°$.

With this simple two-pole configuration, a three-phase voltage system with block-shaped voltages and the frequency $f_{\mathrm{S}} = p \cdot n$ is obtained at constant speed. In actual synchronous motors, however, the winding is not as simple as shown here for various reasons.

The real curves of the induced voltage $u_{\mathrm{P,U}}$, $u_{\mathrm{P,V}}$ and $u_{\mathrm{P,W}}$ are therefore not rectangular as shown in Figure 5.2, but either trapezoidal as shown in Figure 5.3 or almost purely sinusoidal . If the synchronous motor with trapezoidal induced voltage is operated with block-shaped stator currents i_{U}, i_{V} and i_{W}, the result is a constant power $p(t) = P$ i.e. a constant torque.

As shown in Figure 5.3, two phases always conduct electricity, with the third phase being currentless. The sum of the three currents is thus zero at every instant.

A relatively simple control can be used then for the current: the individual phases always carry an almost constant current for a third of the period, so that the currents can be electronically switched from one phase to the next; for this reason one also speaks here of **electronic commutation**. The setpoints for the current commutation can be determined from the rotor position.

The necessary resolution for the rotor position is relatively low ($60°/p$, p: number of pole pairs), so that cheap systems with light barriers or Hall elements can be used. The currents can be controlled via a simple **hysteresis control**. This is shown in Figure 5.4 for one phase.

A constant current I_{G} is used as the current setpoint i_{set} and compared with the actual phase current i_{meas}. As soon as the difference is greater than the tolerance range set in the hysteresis element, either the upper (T1U) or lower transistor (T1L) are switched on.

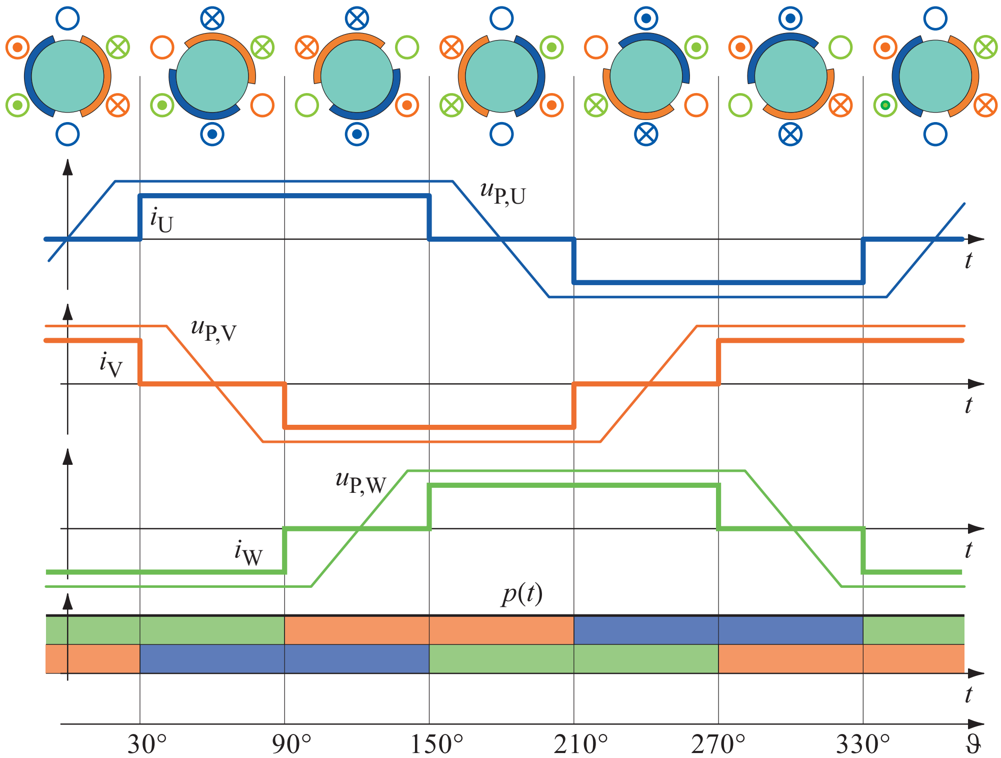


Figure 5.3: Current and induced voltage for an EC motor

When the current reaches the lower limit of the tolerance band, the difference between the setpoint and actual value becomes greater than $+\Delta i_{\max}/2$ and the upper transistor T1U is switched on. As a result, the motor winding is connected to the upper of the two DC voltage sources $U_{\mathrm{d}}/2$; the phase voltage $u(t)$ is equal to $+U_{\mathrm{d}}/2$ and the current raises.

However, if the current reaches the upper limit of the tolerance band, the difference between the reference value and the actual value becomes smaller than $-\Delta i_{\max}/2$ and the lower transistor T1L is switched on. As a result, the motor winding is now connected to the lower of the two DC voltage sources $U_{\mathrm{d}}/2$; the phase voltage $u(t)$ is equal to $-U_{\mathrm{d}}/2$ and the current dicreases. In this way, the actual current value remains always within the defined tolerance band.

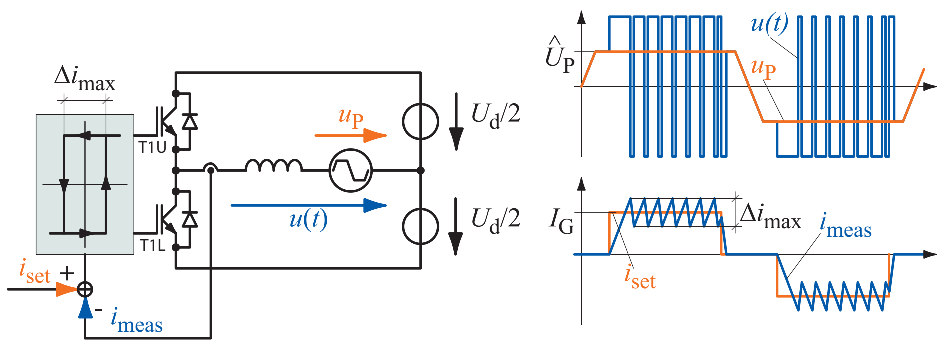


Figure 5.4: Hysteresis current controller principle for one phase

The circuit controlled by the hysteresis controller in Figure 5.4 is called a **half bridge**. If the currents in a three-phase synchronous motor are to be controlled with this basic circuit, three of these half-bridges are required. However, as shown in Figure 5.5, only one hysteresis current controller is required, since the same (direct) current flows in both energized phases. The third one should be currentless, i.e. the half-bridge connected to the currentless phase is simply not controlled.

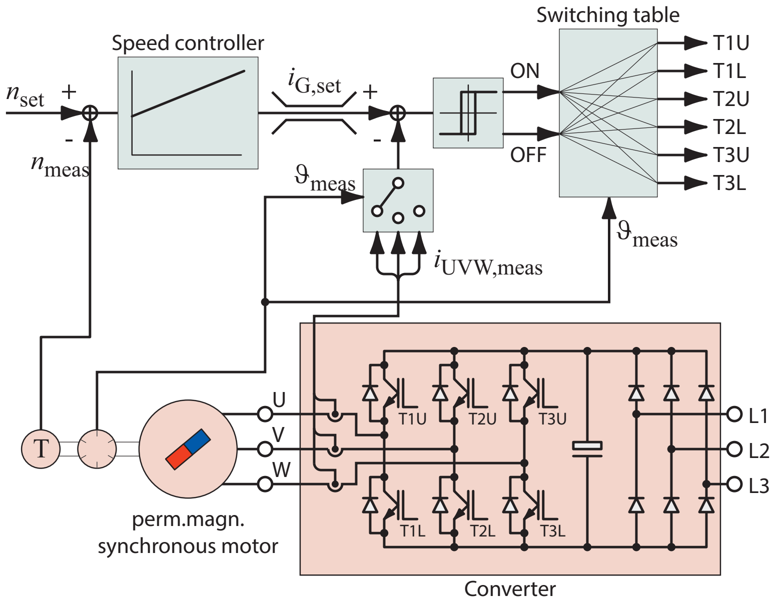


Figure 5.5: Block diagram of an EC motor (electronically commutated DC motor)

From Figure 5.3 you can see that the actual-value for the hysteresis controller in Figure 5.5 is the current value on phase U i_U in the range from $\vartheta = 30°...150°$. In the range of $\vartheta = 150°...270°$ is equal to the current i_W and in the last range of $\vartheta = 270°...360°...30°$ is equal to the current i_V.

The outputs of the hysteresis controller for the one phase inverter in Figure 5.4 directly controls one of the two transistors. In the case of the three-phase converter, however, all four transistors of the two half-bridges used must be activated.

In Figure 5.3, the current controlled via the hysteresis controller flows in the range of $\vartheta = 30°...90°$ over the phases U and W. As a result, the half-bridges consisting of the transistors T1U/T1L and T3U /T3L must be switched on/off. If the transistors T1U and T3L are on, $+U_d$ is set between the terminals U and W, but if the transistors T1L and T3U are on, $-U_d$ is set between the terminals U and W. In this range, the gate signals for T1U and T3L would be connected to the ON output and the gate signals for T1L and T3U would be connected to the OFF output of the hysteresis controller.

For the range $\vartheta = 90°...150°$ the phases U and V and so the half-bridges T1U/T1L and T2U/T2L are controlled. If the transistors T1U and T2L are on, $+U_d$ is present between the terminals U and V, but if the transistors T1L and T2U are on, $-U_d$ is present between the terminals U and V.

The switching logic stored in the switching table can be completely derived in the same way for all further ranges.

The complete control unit for the motor is a **cascade control** (Figure 5.5). The lower level is the current controller (equivalent to torque controller). The higher level is the speed controller. If the actual speed n_{meas} (measured with the tachogenerator T) deviates from the set speed n_{set}, the speed controller counteracts this by changing the set current $i_{\mathrm{G,set}}$. The switching signals for the transistors in the converter are generated from this setpoint depending on the position information obtained from the position sensor (resolution: $60°/p$).

The current I_{G} is set in two phases at any time, so that the average power or torque can be determined with the peak value of the trapezoidal induced voltage:

$$P_{\mathrm{i,mech}} = 2 \cdot \hat{U}_{\mathrm{P}} \cdot I_{\mathrm{G}} \quad \Rightarrow \quad k_{\mathrm{M,EC}} = \frac{M_{\mathrm{i}}}{I_{\mathrm{G}}} = \frac{P_{\mathrm{i,mech}}/\Omega_{\mathrm{m}}}{I_{\mathrm{G}}} = \frac{2 \cdot \hat{U}_{\mathrm{P}} \cdot I_{\mathrm{G}}}{I_{\mathrm{G}} \cdot 2\pi n} = \frac{p}{\pi}\frac{\hat{U}_{\mathrm{P}}}{f_{\mathrm{S}}} \tag{5.1}$$

As the induced voltage is proportional to the speed or stator frequency, the **torque constant** $k_{\mathrm{M,EC}}$ is actually a constant and is often listed as such on the rating plate of an EC servo motor as additional information.

In many applications, an angle sensor can be avoided if the zero crossing of the induced voltage can be detected otherwise. It is then called sensorless control. However, these possibilities will not be discussed further here.

Very similar to the direct current machine, the mechanical variables angular velocity Ω_{m}, torque M_{i} and the electrical variables induced voltage $\hat{U}_{\mathrm{P}}$ and stator current I_{G} can be related to each other using the following definitions:

- each phase has N_{S} turns
- each winding has 2 coil sides in a laminated core of length l_{Fe}
- the permanent magnets on the rotor surface in the air gap generate the magnetic flux density B_{f}
- this excitation field passes under the stator winding with the speed v_{circ}, since the rotor rotates at the speed n
- d_{L} is the average air gap diameter

The induced voltage $\hat{U}_{\mathrm{P}}$ can be then specified in the following way:

$$\hat{U}_{\mathrm{P}} = 2N_{\mathrm{S}} \cdot l_{\mathrm{Fe}} \cdot B_{\mathrm{f}} \cdot v_{\mathrm{circ}} = N_{\mathrm{S}} \cdot l_{\mathrm{Fe}} \cdot B_{\mathrm{f}} \cdot \underbrace{2\pi n}_{\Omega_{\mathrm{m}}} \cdot d_{\mathrm{L}} = \underbrace{N_{\mathrm{S}}\, l_{\mathrm{Fe}}\, d_{\mathrm{L}}\, B_{\mathrm{f}}}_{= k_{\mathrm{M,EC}}/2} \cdot \Omega_{\mathrm{m}} \tag{5.2}$$

The constant $k_{\mathrm{M,EC}}$ is therefore comparable to the „torque constant“ $c\Phi_{\mathrm{f}}$ of the DC machine. The frequency f_{S}, with which the induced voltage is induced in the stator winding, is greater than the speed n by the number of pole pairs p. In addition, the current I_{G} is set in two phases, so that with the peak value of the trapezoidal induced voltage $\hat{U}_{\mathrm{P}}$, the power $P_{\mathrm{i,mech}}$ or the torque M_{i} as in Eq. 5.1 can be specified.

Since the induced voltage is proportional to the speed or frequency, the torque constant or voltage constant $k_{\mathrm{M,EC}}$ in $\mathrm{Nm/A}$ or in $\mathrm{V\,s}$ is actually a constant.

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 $8\,\mathrm{V}$ at a frequency of $80\,\mathrm{Hz}$ and a speed of $1200\,\mathrm{min}^{-1}$. How big is at this speed the current I_{G} at a power of $450\,\mathrm{W}$? 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 $k_{\mathrm{M,EC}}$?

5.3 Alternating fields and rotating fields

The synchronous motor as an electronically commutated direct current motor (EC-Motor) scores with its simple power electronics and control. However, the block-shaped currents cause additional losses and vibrations. For this reason, sinusoidal currents are used in robotics for many applications. This achieves a real rotating field, the motor has fewer losses and runs more smoothly. The following explains how a rotating stator field can be generated with a sinusoidal three-phase system.

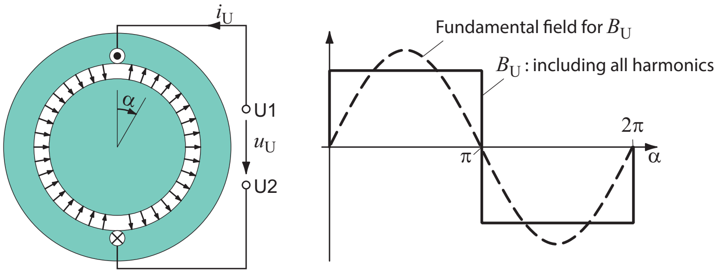


Figure 5.6: Alternating field with one-phase I

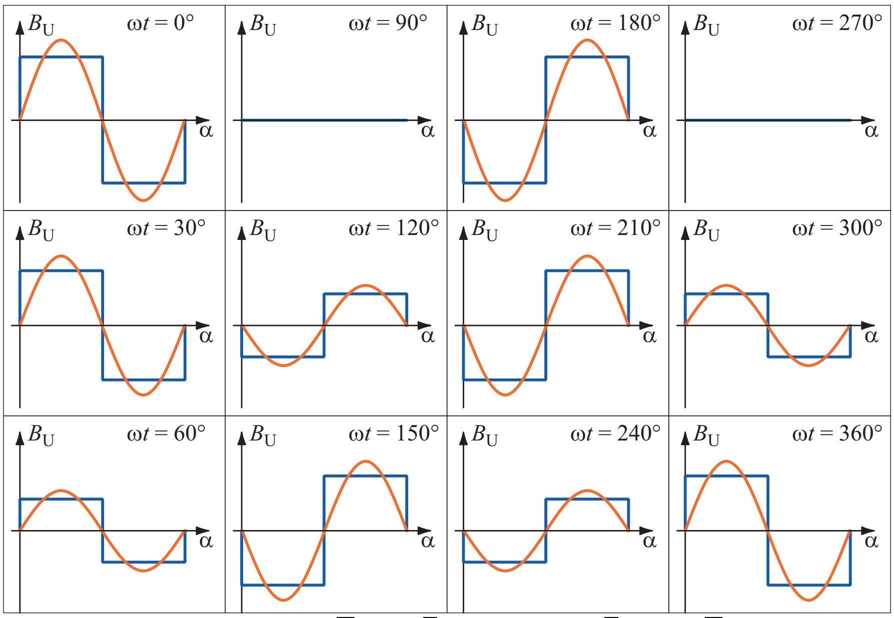
As a first step, the stator of an electrical machine supplied with a single-phase (here phase U with the connection terminals U1 and U2) is considered (see Fig. 5.6). This single phase is supplied with a sinusoidal AC voltage u_U, which in turn results in an alternating current i_U. Assuming a simple diameter coil, the current results in a block-shaped field distribution $B_U(\alpha)$ over the position angle $\alpha = 0$ to 2π.

In the right half ($\alpha = 0$ to π) the magnetic field is directed radially outwards and in the left half (($\alpha = \pi$ to 2π) radially inwards. If an alternating current is used, the position of the zero points of the field distribution $B_U(\alpha)$ remains constant, only the maximum amplitude changes with the instantaneous value of the exciting current $i_U(t)$. Figure 5.7 shows the field curves for one period of the current $i_U(t)$ (assumed to be cosinusoidal with the effective value I_U). It is clear that with a single phase a stationary alternating field is produced.

For further discussions, only the fundamental wave of the flux density $B_U(\alpha)$ (shown in red in Figure 5.7) will be considered, since the consideration of all harmonics would mean a considerable effort. In many cases, however, the neglect of the harmonics when considering the operating behavior of AC machines is permissible without major errors.

Under these conditions, the fundamental wave can be represented as a vector („space vector“), the length of which indicates the peak value and the direction of which indicates the position of the maximum. This type of representation facilitates the superimposition of the field generated by three phases.
The three phases U, V and W are spatially offset by $120°$, so that the three resulting field distributions can each be represented by a space vector, which are mutually rotated by $120°$. However, since the time-functions of the three phases are also phase-shifted by $120°$, all three space vectors can never have the same length at the same time. Figure 5.8 only shows the positive direction of the three space vectors.

In the diagrams in Figure 5.9 the three space vectors $\vec{B}_U$, $\vec{B}_V$ and $\vec{B}_W$, as well as their sum $\vec{B}_{tot}$ are shown for different moments in time.
The length of the space vector $\vec{B}_U$ (**blue** vector in Figure 5.9) is maximum at $\omega t = 0°$, it gets smaller until it disappears at $\omega t = 90°$, then grows again in the opposite



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

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

Figure 5.7: Alternating field with one phase II

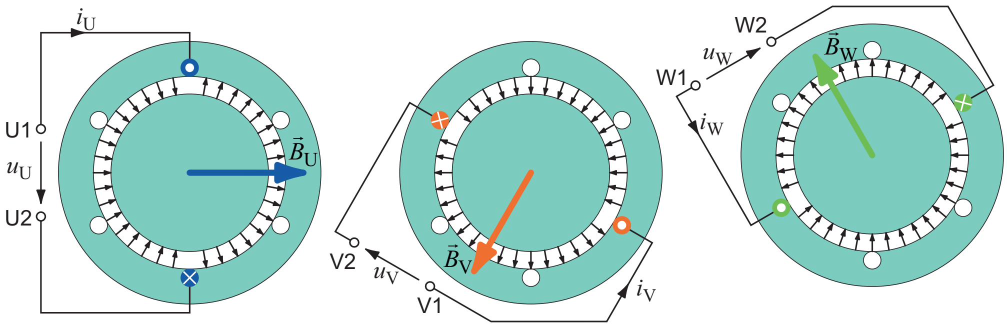


Figure 5.8: Direction specifications for the alternating fields of the three phases

direction until $\omega t = 180°$ and gets shorter again until it disappears again at $\omega t = 270°$. The four significant points in time mentioned for $\vec{B}_U$ (maximum length and zero crossing) are all in the first line.

For the space vector $\vec{B}_V$ (**red** vector), the same process starts at $\omega t = 120°$ with its maximum length, to then disappear until $\omega t = 210°$, until $\omega t = 300°$ growing in the other direction and then disappearing again until $\omega t = 30°$. For this pointer, all significant moments are in the second line.

For the space vector $\vec{B}_W$ (**green** vector), the process, which is also periodic, finally begins at $\omega t = 240°$, here all significant moments are in the third line.

For each time point, the space vector $\vec{B}_{tot}$ (**black** vector in Figure 5.9) is the sum of the three space vectors $\vec{B}_U + \vec{B}_V + \vec{B}_W$. This sum vector obviously has a constant length and rotates with constant speed $\omega/(2p)$ showing that a rotating field is created by overlaying the three alternating fields for the phases U, V and W.

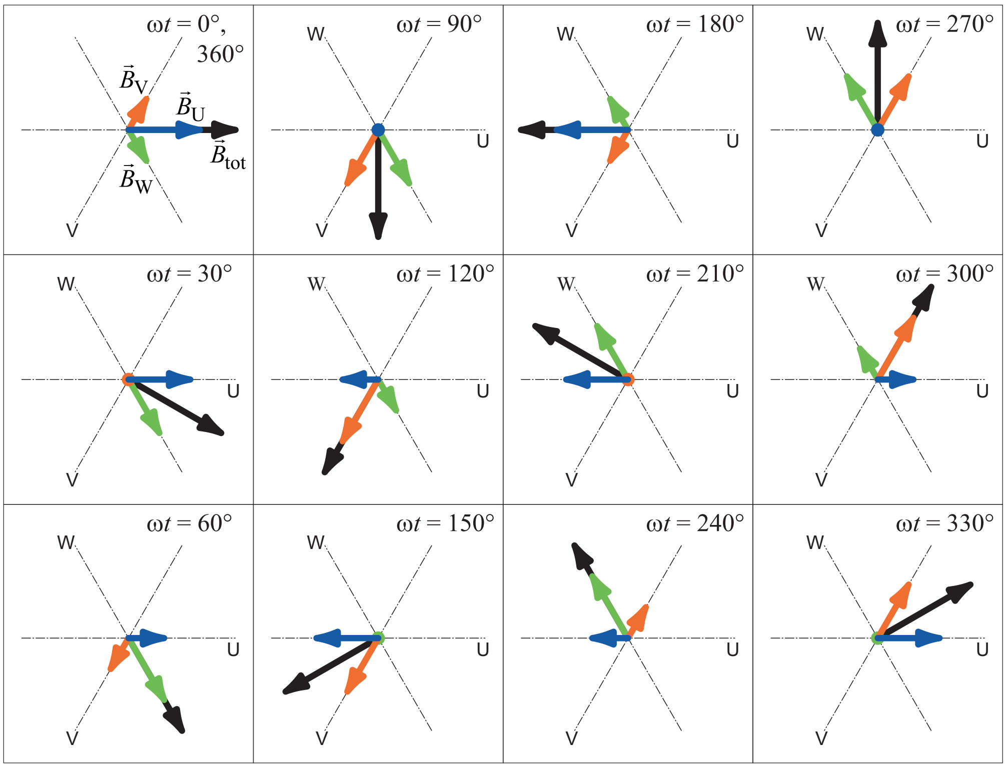


Figure 5.9: Creation of a rotating field by overlaying three alternating fields

5.4 Equivalent circuit diagram and vector diagram

If a symmetrical(!) three-phase system is to be described by an equivalent circuit diagram, one can limit oneself to considering phase U. The behavior between the phase connection U and the neutral point is modeled here with a two-terminal network, regardless of whether a neutral point actually exists or not. Since voltages and currents are sinusoidal quantities, they are not represented as real quantities but as complex effective value vectors.

Compared to the DC machine, in the single-phase equivalent circuit diagram of the synchronous machine, in addition to the stator resistance R_S (corresponding to the armature resistance of the DC machine), the stator inductance L_S or the (purely imaginary) **stator reactance** $\mathrm{j}\,X_S$ needs to be considered. The index S here indicates a stator value; in the DC machine, the index A was a reference to the armature or rotor.

The single phase equivalent circuit is completed with the induced voltage U_P (corresponds to the induced voltage U_i), the stator voltage U_S (corresponds to the armature voltage U_A) and the stator current I_S (corresponds to the armature current I_A) and it can be found (with the associated phasor diagram) in Figure 5.10.
The voltage equation with the complex variables can be derived from the single-phase equivalent circuit diagram:

$$\underline{U}_S = R_S \underline{I}_S + \mathrm{j}\,X_S \underline{I}_S + \underline{U}_P \tag{5.3}$$

The stator voltage $\underline{U}_S$ results as the sum of the voltage drop at the winding resistance R_S and the stator reactance $\mathrm{j}\,X_S$, as well as the induced voltage $\underline{U}_P$.

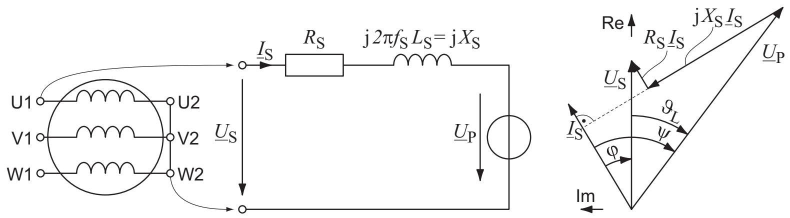


Figure 5.10: Single-phase equivalent circuit and phasor diagram of the synchronous machine

The stator voltage phasor $\underline{U}_S$ has been placed in the real axis. If motor operation is assumed for the synchronous machine, then the current vector $\underline{I}_S$ must be in the upper (positive real) half-plane, since the consumer reference system (= motor operation assumed) has been selected in the equivalent circuit diagram. In addition, the current vector $\underline{I}_S$ has also been assumed to be ahead of the stator voltage vector $\underline{U}_S$, so that the synchronous machine should therefore deliver inductive reactive power to the supply network. The phase angle φ is counted from the current phasor $\underline{I}_S$ to the voltage phasor $\underline{U}_S$ and is negative here because of the inductive reactive power output ($\varphi < 0$).

The voltage drop across the winding resistance $R_S\underline{I}_S$ must be parallel to $\underline{I}_S$ because the current vector is only scaled by the real factor R_S. The voltage drop at the stator reactance j X_S, on the other hand, must be rotated counterclockwise by $90°$ because of the factor j $= e^{\mathrm{j}\,\pi}$ and is therefore perpendicular to the voltage vector $R_S\underline{I}_S$. The induced voltage phasor $\underline{U}_P$ results then from the geometry addition.

As with the DC machine, the induced voltage is proportional to the excitation flux and the mechanical speed. The excitation flux is almost constant in machines excited by permanent magnets. In the case of an electrical excitation, the induced voltage can be adjusted by the level of the excitation current and this allows to control the reactive power flow of the machines. This is used in synchronous generators to supply the grid with the required reactive power. However, this will not be discussed in detail here.

The **load angle** ϑ_L indicates the angle from of the induced voltage $\underline{U}_P$ to the phase voltage $\underline{U}_S$. The sign of the load angle ϑ_L indicates the direction of the active power flow, the sign of the phase angle φ the direction of the reactive power flow.

The angle $\psi = \varphi + \vartheta_L$ is the sum of the phase and load angle and represents the phase shift from the current phasor $\underline{I}_S$ to the induced voltage phasor $\underline{U}_P$.

5.5 Permanently excited synchronous motor

Especially for lower outputs (up to approx. 15 kW), the electrical excitation of the synchronous machine can be economically replaced by excitation with permanent magnets. Because of the new efficiency classes, the replacement of asynchronous motors with permanently excited synchronous motors is also being discussed. The main application of permanently excited synchronous motors is however as speed-variable servo drives for robots, machine tools and handling devices on pulse-controlled inverters. Because of the permanent magnetic excitation, however, it is no longer possible to control the flow of reactive power.

In addition to being used as a servo motor, permanently excited synchronous motors are also used as ship propulsion systems. The motors are used as a direct drive for the propellers in gondolas, which in turn can be pivoted. The propeller nacelles make the ship extremely manoeuvrable, which is particularly beneficial for cruise ships.

5.5.1 Operating behavior

In the case of excitation by means of permanent magnets, as with the EC motor, an approximately block-shaped function of the air gap field can be assumed. However, an almost sinusoidal induced voltage can be achieved by appropriate winding design.

The motor absorbs the active power P_S, which covers the power loss $P_\mathrm{V,Cu,S}$ in the winding resistances R_S of the three strands and the air-gap power P_δ (converted in mechanical power in the induced voltage U_P) :

$$P_\mathrm{S} = 3U_\mathrm{S}I_\mathrm{S}\cos\varphi = P_\mathrm{V,Cu,S} + P_\delta = \underbrace{3R_\mathrm{S}I_\mathrm{S}^2}_{P_\mathrm{V,Cu,S}} + \underbrace{3U_\mathrm{P}I_\mathrm{S}\cos\psi}_{P_\delta} \tag{5.4}$$

The air-gap power P_δ is maximized if the stator current I_S is in phase with the induced voltage U_P ($\psi = 0$). As a result, the stator and excitation fields are perpendicular to each other, as in the DC machine, and the torque M_i is then proportional to the stator current I_S (Figure 5.11):

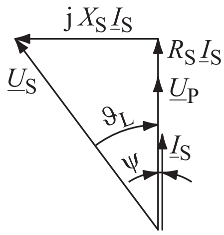


Figure 5.11: Phasor diagram and torque for PSM

$$M_\mathrm{i} = \frac{P_\delta}{\omega_\mathrm{S}/p} = \frac{3\,U_\mathrm{P}I_\mathrm{S}\cos\psi}{\omega_\mathrm{S}/p}$$
$$= \frac{3\,U_\mathrm{P}}{\omega_\mathrm{S}/p}\cdot I_\mathrm{S},\ \text{if } \psi = 0°$$

The excitation of the permanently excited synchronous machine is constant:

$$\frac{U_\mathrm{P}}{\omega_\mathrm{S}} = \text{const.} \qquad \Rightarrow \qquad \boxed{k_\mathrm{M,PSM} = \frac{M_\mathrm{i}}{I_\mathrm{S}} = \frac{3\,U_\mathrm{P}}{\omega_\mathrm{S}/p} = \frac{3}{2}\frac{p}{\pi}\frac{U_\mathrm{P}}{f_\mathrm{S}}} \tag{5.5}$$

Since in this operating mode the torque M_i is proportional to the stator current I_S (armature current), as with the DC machine, the literature often speaks of **electronically commutated DC motor** (EC Motor or „**brushless DC motor**“), even if servomotors are almost exclusively operated with sinusoidal currents.

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 $8\,\mathrm{V}$ at a frequency of $80\,\mathrm{Hz}$ 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 $750\,\mathrm{W}$?

The mode of operation with block-shaped currents shown in Figure 5.5 is used for small permanently excited synchronous motors (e.g. fan drives in vehicles) because of the simpler control and the simpler position sensor. For operation with sinusoidal currents, a position encoder with a resolution of at least $1°/p$ is required, so that, as in Figure 5.12, the current setpoint i_{set} determined by the speed controller can be compared with the corresponding sinusoidal functions. The setpoint i_{set} then corresponds to the peak value of the phase currents $i_{\text{U,set}}$, $i_{\text{V,set}}$ and $i_{\text{W,set}}$, which are tracked by the current controllers. The only difference between the structure in Figure 5.12 and that in Figure 5.5 is the generation of the current setpoints.

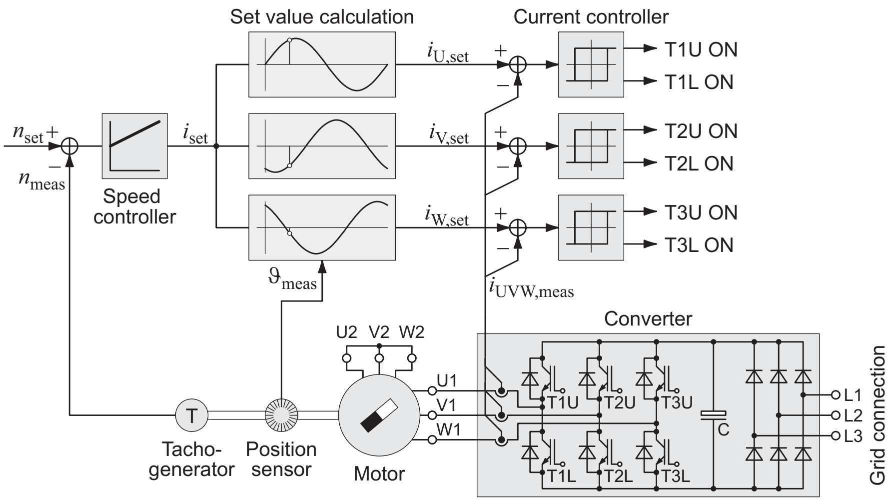


Figure 5.12: Block diagram of a synchronous servo motor with sinusoidal currents

As with permanent magnet DC motors, field weakening is not possible with permanent magnet synchronous motors. In contrast to the DC motor, however, the excitation field generated by the permanent magnet can be partially compensated by the stator field. To understand this active field weakening, it is helpful to divide the stator current and the stator flux into a direct component (d-component) and a quadrature component (q-component). These two components are shown in a motor geometry in Figure 5.13. The direct axis is parallel to the PM rotor flux. The quadrature axis is perpendicular to it. The induced voltage is then by definition on the q-axis, and the d and q components of the stator current and flux can be calculated using the angle Φ (angle of the stator current to the induced voltage).

$$\Phi_{\text{Sd}} = \Phi_{\text{S}} \sin \psi \qquad \text{and} \qquad \Phi_{\text{Sq}} = \Phi_{\text{S}} \cos \psi \tag{5.6}$$

$$I_{\text{Sd}} = I_{\text{S}} \sin \psi \qquad \text{and} \qquad I_{\text{Sq}} = I_{\text{S}} \cos \psi \tag{5.7}$$

It then turns out that only the q-current contributes to the torque. For this reason, only q-current is used in the basic speed range or, as shown above, the current is impressed in phase with the induced voltage.

$$M_{\text{i}} = \frac{P_{\delta}}{\omega_{\text{S}}/p} = \frac{3\, U_{\text{P}} I_{\text{S}} \cos \psi}{\omega_{\text{S}}/p} = \frac{3\, U_{\text{P}} I_{\text{Sq}}}{\omega_{\text{S}}/p} \tag{5.8}$$

If the speed of a synchronous motor increases, the induced voltage U_{P} and the voltage drop at the synchronous reactance $X_{\text{S}} I_{\text{S}} = \omega_{\text{S}} L_{\text{S}} I_{\text{S}}$ increase proportional to

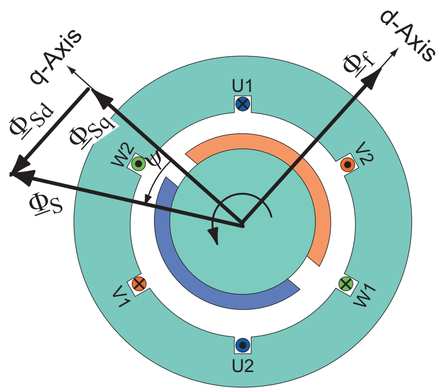


Figure 5.13: Definition of the direct axis (d) and the quadrature axis (q) of a permanent magnet excited synchronous motor

the speed. As long as the current and rotor voltage are in phase, the stator voltage U_S must also increase in proportion to the speed (Figure 5.14a,b).

If the speed continues to increase and the stator voltage U_S cannot be further increased above the type or rated speed n_t, the stator current I_S must be set ahead of the induced voltage U_P. A negative d-current is required and the q-current and thus the torque must be reduced accordingly. As a result, the angle φ between the stator current I_S and the stator voltage U_S becomes smaller and the power factor $\cos\varphi$ increases or improves (Figure 5.14c).

The stator current I_S must continue to outpace the induced voltage U_P with increasing speed until the stator voltage U_S and current I_S are in phase ($\varphi = 0$). If the speed increases further, the current I_S then also is ahead of the stator voltage U_S, and $\cos\varphi$ becomes smaller or worse again (Figure 5.14d).

The speed range from the type speed n_t to the speed with $\cos\varphi = 1$ is also referred to as **lower field weakening range** (Figure 5.14c), the speed range from this point as **upper field weakening range** (Figure 5.14d).

The following applies to the course of the torque and power as a function of the speed:

$$\frac{M_i}{M_{i,t}} = \cos\psi \qquad\qquad \frac{P_{i,mech}}{P_{i,mech,t}} = \frac{n}{n_t}\cos\psi \tag{5.9}$$

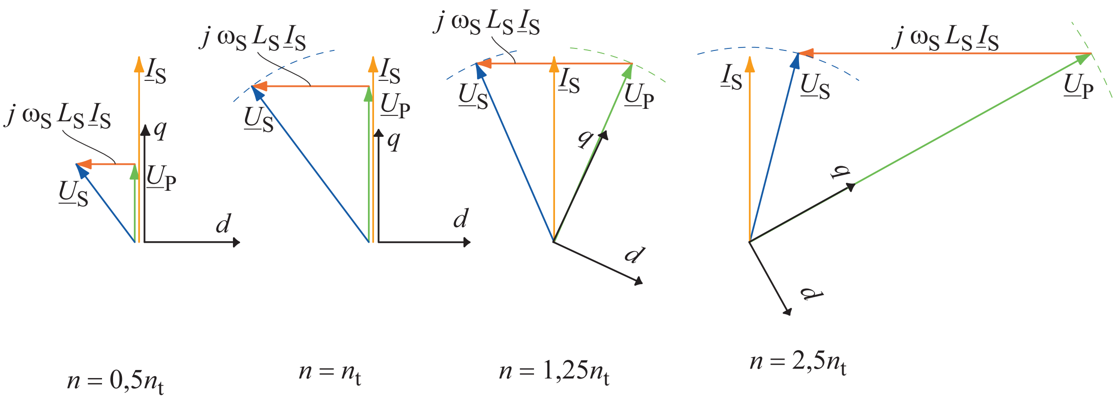


Figure 5.14: Field weakening with permanently excited synchronous motors

The maximum torque or the maximum mechanical power can then be determined numerically and graphically as displayed in Figure 5.15.

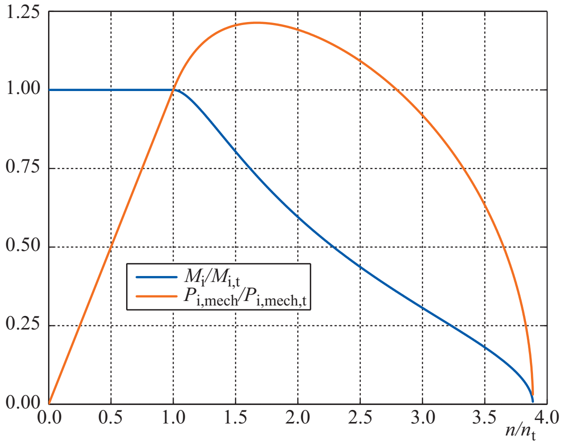


Figure 5.15: Power and torque of a permanent excited synchronous machine

The torque becomes zero when the stator current is a pure reactive current (see Figure 5.16), i.e. the synchronous machine works as a pure phase shifter. This is the case when the induced voltage and the terminal voltage are exactly in phase. In the case of the permanently excited synchronous machine, the overall field can only be reduced by an additional negative direct current in stator. This type of field weakening is therefore associated with additional current heat losses in the stator winding and is called **active field weakening**.

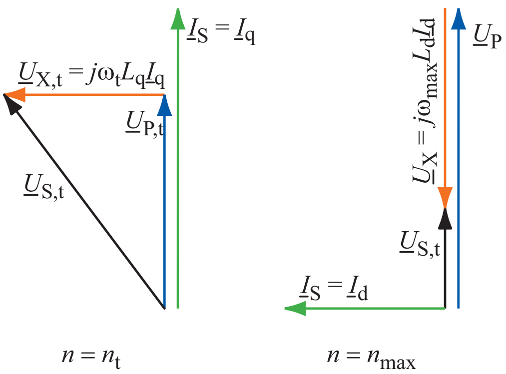


Figure 5.16: Phasor diagrams for type speed and maximum speed (not with same scale!)

5.6 Tasks

Example 5-3: Synchronous servo drive on converter

A six-pole, star connected, permanent magnet excited synchronous servo drive is given. At a speed of $3000\,\mathrm{min}^{-1}$, a sinusoidal line-to-line voltage of $200\,\mathrm{V}$ was measured in no-load operation. The measured winding resistance at operating temperature is $0.5\,\Omega$. The maximum continuous current is $12\,\mathrm{A}$ and the maximum short-term current is $36\,\mathrm{A}$.

At a speed of $100\,\mathrm{min}^{-1}$, a winding current of $7.5\,\mathrm{A}$ 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 $U_\mathrm{d} \approx \sqrt{2} \cdot 400\,\mathrm{V}$). 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?

Example 5-4: Data sheet servo motor

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

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} kgm²	0.98	
Moment of inertia (without brake)	J_{Mot}	10^{-4} kgm²	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 5.17: Data sheet servo motor

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 5-5: Traction drive

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

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

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. $50\,\mathrm{V/cm}$)! 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: $\cos\vartheta_\mathrm{L} = \dfrac{U_\mathrm{S}^2 + U_\mathrm{P}^2 - (X_\mathrm{S} I_\mathrm{S})^2}{2\,U_\mathrm{S} U_\mathrm{P}}$

5.7 Questions

Q5-1: Give the simplified equivalent circuit ($R_\mathrm{S} = 0$) of a synchronous machine and sketch the phasor diagram of a synchronous motor.

Q5-2: Sketch the principal structure of a permanent magnet synchronous motor and state the position of the d and q axes.

Q5-3: Sketch the torque-speed characteristic of a permanent magnet synchronous motor.

Q5-4: What is meant by active field weakening?

Q5-5: Sketch the induced voltage and current in one phase of an electronically commutated DC motor (EC motor or brushless DC)! Give the phasor diagram for the fundamental wave behavior

Q5-6: In an EC motor, how is it ensured that the phase current is always in phase with the induced voltage?