Exam

Electrical Machines and Drives

Winter 2024/25

First name: Last name:

Matriculation number: Study program:

Instructions:

- You can only take part in the exam, if you are registered in the campus management system.
- Prepare your student ID and a photo ID card on your desk.
- Label each exam sheet with your name. Start a new exam sheet for each task.
- Answers must be given with a complete, comprehensible solution. Answers without any context will not be considered. Answers are accepted in German and English.
- Permitted tools are (exclusively): black / blue pens (indelible ink), triangle, a non-programmable calculator without graphic display and two DIN A4 cheat sheets.
- The exam time is 90 minutes.

Evaluation:

Task	1	2	3	4	$\sum$
Maximum score	13	11	8	13	45
Achieved score					

Task 1: Deflecting magnet **[13 Points]**

A dipole magnet with an axial cross-section as shown in Fig. 1 is used to deflect the particle beam of charged heavy ions in a particle accelerator. A rated direct current $I_\mathrm{n} = 5000$ A flows through the two excitation coils. The copper conductors of the coil winding are directly water-cooled due to the high current density of $J = 18$ A/mm^2.

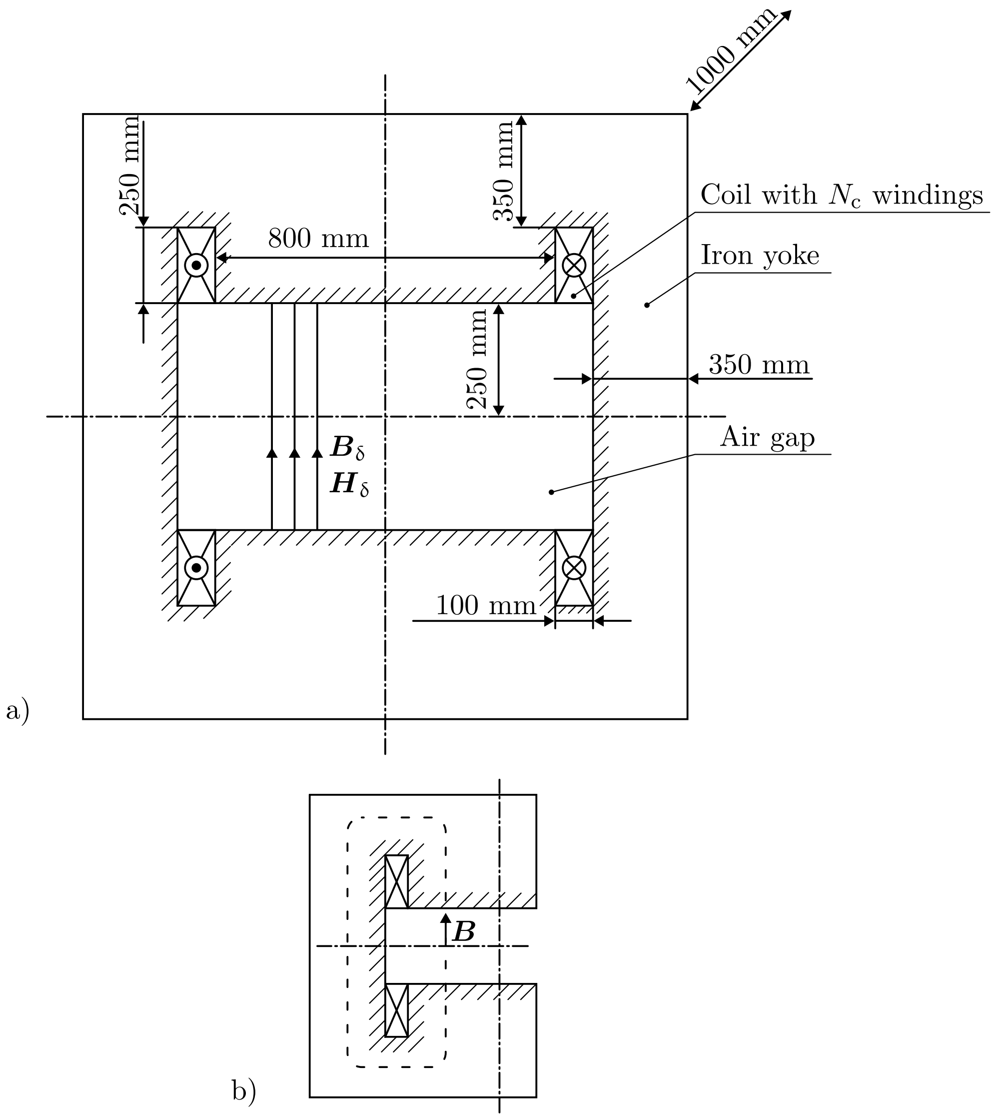


Figure 1: Sketch of the deflecting magnet a) and an idealized field line b).

1.1 How large is the magnetic field in the air gap, when there is a homogeneous magnetic flux density of $B_\delta = 3.141$ T? How many windings per coil N_c are necessary? Neglect the magnetization effort of the iron yoke. [3 Points]

Hint: If you have not found a solution for the number of winding turns in this subtask, continue with $N_\mathrm{c} = 140$.

Answer:

The relationship between the magnetic flux density B_δ and the magnetic field is given by:

$$H_\delta = \frac{B_\delta}{\mu_0} = \frac{3.141 \text{ T}}{4\pi 10^{-7} \frac{\text{Vs}}{\text{Am}}} = 2499528 \ \frac{\text{A}}{\text{m}}.$$

The general form of Ampère's circuital law is defined as

$$\oint_{\partial S} \boldsymbol{H} \cdot \mathrm{d}\boldsymbol{s} = \sum_k \theta_k$$

which can be simplified based on the made assumptions:

$$\theta_\delta = l_\delta H_\delta = 500 \text{ mm} \cdot 2499528 \ \frac{\text{A}}{\text{m}} = 1249764 \text{ A}.$$

The given magneto static situation is represented with

$$\sum_k \theta_k = NI,$$

which leads to the number of winding turns:

$$N_\mathrm{c} = \frac{\theta_\delta}{I} = \frac{1249764 \text{ A}}{2 \cdot 5 \text{ kA}} = 124.97,$$

therefore, 125 turns are selected.

1.2 How lare is the magnetic flux in the air gap? [1 Point]

Answer:
The magnetic flux is calculated by

$$\phi_\delta = B_\delta A_\delta = 3.141 \text{ T} \cdot (0.8 \cdot 1) \text{ m}^2 = 2.51 \text{ Wb},$$

where the surface is taken from the sketch in Fig. 1.

1.3 Calculate the magnetic flux density B_Fe in the iron yoke. Therefore, neglect magnetic leakage fluxes. [1 Point]

Answer:
Since the leakage fluxes are neglected, the flux ϕ_δ in the air gap and the ϕ_Fe in the iron yoke are equal. Thus

$$\phi_\delta = \phi_\mathrm{Fe} = B_\mathrm{Fe} A_\mathrm{Fe} = B_\delta A_\delta,$$

which results into:

$$B_\mathrm{Fe} = \frac{A_\delta}{A_\mathrm{Fe}} B_\delta = \frac{(0.8 \cdot 1) \text{ m}^2}{2 \cdot (0.35 \cdot 1) \text{ m}^2} \cdot 3.141 \text{ T} = 3.59 \text{ T}.$$

1.4 The average length of the iron yoke is given with $l_\mathrm{Fe} = 1.2$ m. How large is the magnetization effort of the iron yoke, when the permeability $\mu_{\mathrm{Fe}} = 126\mu_0$? Is the assumption of zero magnetization effort from subtask 1 correct? [2 Points]

Answer:

With the calculated flux density in the previous task and the given information of μ_{r}, the magnetic field is calculated as

$$H_{\mathrm{Fe}} = \frac{B_{\mathrm{Fe}}}{\mu_0\mu_{\mathrm{r}}} = \frac{B_{\mathrm{Fe}}}{126\mu_0} = \frac{3.59\ \mathrm{T}}{126\cdot 4\pi 10^{-7}\ \frac{\mathrm{Vs}}{\mathrm{Am}}} = 22673\ \frac{\mathrm{A}}{\mathrm{m}},$$

which results into the magnetic voltage of:

$$\theta_{\mathrm{Fe}} = H_{\mathrm{Fe}}\cdot l_{\mathrm{Fe}} = 22673\ \frac{\mathrm{A}}{\mathrm{m}}\cdot 1.2\ \mathrm{m} = 27208\ \mathrm{A}.$$

The comparison between the magnetic voltage between the iron yoke and the air gap results in

$$\frac{\theta_{\mathrm{Fe}}}{\theta_\delta} = \frac{27208\ \mathrm{A}}{1249764\ \mathrm{A}} = 0.022,$$

which is very small and, therefore, the assumption from subtask 1 is valid.

1.5 How lage is the electrical resistance of the excitation coil at 50 °C with an average winding length $l_{\mathrm{w}} = 4$ m and an electrical conductivity of $\kappa_{\mathrm{Cu}} = 50\cdot 10^6\ \frac{\mathrm{S}}{\mathrm{m}}$? [2 Points]

Answer:

The cross section of the conductor is given by

$$q_{\mathrm{Cu}} = \frac{I_{\mathrm{n}}}{J} = \frac{5000\ \mathrm{A}}{18\ \mathrm{A/mm^2}} = 277.8\ \mathrm{mm}^2,$$

whichs results in the resistance per coil as follows:

$$R_{\mathrm{c}} = \frac{1}{\kappa_{\mathrm{Cu}}}\frac{N_{\mathrm{c}}l_{\mathrm{w}}}{q_{\mathrm{Cu}}} = \frac{1}{50\cdot 10^6\ \frac{\mathrm{S}}{\mathrm{m}}}\frac{125\cdot 4\ \mathrm{m}}{277.8\ \mathrm{mm}^2} = 0.036\ \Omega.$$

1.6 Calculate the necessary voltage U and the excitation losses P_{l}. [2 Points]

Answer:

The necessary voltage is calculated with:

$$U = RI_{\mathrm{n}} = 2R_{\mathrm{c}}I_{\mathrm{n}} = 0.072\ \Omega\cdot 5000\ \mathrm{A} = 360\ \mathrm{V}.$$

The resulting loss is determined by:

$$P_{\mathrm{l}} = RI_{\mathrm{n}}^2 = 2R_{\mathrm{c}}I_{\mathrm{n}}^2 = 0.072\ \Omega\cdot (5000\ \mathrm{A})^2 = 1.8\ \mathrm{MW}.$$

1.7 Calculate the flux linkage ψ_{coil} of one coil. [1 Point]

Answer:

The flux linkage of one coil is calculated by:

$$\psi_{\mathrm{coil}} = N\phi_{\mathrm{coil}} = N\phi_{\delta} = 125 \cdot 2.51\ \mathrm{Vs} = 313.8\ \mathrm{Vs}.$$

1.8 How large is the inductivity L, when the two coils are connected in series? [1 Point]

Answer:

The inductivity for one coil is given with

$$L_{\mathrm{c}} = \frac{\psi_{\mathrm{coil}}}{I_{\mathrm{n}}} = \frac{313.8\ \mathrm{Vs}}{5000\ \mathrm{A}} = 62.8\ \mathrm{mH},$$

and, results in the total inductivity of:

$$L = 2L_{\mathrm{c}} = 2 \cdot 62.8\ \mathrm{mH} = 125.6\ \mathrm{mH}.$$

Task 2: Series DC machine **[11 Points]**

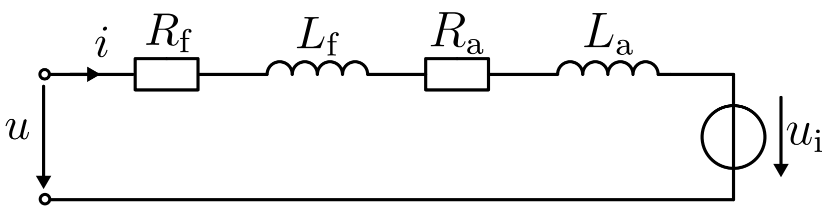
Electric vehicle drives were used in mines at an early historic stage in order to avoid exhausts from combustion engines in the tunnels. Historically, series DC machines were used for this purpose, such as the machine with the parameters summarized in the following table.

Table 1: DC machine parameters.

Symbol	Description	Values
U_{n}	Nominal voltage	440 V
I_{n}	Nominal armature current	500 A
T_{n}	Nominal torque	1407 Nm
R_{a}	Armature resistance	0.02 Ω
R_{f}	Field resistance	0.025 Ω
L_{a}	Armature inductance	2 mH
L_{f}	Field inductance	8 mH

2.1 Draw the equivalent circuit diagram of the series DC machine. [1 Point]

Answer:



Solution Figure 1: Equivalent circuit diagram of the series DC machine

2.2 Determine the effective field inductance L'_{f} and the effective flux linkage ψ'_{f} for the nominal steady-state operating point. [2 Points]
Hint: if and if only you are not able to solve this task, use $L'_{\mathrm{f}} = 8$ mH and $\psi'_{\mathrm{f}} = 4$ Vs as a substitute result for the subsequent tasks.

Answer:
The series DC machine torque equation reads

$$T = L'_{\mathrm{f}} I^2$$

allowing to calculate the effective field inductance utilizing the nominal values of the machine:

$$L'_{\mathrm{f}} = \frac{T_{\mathrm{n}}}{I_{\mathrm{n}}^2} = 5.63\ \mathrm{mH}.$$

The effective flux linkage then results in

$$\psi'_{\mathrm{f,n}} = L'_{\mathrm{f}} I_{\mathrm{n}} = 2.81\ \mathrm{Vs}.$$

2.3 What is the machine's nominal speed n_{n} and efficiency η_{n}? [2 Points]

Answer:
First, the induced voltage is calculated via

$$U_{\mathrm{i,n}} = U_{\mathrm{n}} - (R_{\mathrm{a}} + R_{\mathrm{f}}) I_{\mathrm{n}} = 417.5\ \mathrm{V}.$$

The nominal angular velocity is

$$\omega_{\mathrm{n}} = \frac{U_{\mathrm{i,n}}}{\psi'_{\mathrm{f,n}}} = 148.6\ \frac{1}{\mathrm{s}}$$

resulting in

$$n_{\mathrm{n}} = \omega_{\mathrm{n}} \frac{60}{2\pi} \frac{\mathrm{s}}{\mathrm{min}} = 1418.8\ \frac{1}{\mathrm{min}}.$$

For determining the nominal efficiency, we first calculate the nominal electrical and mechanical powers

$$P_{\mathrm{el,n}} = U_{\mathrm{n}} I_{\mathrm{n}} = 220\ \mathrm{kW}, \quad P_{\mathrm{me,n}} = T_{\mathrm{n}} \omega_{\mathrm{n}} = 209.1\ \mathrm{kW}$$

leading to

$$\eta_{\mathrm{n}} = \frac{P_{\mathrm{me,n}}}{P_{\mathrm{el,n}}} = 95.05\ \%.$$

2.4 Due to a fault in the cooling system, the dissipated power losses must be reduced to 1/4 of the nominal rating to prevent overheating. What are the achievable torque and mechanical power in this scenario assuming that the ohmic losses dominate the machine's loss characteristic? What mechanical issue could occur in this new operating point? [3 Points]

Answer:
As the power losses

$$P_{\mathrm{l}} = (R_{\mathrm{a}} + R_{\mathrm{f}}) I^2$$

must be quartered, the machine's input current must be halved. Hence, the achievable torque results in

$$T = L'_{\mathrm{f}} \left(\frac{I_{\mathrm{n}}}{2}\right)^2 = \frac{1}{4} T_{\mathrm{n}} = 351.8\ \mathrm{Nm}.$$

Due the the halved input current, the induced voltage as well as the effective flux linkage are varying:

$$U_{\mathrm{i}} = U_{\mathrm{n}} - (R_{\mathrm{a}} + R_{\mathrm{f}}) \left(\frac{I_{\mathrm{n}}}{2}\right) = 428.8\ \mathrm{V}, \quad \psi'_{\mathrm{f}} = L'_{\mathrm{f}} \left(\frac{I_{\mathrm{n}}}{2}\right) = 1.41\ \mathrm{Vs}.$$

The resulting speed is

$$n = \frac{U_\mathrm{i}}{\psi_\mathrm{f}'}\frac{60}{2\pi}\frac{\mathrm{s}}{\mathrm{min}} = 2904.1\ \frac{1}{\mathrm{min}}$$

leading to the mechanical power of

$$P_\mathrm{me} = \omega T = 106.99\ \mathrm{kW}.$$

Since the rotational speed of the machine has more than doubled compared to its nominal value, mechanical integrity problems could occur due to the much higher centrifugal forces occurring within the rotor. Also, the bearings must withstand the higher rotational speed.

2.5 What steady-state starting current can be expected when the nominal machine voltage is applied from the stall position? After what time interval ΔT is 95 % of this steady-state value reached when starting from an entirely currentless, non-rotating machine? [2 Points]

Answer:
During start up, the mechanical speed is zero and the entire machine's voltage drops via the armature and field resistance leading to

$$I_0 = \frac{U_\mathrm{n}}{R_\mathrm{a} + R_\mathrm{f}} = 9.78\ \mathrm{kA}.$$

The DC series machine's ECD represents an ohmic-inductive element with

$$R = R_\mathrm{a} + R_\mathrm{f}, \quad L = L_\mathrm{a} + L_\mathrm{f}.$$

The resulting time constant of this circuit is

$$\tau = \frac{L}{R} = 0.22\ \mathrm{s}.$$

Based on the exponentially limited increase in the machine current, 95 % of the final value is reached after 3τ, i.e.,

$$\Delta T = 3\tau = 0.66\ \mathrm{s}.$$

2.6 What dropping resistor must be added to the machine's circuit to limit the starting current to twice the nominal value? [1 Point]

Answer:
Considering an additional dropping resistor to limit the starting current to twice the nominal current results in

$$2I_\mathrm{n} = \frac{U_\mathrm{n}}{R_\mathrm{a} + R_\mathrm{f} + R_\mathrm{d}}$$

and delivering

$$R_\mathrm{d} = \frac{U_\mathrm{n}}{2I_\mathrm{n}} - R_\mathrm{a} - R_\mathrm{f} = 0.395\ \Omega.$$

Task 3: Transformer **[8 Points]**

A single-phase 50 Hz transformer with a rated apparent power of 3 kVA for a welding application was delivered without further information regarding its operation characteristics. Hence, experimental tests need to be conducted to identify its T-type equivalent circuit diagram parameters.

3.1 During an open-circuit test with $U_{1,\mathrm{o}} = 230$ V, a secondary voltage of $U_{2,\mathrm{o}} = 5.476$ V is measured. Estimate the transformation ratio as well as the nominal primary and secondary current. [2 Points]

Answer:
Assuming that the no-load losses can be neglected, the transformation ratio is

$$\ddot{u} \approx \frac{U_{1,\mathrm{o}}}{U_{2,\mathrm{o}}} = 42.$$

The primary and secondary nominal currents can be estimated as

$$I_{1,\mathrm{n}} \approx \frac{S}{U_{1,\mathrm{o}}} = 13.04 \text{ A}, \quad I_{2,\mathrm{n}} \approx \frac{S}{U_{2,\mathrm{o}}} = 547.85 \text{ A}.$$

3.2 During the same open-circuit test, an active input power of $P_{1,\mathrm{o}} = 60$ W and apparent power of $S_{1,\mathrm{o}} = 90$ VA were measured. Neglecting ohmic power losses and stray inductances, determine the iron loss resistance R_c as well as the mutual inductance M' and M (transformed to primary side and untransformed value). [3 Points]

Answer:
Based on the made assumptions, the measured active input power is dissipated as iron losses yielding

$$R_\mathrm{c} = \frac{U_{1,\mathrm{o}}^2}{P_{1,\mathrm{o}}} = 881.6\ \Omega.$$

Based on the measured input powers, the power factor for the open-circuit test is

$$\cos(\varphi_\mathrm{o}) = \frac{P_{1,\mathrm{o}}}{S_{1,\mathrm{o}}} = \frac{2}{3} \quad \Leftrightarrow \quad \varphi_\mathrm{o} = 48.19°.$$

The input current during the open-circuit test must have been

$$I_{1,\mathrm{o}} = \frac{S_{1,\mathrm{o}}}{U_{1,\mathrm{o}}} = 0.39 \text{ A}.$$

The reactance of the open-circuit transformer is

$$X_\mathrm{o} = \frac{U_{1,\mathrm{o}}}{I_{1,\mathrm{o}}} \frac{1}{\sin(\varphi_\mathrm{o})} = Z_0 \frac{1}{\sin(\varphi_\mathrm{o})} = 793.58\ \Omega.$$

This reactance must be identical to the reactance provided by the transformed mutual inductance as the stray inductance impact is neglected:

$$\omega M' = X_\mathrm{o} \quad \Leftrightarrow \quad M' = \frac{X_\mathrm{o}}{\omega} = 2.53\ \mathrm{H}.$$

Based on the estimated transformation ratio, the original mutual inductance yields

$$M = \frac{1}{\ddot{u}} M' = 0.06\ \mathrm{H}.$$

3.3 During a subsequent short-circuit test with $U_{1,\mathrm{s}} = 20$ V, the following measurements have been obtained: $I_{1,\mathrm{s}} = 13$ A, $P_{1,\mathrm{s}} = 100$ W. Determine $R_1 = R_2'$ as well as the untransformed R_2. Likewise, find $L_{1,\sigma} = L_{2,\sigma}'$ as well as the untransformed $L_{2,\sigma}$. Neglect the mutual inductance's impact. [3 Points]

Answer:
The short-circuit impedance is

$$Z_\mathrm{s} = \frac{U_{1,\mathrm{s}}}{I_{1,\mathrm{s}}} = 1.54\ \Omega,$$

while the corresponding power factor is

$$\cos(\varphi_\mathrm{s}) = \frac{P_{1,\mathrm{s}}}{U_{1,\mathrm{s}} I_{1,\mathrm{s}}} = 0.385 \quad \Leftrightarrow \quad \varphi_\mathrm{s} = 67.38^\circ.$$

Separating the real and imaginary part of the impedance, one receives

$$R_1 + R_2' = Z_\mathrm{s} \cos(\varphi_\mathrm{s}) = 0.593\ \Omega \quad \Longrightarrow \quad R_1 = R_2' = 0.297\ \Omega$$

and

$$(L_{1,\sigma} + L_{2,\sigma}')\omega = Z_\mathrm{s} \sin(\varphi_\mathrm{s}) = 1.422\ \Omega \quad \Longrightarrow \quad L_{1,\sigma} = L_{2,\sigma}' = 2.26\ \mathrm{mH}.$$

The untransformed secondary values result in

$$R_2 = \frac{1}{\ddot{u}^2} R_2' = 0.17\ \mathrm{m\Omega}, \quad L_{2,\sigma} = \frac{1}{\ddot{u}^2} L_{2,\sigma}' = 1.28\ \mathrm{\mu H}.$$

Task 4: Steady-state operation curves of an induction machine [13 Points]

The paramters of a six-pole three-phase induction machine are shown in Tab. 2. The nominal stator current is given with $I_{\mathrm{s,n}} = 22.5$ A at a power factor of $\cos(\varphi_{\mathrm{n}}) = 0.8$.

Table 2: Parameters of the induction machine.

Symbol	Value	Symbol	Value	Symbol	Value
$P_{\mathrm{me,n}}$	11 kW	U_{n}	400 V	$f_{\mathrm{s,n}}$	50 Hz
s_{n}	0.0444	R_{s}	0.42 Ω	R'_{r}	0.459 Ω
$L_{\sigma,\mathrm{s}}$	5.1 mH	$L'_{\sigma,\mathrm{r}}$	2.4 mH	M	53.2 mH

4.1 Calculate the nominal rotational speed n_{n} and the nominal torque T_{n}. [2 Points]

Answer:

The nominal rotor frequency is determined by

$$f_{\mathrm{r,n}} = \frac{(1-s_{\mathrm{n}})f_{\mathrm{s}}}{p} = \frac{(1-0.0444)\cdot 50\ \mathrm{Hz}}{3} = 15.93\ \frac{1}{\mathrm{s}},$$

which leads to the nominal rotational speed of 955.6 $\frac{1}{\mathrm{min}}$. Hence, the nominal torque is given by:

$$T_{\mathrm{n}} = \frac{P_{\mathrm{me,n}}}{\omega_{\mathrm{r,n}}} = \frac{11\ \mathrm{kW}}{2\pi\cdot 15.93\ \frac{1}{\mathrm{s}}} = 109.9\ \mathrm{Nm}.$$

4.2 Calculate the nominal electrical power $P_{\mathrm{el,n}}$ and the efficiency η_{n}. [2 Points]

Answer:

The electrical power is calculated by:

$$P_{\mathrm{el,n}} = 3U_{\mathrm{s}}I_{\mathrm{s,n}}\cos(\varphi_{\mathrm{n}}) = 3\frac{U_{\mathrm{n}}}{\sqrt{3}}I_{\mathrm{s,n}}\cos(\varphi_{\mathrm{n}}) = 3\cdot\frac{400\ \mathrm{V}}{\sqrt{3}}\cdot 22,5\ \mathrm{A}\cdot 0.8 = 12471\ \mathrm{W}.$$

Moreover, the efficiency is determined as follows:

$$\eta_{\mathrm{n}} = \frac{P_{\mathrm{me,n}}}{P_{\mathrm{el,n}}} = \frac{11000\ \mathrm{W}}{12471\ \mathrm{W}} = 0.88.$$

4.3 Determine the leakage coefficient σ. [1 Point]

Answer:

The leakage coefficient is determined as:

$$\sigma = 1 - \frac{M^2}{\left(M + L_{\sigma,\mathrm{s}}\right)\left(M + L'_{\sigma,\mathrm{r}}\right)}$$
$$= 1 - \frac{(53.2\ \mathrm{mH})^2}{(53.2\ \mathrm{mH} + 5.1\ \mathrm{mH})\,(53.2\ \mathrm{mH} + 2.4\ \mathrm{mH})} = 0.13.$$

4.4 Calculate the nominal slip frequency ω_{slip} and the maximum angular frequency ω_{max}. [2 Points]

Answer:
The angular slip frequency is defined by

$$\omega_{\mathrm{slip}} = s_\mathrm{n}\omega_\mathrm{s} = 0.0444 \cdot 2\pi \cdot 50\ \frac{1}{\mathrm{s}} = 13.95\ \frac{1}{\mathrm{s}},$$

and the maximum angular frequency is given with:

$$\omega_{\mathrm{max}} = \frac{R'_\mathrm{r}}{\sigma\left(L'_{\sigma,\mathrm{r}} + M\right)} = \frac{0.459\ \Omega}{0.13 \cdot (2.4\ \mathrm{mH} + 53.2\ \mathrm{mH})} = 65.3\ \frac{1}{\mathrm{s}}.$$

4.5 Determine the torque and mechanical power for different slip ratios and use these support points to draw the torque and power curves in Fig. 2. [4 Points]
Hint: The torque equation is given with: $T = T_{\mathrm{max}}\frac{2}{\frac{s}{s_{\mathrm{max}}} + \frac{s_{\mathrm{max}}}{s}}$.

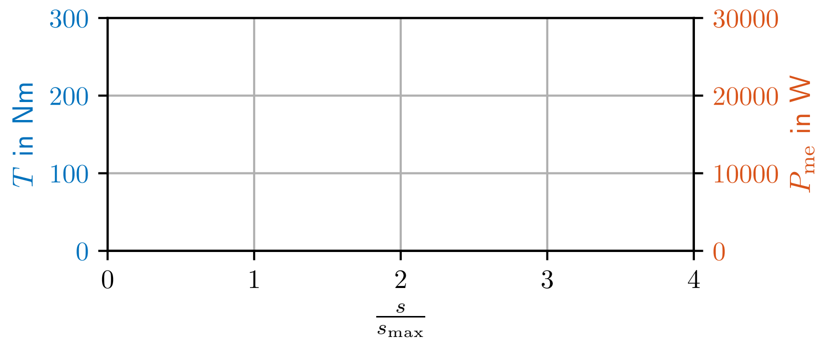


Figure 2: Given template to draw the curves for the torque and mechanical power.

Answer:
The maximum achievable torque for a constant stator excitation is:

$$T_{\mathrm{max}} = \frac{3}{2}p\frac{U_\mathrm{s}^2}{\omega_\mathrm{s}^2}\frac{M^2}{\sigma\left(L_{\sigma,s} + M\right)^2\left(L'_{\sigma,\mathrm{r}} + M\right)}$$
$$= \frac{3}{2} \cdot 3 \cdot \frac{\left(\frac{400}{\sqrt{3}}\ \mathrm{V}\right)^2}{\left(2\pi \cdot 50\ \frac{1}{\mathrm{s}}\right)} \cdot \frac{(53.2\ \mathrm{mH})}{(5.1\ \mathrm{mH} + 53.2\ \mathrm{mH})^2\,(2.4\ \mathrm{mH} + 53.2\ \mathrm{mH})}$$
$$= 287.8\ \mathrm{Nm}.$$

The machine-dependent parameter $s_{\max}$ is given with:

$$s_{\max} = \frac{\omega_{\max}}{\omega_{\mathrm{s}}} = \frac{R'_{\mathrm{r}}}{\sigma\left(L'_{\sigma,\mathrm{r}} + M\right)\omega_{\mathrm{s}}} = \frac{0.459\ \Omega}{0.13 \cdot (2.4\ \mathrm{mH} + 53.2\ \mathrm{mH}) \cdot 2\pi \cdot 50\ \frac{1}{\mathrm{s}}} = 0.21.$$

With the utilization of the Kloss's formula, the torque is calculated for given slip ratios, e.g., for $s/s_{\max} = 2$ as:

$$T\left(\frac{s}{s_{\max}} = 2\right) = T_{\max}\frac{2}{\frac{s}{s_{\max}} + \frac{s_{\max}}{s}} = 287.8\ \mathrm{Nm} \cdot \frac{2}{2 + \frac{1}{2}} = 230.2\ \mathrm{Nm}.$$

The mechanical power is given with

$$P_{\mathrm{me}} = T\omega_{\mathrm{r}} = T\frac{(1-s)f_{\mathrm{s}}}{p}2\pi,$$

and, e.g., for $s/s_{\max} = 2$ as:

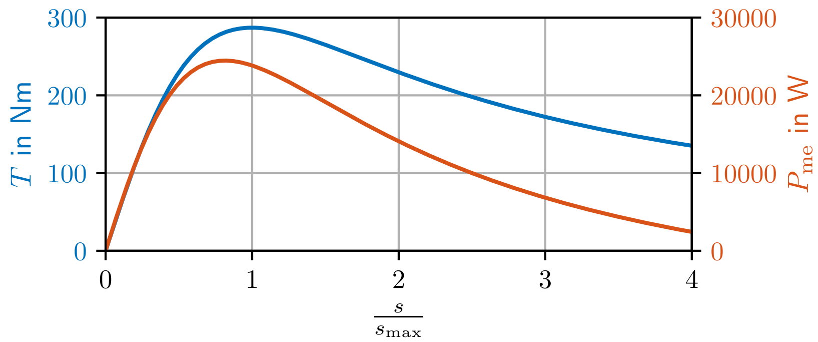
$$P_{\mathrm{me}}\left(\frac{s}{s_{\max}} = 2\right) = 230.2\ \mathrm{Nm} \cdot \frac{(1 - 2 \cdot 0.21) \cdot 50\ \frac{1}{\mathrm{s}}}{3} \cdot 2\pi = 13981\ \mathrm{W}.$$

To sketch the torque and mechanical power curves, some support points are calculated, which are shown in Sol.-Tab. 1.

Solution Table 1: Calculated torque and mechanical power dependant on the ratio $s/s_{\max}$.

$\frac{s}{s_{\max}}$	0	1	2	3	4
T	0	287.8 Nm	230.2 Nm	172.7 Nm	135.4 Nm
P_{me}	0	23809 W	13981 W	6691 W	2267 W

Hence, the resulting trajectories are shown in Sol.-Fig. 2.



Solution Figure 2: Trajectory of the torque and mechanical power.

4.6 Is the mechanical power zero for a theoretical consideration of an infinitely large mechanical speed (negative and positive speed values)? [2 Points]

Answer:
The mechanical power is given with

$$P_{\mathrm{me}} = T\omega_{\mathrm{r}},$$

considering the given hint results into:

$$P_{\mathrm{me}} = T_{\max}\frac{2}{\frac{s}{s_{\max}}+\frac{s_{\max}}{s}}\frac{(1-s)f_{\mathrm{s}}}{p}2\pi.$$

The power for an infinite high or low rotational speed is given as:

$$\lim_{s\to\pm\infty} P_{\mathrm{me}} = -T_{\max}\frac{2}{\frac{1}{s_{\max}}}\frac{f_{\mathrm{s}}}{p}2\pi = -287.8\ \mathrm{Nm}\cdot\frac{2}{\frac{1}{0.21}}\cdot\frac{50\ \frac{1}{\mathrm{s}}}{3}\cdot 2\pi = -12658\ \mathrm{W}.$$