Exam

Electrical Machines and Drives

Summer 2024

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	11	12	8	11	42
Achieved score					

Task 1: Lifting magnet **[11 Points]**

A lifting magnet made of steel with the dimensions shown in Fig. 1 is to carry an iron load with a mass of 700 kg. The average field line length in the load is $l_{\mathrm{load}} = 250$ mm, the flux-carrying cross-section A_{load} is 0.0095 m^2. The winding of both coils have $N = 300$ turns. The magnet has a circular cross-section with a diameter of 70 mm. The roughness of the surfaces of the magnet and load results in an average air gap length of $\delta = 0.5$ mm. Neglect all leakage fluxes.

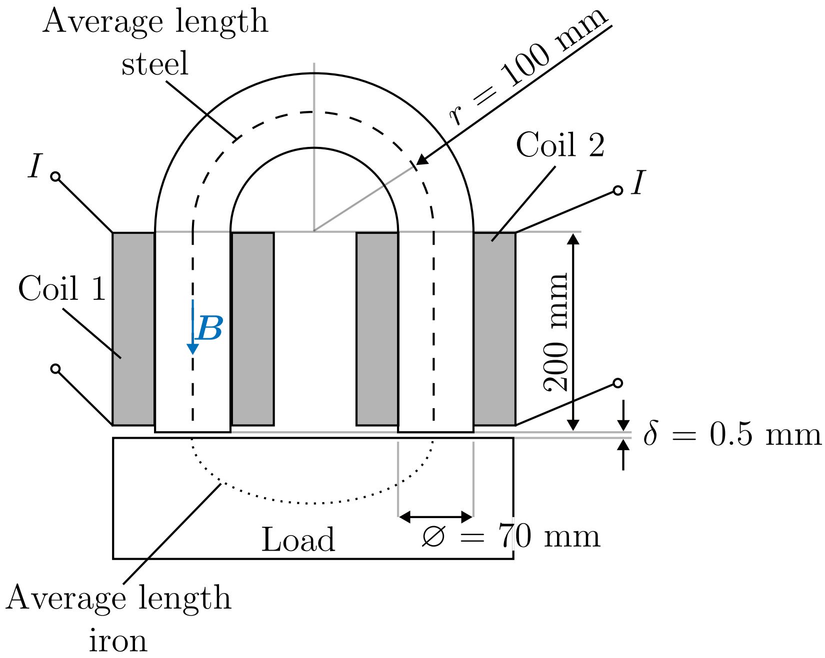

Figure 1: Sketch of the lifting magnet and load with their dimensions.

1.1 Formulate Ampère's circuital law in the general form and in a form adapted to the magnetic circuit shown here. Use the average field line length indication as the closed curve ∂S. [2 Points]

1.2 Add current direction symbols of the two coils to the above figure such that they fit to the already indicated magnetic flux orientation. [2 Points]

1.3 How large is the weight force acting on the load assuming nominal gravity at sea level? Calculate the magnetic flux density in the air gap, so that the load floats straight. Use $F = \frac{B_\delta^2}{2\mu_0} 2A_{\mathrm{m}}$ to calculate the force with $\mu_0 = 4\pi \cdot 10^{-7}\ \frac{\mathrm{Vs}}{\mathrm{Am}}$ being the magnetic field constant. [2 Points]
Hint: if and only if you are not able to solve this subtask, use $B_\delta = 1.6$ T as a substitute result for the following questions.

1.4 How large is the necessary current I for both coils to achieve this lifting task? Use the magnetization curves in Fig. 2. [3 Points]

1.5 Determine the flux ϕ_{coil} through one coil. [1 Point]

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

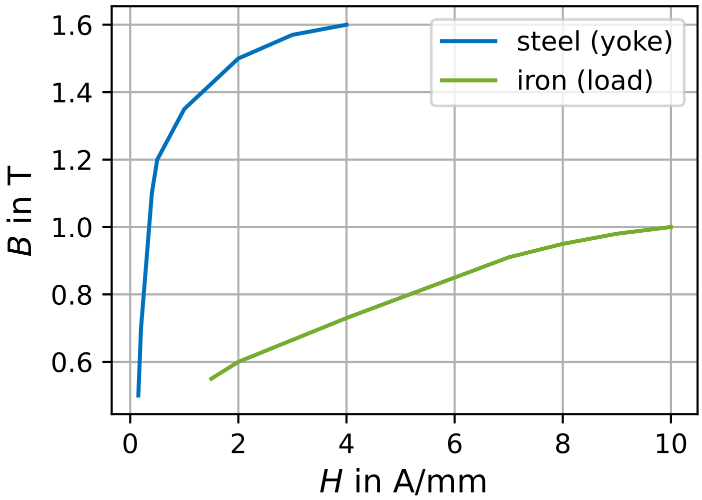

Figure 2: Magnetization curves for the yoke (steel) and the load (iron).

Task 2: Separately excited DC machine **[12 Points]**

Table 1: DC machine parameters.

Symbol	Description	Values
$U_{\mathrm{a,n}}$	Nominal armature voltage	230 V
$I_{\mathrm{a,n}}$	Nominal armature current	22 A
$U_{\mathrm{f,n}}$	Nominal field voltage	230 V
$I_{\mathrm{f,n}}$	Nominal field current	0.5 A
P_{n}	Nominal power	4.5 kW
n_{n}	Nominal speed	1440 $^1/_{\mathrm{min}}$
n_0	No-load speed	1615 $^1/_{\mathrm{min}}$
p	Pole pair number	2
L_{a}	Armature inductance	6.92 H

2.1 Determine the torque T_{n} and the efficiency η_{n} at the nominal operating point. [2 Points]

2.2 How large are the armature resistance R_{a} and the resulting armature losses $P_{\mathrm{l,a}}$ at the nominal operation neglecting iron and mechanical losses? [2 Points]
Hint: if and if only you are not able to solve this task, use $R_{\mathrm{a}} = 3.2\ \Omega$ and $\psi_{\mathrm{f}}' = 1.1$ Vs as a substitute result for the subsequent tasks.

2.3 For a new operating point at $n = 900\ ^1/_{\mathrm{min}}$, a torque of $T = 20$ Nm is to be achieved. For this purpose, an additional dropping resistor R_{d} is introduced into the armature circuit. Determine its required resistance value. [2 Points]
Hint: if and if only you are not able to solve this task, use $R_{\mathrm{d}} = 4.2\ \Omega$ as a substitute result for the subsequent tasks.

2.4 Determine the efficiency at this new operating point. What are the alternatives to introducing a dropping resistor to achieve the required torque at the new operating point and why should these alternatives be considered? [2 Points]

2.5 Now the transient response of a machine supply fault should be investigated: calculate $i_{\mathrm{a}}(t)$ for $t \geq 0$ assuming $i_{\mathrm{a}}(t=0) = I_{\mathrm{a,n}}$ and $u_{\mathrm{a}}(t) = 0$ for $t \geq 0$ (short circuit of armature voltage supply). Assume further that the machine speed $n(t) = n_{\mathrm{n}}$ for $t \geq 0$ remains constant and that the field winding is unaffected by the armature supply fault, i.e., delivering nominal excitation. [2 Points]

2.6 Sketch the current response $i_{\mathrm{a}}(t)$ as a function of time t. Also calculate the steady-state value for $t \to \infty$. [2 Points]
Hint: if and if only you have not solved the previous subtask, you can draw the current trajectory qualitatively to highlight the general system response characteristic for the given differential equation model. Also note, that the question addressing the steady-state armature current can be answered independently of the previous subtask.

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

3.1 Draw and label the T-type equivalent circuit diagram of a single phase transformer. [1 Point]

3.2 The primary side has $N_1 = 23$ and the secondary side has $N_2 = 10$ turns. For $\underline{U}_1 = 230$ V, which secondary voltage U_2 would you expect for an unloaded, idealized transformer? [1 Point]

3.3 Which actual voltage U_2 is to be expected if the transformer is loaded with $\underline{I}_2 = -10$ A considering the following parameters: $R_1 \approx 0\ \Omega$, $R_2 = 0.1\ \Omega$, $M = 0.42$ H, $L_1 = 1$ H, $L_2 = 0.17$ H? [2 Points]

3.4 Which primary prospective short-circuit current $I_{1,\mathrm{psc}}$ occurs if the secondary side is short-circuited? [2 Points]

3.5 What idealized secondary output voltage results in the unloaded case when the transformer is reconfigured as an autotransformer connecting the terminals 1.1 and 2.2? [1 Point]

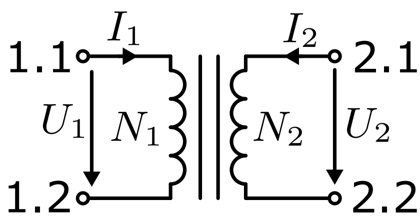

Figure 3: Transformer connection nomenclature

3.6 Calculate the change in primary current in the event of a short circuit on the secondary side of the autotransformer compared to the original galvanically isolated transformer. [1 Point]

Task 4: Synchronous generator **[11 Points]**

An externally excited synchronous generator is directly fed from a wind turbine without utilizing a gear. For the three-phase generator the parameters from Tab. 2 are known.

Ein elektrisch erregter Synchrongenerator wird von einer Windturbine direkt angetrieben (getriebeloser Windgenerator). Für den Drehstromgenerator sind die Parameter aus Tab. 2 bekannt.

Table 2: Parameters of the synchronous generator.

Symbol	Value	Symbol	Value
$P_{\mathrm{n,el}}$	-1.5 MW	l_{z}	700 mm
d_{s}	5 m	n_{n}	15 $\frac{1}{\mathrm{min}}$
N_{w}	3 windings per coil	q	2
$2p$	90	$\frac{y}{\rho_{\mathrm{p}}}$	$\frac{5}{6}$

4.1 Calculate the nominal torque T_{n} at the rated conditions of the generator. At this operating point, the efficiency is given with $\eta_{\mathrm{n}} = 95$ %. [2 Points]

4.2 How large is the number of winding turns per phase $N_{\mathrm{w,phase}}$, when the total 90 coils are parallelized in 5 groups? [1 Point]

4.3 Calculate the winding factor $\zeta_{\mathrm{w},k}$ for the fundamental wave ($k = 1$). [2 Points]

4.4 The flux density of the fundamental wave of one phase is given with $\hat{B}_{\delta}^{(1)} = 1$ T. Determine at nominal speed n_{n} the flux per pole ϕ_{δ} and the induced voltage per phase $U_{\mathrm{i,phase}}$. [2 Points]

4.5 Assume that the flux density in the air gap is a superposition of sine waves. Draw the trajectories of the flux densities $B_{\delta}^{(1)}(\vartheta)$ and $B_{\delta}^{(3)}(\vartheta)$ for one phase in the template (Fig. 4). [2 Points]

4.6 Is the third harmonic ($k = 3$) problematic for this type of machine? [1 Point]

4.7 Is it possible to connect the wind turbine directly to the grid? [1 Point]

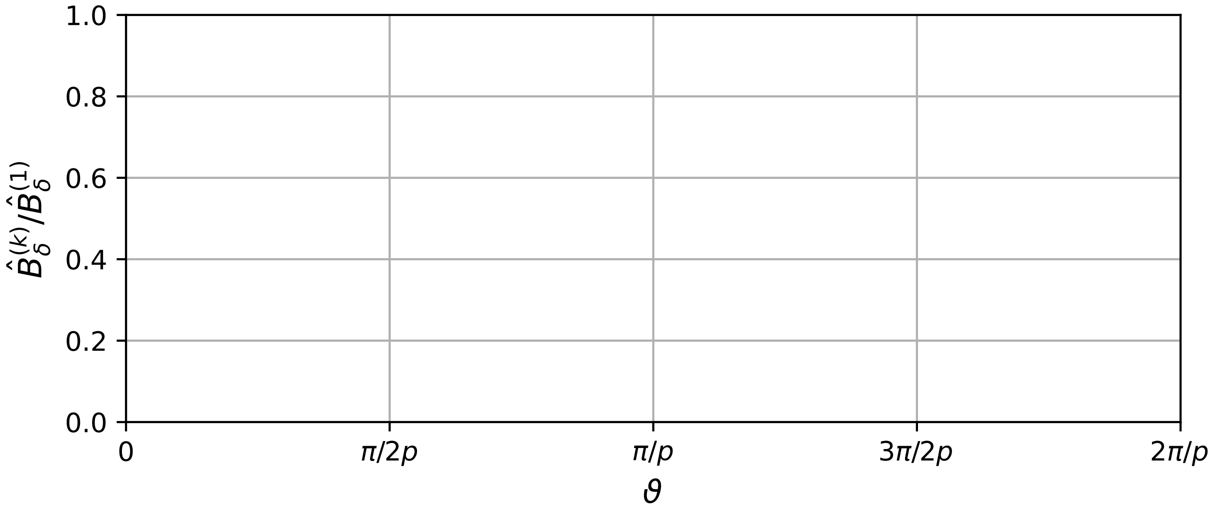

Figure 4: Template to draw the flux densities over the stator circumference ϑ.