Exam

Electrical Machines and Drives

Summer 2025

First name: Last name:

Matriculation number: Study program:

Instructions:

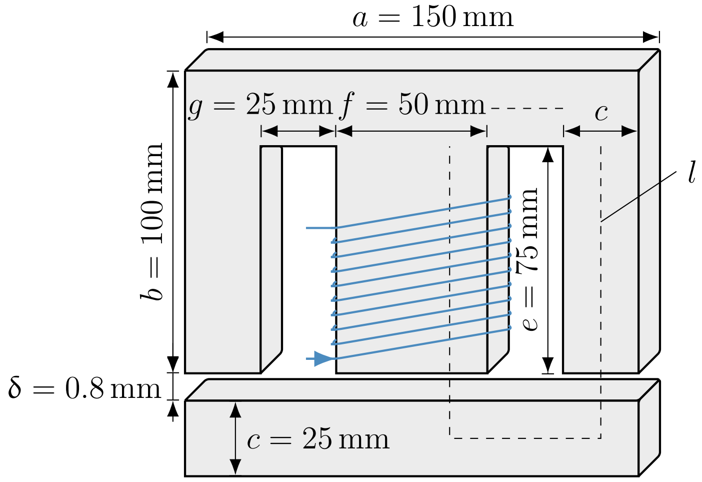
- You can only take part in the exam, if you are registered in the campus management system.
- Prepare your student ID and a photo ID card on your desk.
- Label each exam sheet with your name. Start a new exam sheet for each task.
- Answers must be given with a complete, comprehensible solution. Answers 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:

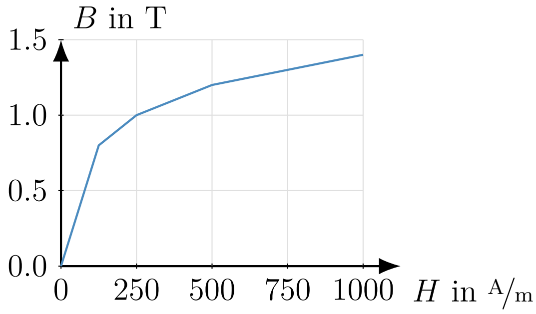
Task	1	2	3	4	$\sum$
Maximum score	10	9	9	14	42
Achieved score					

Task 1: Electromagnetic behavior of an EI-150 core **[10 Points]**

A standardized EI-150 core made of electrical steel sheet with the geometry from Fig. 1 is to be analyzed. Its air gap length is $\delta = 0.8$ mm and all parts have a depth of 50 mm. A coil with $N = 500$ turns around the middle yoke of the core leads to a magnetic flux density of $B_{\mathrm{Fe}} = 1.2$ T in this yoke (at rated current). The magnetization curve of electrical steel is also depicted in Fig. 1.



(a) EI-150 core geometry.



(b) Magnetization curve.

Fig. 1: EI-150 core and electrical steel magnetization curve.

1.1 Calculate the magnetic flux ϕ_{Fe} in the middle yoke. [2 Points]

1.2 How large is the magnetic flux density B_δ in the middle yoke's air gap, when all leakage fluxes are neglected and there is no expansion of the magnetic field lines in the air gap? [2 Points]
Hint: if and only if you are not able to solve this subtask, use $B_\delta = 1.0$ T as a substitute result for the following questions.

1.3 Determine the electrical steel sheet permeability μ_{Fe} as well as the magnetic field strength in both the air gap H_δ and in the electrical steel sheet H_{Fe}. Use $\mu_0 = 4\pi 10^{-7}\,\frac{\mathrm{Vs}}{\mathrm{Am}}$ for the magnetic field constant. [2 Points]

1.4 Calculate the magnetomotive force θ along an idealized, closed field line through the middle and one outer yoke (cf. the field line contour l in Fig. 1a). [2 Points]

1.5 After the I core has been connected to the E core, only a parasitic air gap of $\delta = 0.1$ mm remains. What is the necessary current I'_{n} to produce the same magnetic field density in the middle yoke compared to the previous configuration? [2 Points]

Task 2: Permanent magnet DC machine [9 Points]

Permanent magnet DC (PMDC) machines are often used in low power applications, such as machine tools or micromobility. In those applications, low voltage ratings are common to ensure safety, in particular regarding touch protection. In the following, you will analyze the operation behavior of a PMDC machine with the parameters given in Tab. 1 for an electric scooter application. A gearbox for torque and speed adaptation can be neglected.

Tab. 1: PMDC machine parameters.

Symbol	Description	Values
U_{n}	Nominal voltage	48 V
I_{n}	Nominal current	5.75 A
T_{n}	Nominal torque	1.67 Nm
$P_{\mathrm{me,n}}$	Nominal mech. power	200 W
R_{a}	Armature resistance	2.4 Ω
L_{a}	Armature inductance	3.7 H

2.1 Draw the equivalent circuit diagram of a PMDC machine. [1 Point]

2.2 Determine the effective PM flux linkage ψ_{f}' for the nominal steady-state operating point. [1 Point]
<u>Hint:</u> if and if only you are not able to solve this task, use $\psi_{\mathrm{f}}' = 0.4$ Vs as a substitute result for the subsequent tasks.

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

2.4 Assume that the scooter's load torque T_{L} is quadratically depending on the speed since the air drag is dominant. This is represented via the equation below utilizing the friction coefficient b with:

$$T_{\mathrm{L}}(\omega) = b\omega^2 \quad \text{with} \quad b = 0.001 \text{ Nms}^2.$$

Calculate the resulting operating point assuming the scooter drive is powered with the fixed, nominal voltage. [3 Points]

2.5 What is the theoretical maximum speed of the PMDC machine if unloaded? Discuss why this maximum speed is an inherent limitation of the PMDC machine. [2 Points]

Task 3: Winding factors **[9 Points]**

The cross-section of a permanent magnet synchronous machine (PMSM) is given in Fig. 2 with the parameters from Tab. 2. All windings per phase are connected in parallel ($a = 2$).

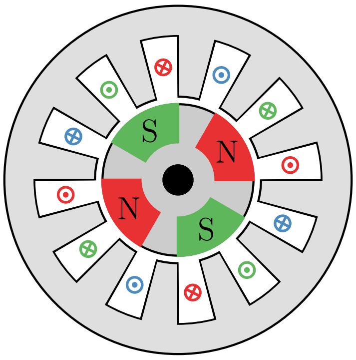


Fig. 2: Sketch of the utilized PMSM.

Tab. 2: Parameters of the PMSM.

Symbol	Value	Symbol	Value
l_z	0.45 m	d_{si}	0.3 m
n_n	2500 $^1/_{min}$	N_c	5 windings per coil

3.1 What is the number of slots Q, the number of phases m and the number of notches q? In addition, calculate the pole pitch ρ_p. [2 Points]

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

3.3 The air gap flux density is given with $\hat{B}_\delta^{(1)} = 1.2$ T. Calculate the flux per pole ϕ_δ and the flux linkage ψ_{phase}. [4 Points]
Hint: if and only if you are not able to solve this task, use $\psi_{phase} = 0.5$ Vs as a substitute result for the following questions.

3.4 Calculate fundamental component of the induced voltage $U_{i,phase}$ for one phase. [1 Point]

Task 4: Synchronous machine **[14 Points]**

A four-pole synchronous machine operates as a generator in a power plant and supplies 17 MW of active power to the power grid. The grid frequency is 50 Hz. The stator ohmic winding resistance of the synchronous machine is negligible and the excitation current is set to a constant value of 100 A. Fig. 3 shows the phasor diagram of the synchronous machine at a given operating point.

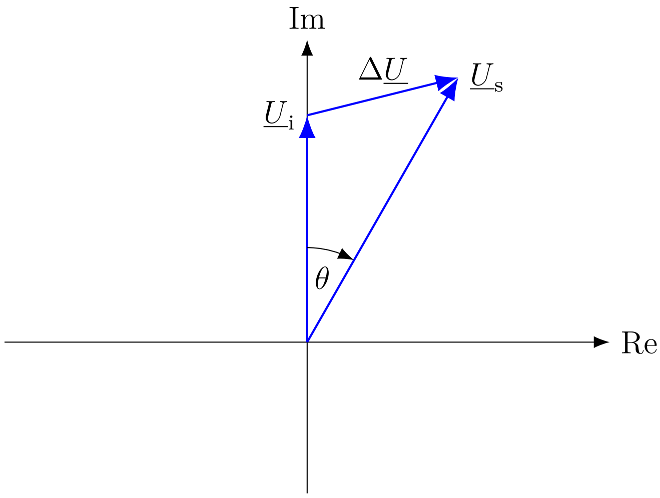


Fig. 3: Phasor diagram of a synchronous machine with scaling 1 kV = 1 cm and 1 kA = 1 cm.

4.1 Determine the operating mode of the synchronous machine based on the phasor diagram. [1 Point]

4.2 Determine the short-circuit current I_sc and add its phasor $\underline{I}_\mathrm{sc}$ to Fig. 3. [2 Points]
Hint: if and if only you are not able to solve this task, assume $I_\mathrm{sc} = 3$ kA as a substitute result.

4.3 Determine the synchronous reactance X_s. [1 Point]
Hint: if and if only you are not able to solve this task, assume $X_\mathrm{s} = 1\ \Omega$ as a substitute result.

4.4 Determine the stator current I_s, the phase shift angle φ between stator current and voltage, and add the phasor $\underline{I}_\mathrm{s}$ to Fig. 3. [3 Points]
Hint: if and if only you are not able to solve this task, assume $I_\mathrm{s} = 3$ kA and $\varphi = 150°$ as substitute results.

4.5 Determine the power factor $\cos(\varphi)$, the reactive power Q and the apparent power S. [3 Points]

4.6 What is the generator's torque T at the given operating point and what is its theoretical maximum stable torque for the given excitation? [2 Points]

4.7 Now, the generator should only supply the active power specified above to the grid, but no reactive power. To what value must the excitation current I_f be changed to achieve this? [2 Points]