



Mechatronics and Electrical Drives

16.09.2015

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Course of Study:																																						
Exercise:	1	2	3																																			
(Points)	(16)	(24)	(20)				Total	Grade																														
							(60)																															

Duration:
120 Minutes

- Permitted:**
- a non-programmable calculator without graphic display
 - drawing materials (compasses, protractor, ruler, pens ...)

Please note:
 Please prepare your student ID card (with photo) on your desk for the attendance check.
 Please label each exam sheet with your name and student number.
 Use a new exam sheet for each task. Do not use pencils or red pens.
 With numerical calculations, the units must be considered in every step. Not following that rule will result in deduction of points. All solutions must be clearly documented and wherever required explained!
 The entry of a mere final result without any approach will not be counted.

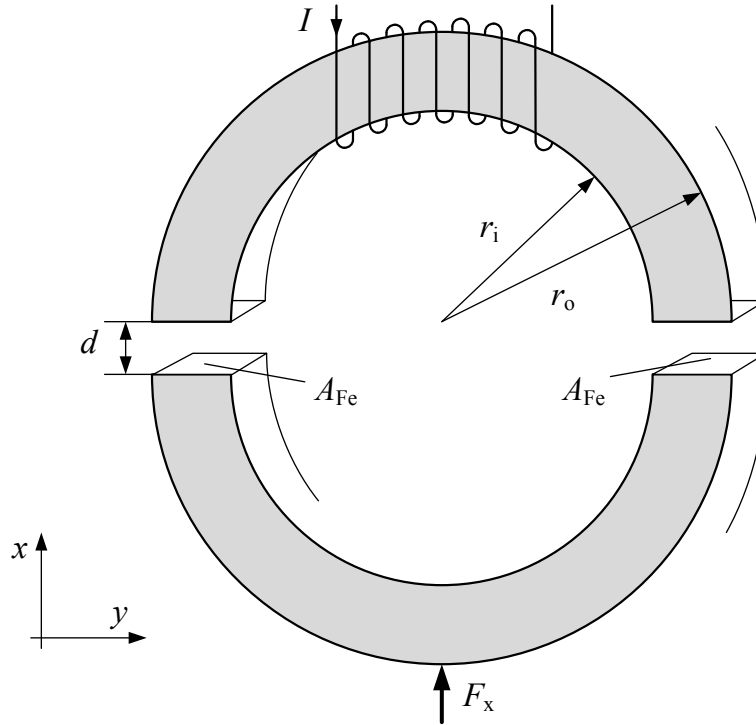
You can only take part in the exam, if you are registered in the PAUL system. If you take part without registration, the exam result will not be considered.

Good Luck!

Task 1: Magnetic Bearing

(16 Points)

Shown below are two identical iron sections with an air-gap $d = 1$ mm. In this case, only the upper core is provided with a winding of $N = 125$ turns. The geometric dimensions are given below.



$$r_i = 8 \text{ cm}, r_o = 10 \text{ cm}, A_{Fe} = 350 \text{ mm}^2, \mu_0 = 4\pi \cdot 10^{-7} \text{ Vs/Am}, \mu_r = 1800$$

- 1.1** Obtain the magnetic equivalent circuit model and calculate the individual reluctances (4 P)

In the following tasks the behavior of the iron can be idealized ($\mu_{r,Fe} \rightarrow \infty$).

- 1.2** Calculate the attraction force $F_{x,0}$ of the lower core, when the winding is excited with a constant current of $I = 8.5$ A. (4 P)

Now, an additional force F_x will be applied to the lower section. Gravitational force is not to be considered.

- 1.3** Is it possible to compensate the force $F_x = -F_G(1 + \sin(2\pi ft))^2$ with the magnetic bearing?

If yes, calculate the needed current $i(t)$, if no, give reasons, and propose a modification of the system so that the case can be covered. (4 P)

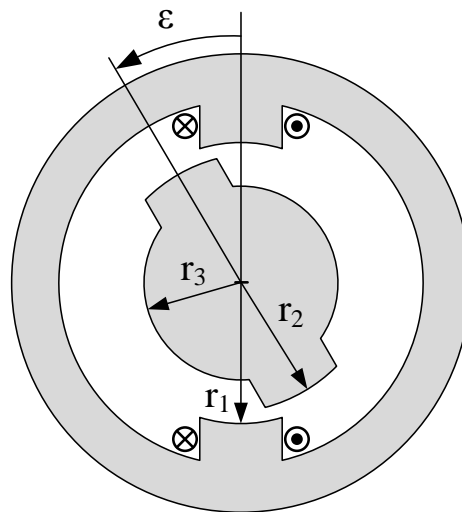
- 1.4** Is it possible to compensate the force $F_x = +F_G(1 + \sin(2\pi ft))^2$ with the magnetic bearing?

If yes, calculate the needed current $i(t)$, if no, give reasons, and propose a modification of the system so that the case can be covered. (4 P)

Task 2: Switched Reluctance Motor
(24 Points)

Given is a switched reluctance motor with two stator and two rotor poles of equal cross-section areas A_p . The influence of iron can be seen as idealized ($\mu_{r,Fe} \rightarrow \infty$). The stator has two windings with $N = 125$ turns each. Other parameters of the motor can be found in the overview:

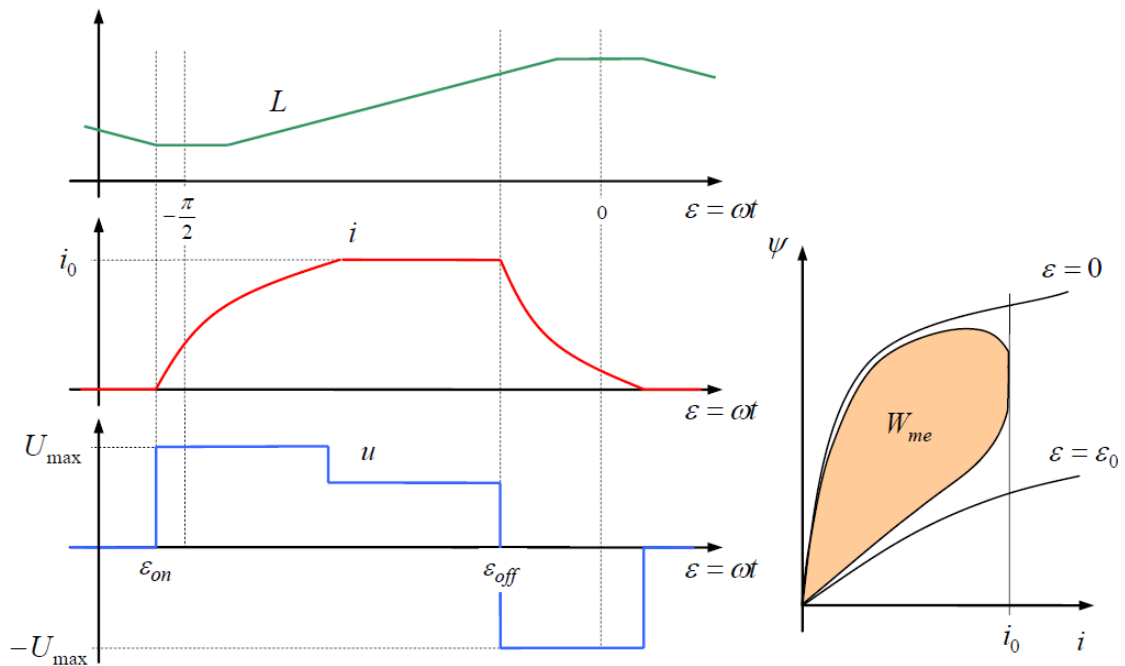
$$A_p = 100 \text{ mm}^2, r_1 = 122 \text{ mm}, r_2 = 120 \text{ mm}, r_3 = 80 \text{ mm}, I = 75 \text{ A}, \mu_0 = 4\pi \cdot 10^{-7} \frac{\text{Vs}}{\text{Am}}$$



- 2.1 Calculate the air gap reluctance between one stator pole and the rotor for the aligned and unaligned case. (3 P)
- 2.2 Calculate the winding inductance of one pole for both cases. (4 P)
- 2.3 Calculate the co-energy for both cases. (4 P)

Please also see the tasks on the next page.

The following profiles are independent of the motor given above!



2.4 Give reasons for the three different voltage levels. (3 P)

2.5 Explain why the current is reduced before the position $\epsilon = 0$ is reached. (2 P)

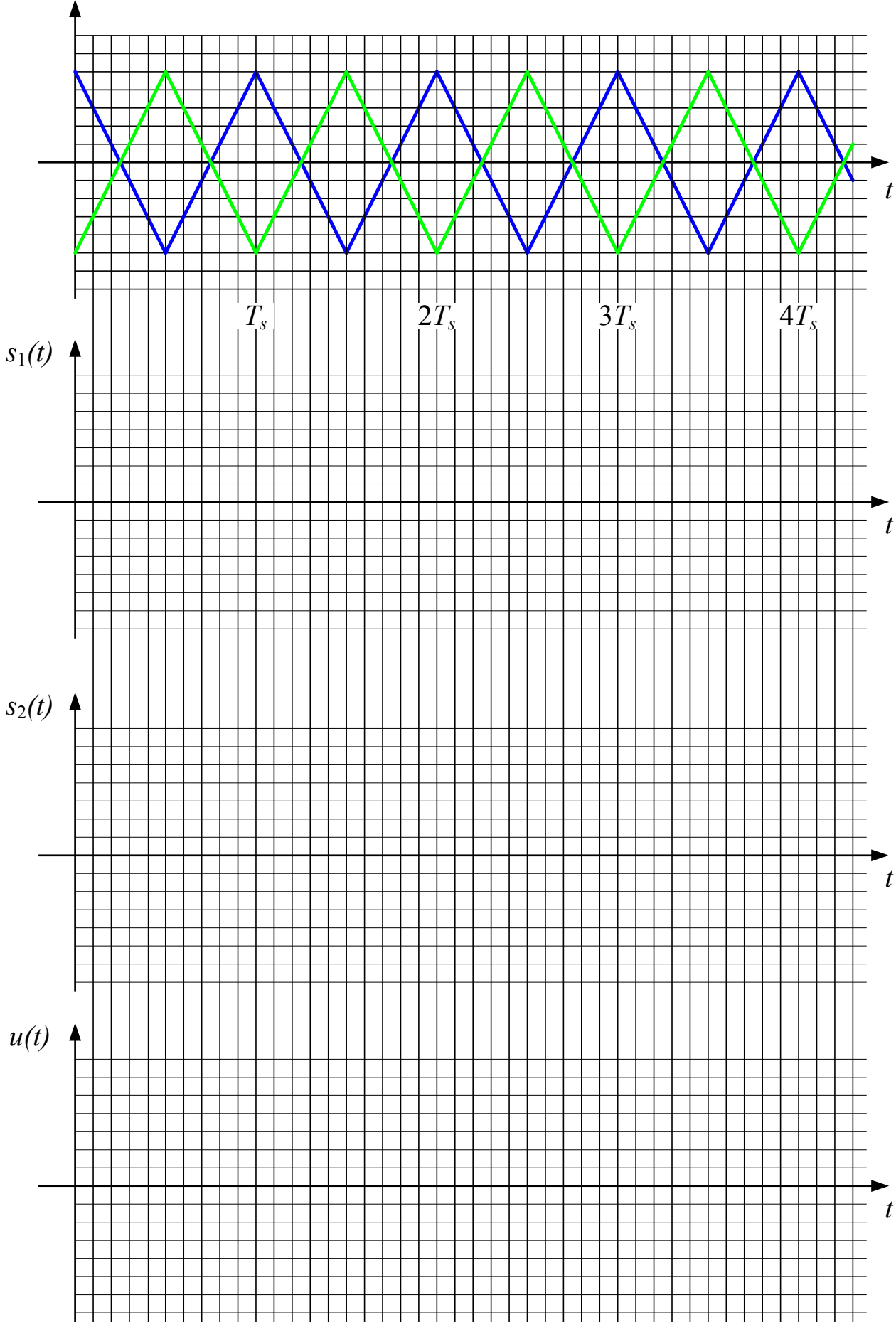
2.6 Assume that the inductance curve behaves really exactly like shown in the figure above. Give reasons for the plateaus in the profile. (2 P)

2.7 The switched reluctance drive is fed by a pulse-width modulated converter. The DC-link voltage is $U_{DC} = 300 \text{ V}$.

Give a sketch of the circuit diagram of the best suitable converter. (2 P)

Sketch the profile of the switching states $s_1(t), s_2(t)$ and the resulting pulsating voltage $u(t)$ in the figure on the next page when the requested voltage level is 180 V. The carrier signals are given in the graph on top. Indicate how the switching states $s_1(t), s_2(t)$ refer to the circuit diagram. (4 P)

Make sure to complete axis labels!



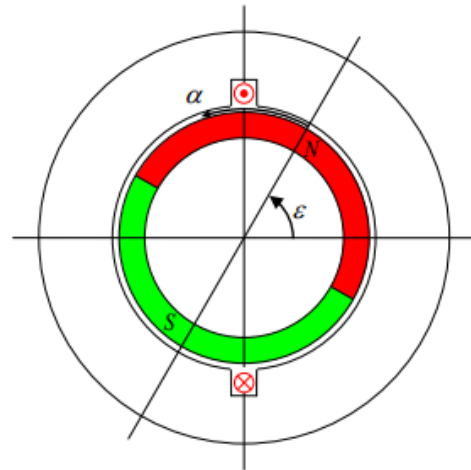
Task 3: BLDC Motor

(20 Points)

Given below are the data and the cross section sketch of a 2-pole, 3-phase, electronically commutated DC Motor (Brushless DC Motor - BLDC). The stator has a 3-phase distributed single layer winding with the series turns per phase $N_S = 10$ (only one phase winding is shown in the figure). The rotor has two radially magnetized NdFeB permanent magnets with $b_r = 1.2$ T.

The motor has the following specifications:

- Stator diameter at airgap $d = 100$ mm
- Active length $l = 100$ mm
- Airgap length $l_L = 1$ mm
- Magnet thickness $l_{PM} = 7$ mm
- Magnet relative permeability $\mu_{r,PM} = 1$.



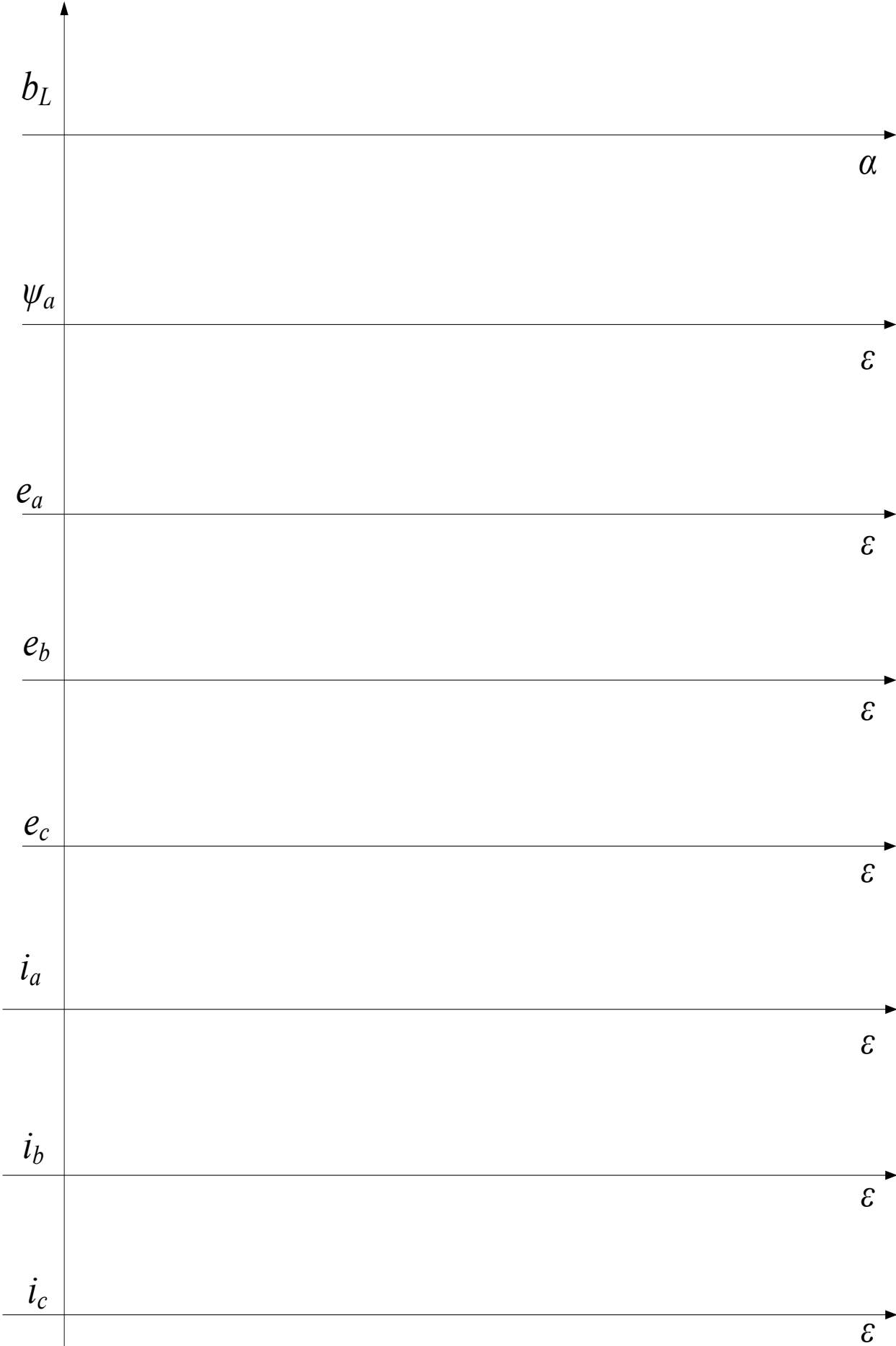
The stator and rotor iron reluctance can be idealized.

3.1 Initially the motor is operated on no-load.

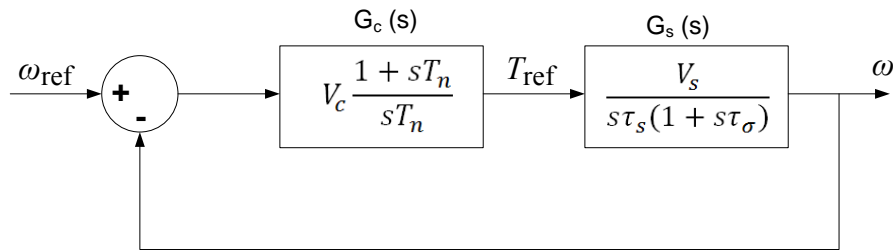
- a) Calculate the magnitude of flux density b_L in the airgap. Plot the variation of flux density variation along the circumferential angle α . (3 P)
- b) Calculate the value of flux per pole ϕ and flux linkage per phase ψ . Plot the variation of flux-linkage per phase depending on the rotor position angle ϵ . (3 P)
- c) Calculate and plot the induced phase EMFs for rotor speed of $n = 3000 \text{ min}^{-1}$ (3 P)

The windings should now be excited with a block-shaped current of peak value $I_0 = 10$ A.

- a) Plot the resulting variation of the phase currents as a function of the rotor position angle in the next sheet. (3 P)
- b) Calculate the torque delivered by the motor. (1 P)



3.2 The simplified control structure for the speed control of the BLDC motor is shown in the figure below. The simplified plant transfer function $G_s(s)$ represents the dynamic behavior from torque demand T_{ref} to angular speed ω . $G_s(s)$ includes the current controlled electrical subsystem and inertia. A load torque is not considered in the control loop. (These details are given to understand the background, however, they are not necessary to solve the following tasks.). The given plant data are $\tau_s = 0.2$ s, $\tau_\sigma = 5$ ms and $V_s = 0.1 \frac{1}{\text{Nms}}$. The speed controller transfer function is $G_c(s)$,



If the controller $G_c(s)$ is assumed as PI-type and is designed using symmetric optimum method, obtain the following:

- a) The open-loop transfer function (1 P)
- b) The controller reset time T_n if the desired crossover frequency is $\omega_c = 100 \text{ s}^{-1}$. (2 P)
- c) The closed-loop transfer function $\frac{\omega(s)}{\omega_{ref}(s)}$ (3 P)
- d) Magnitude of the controller gain V_c (1 P)