Exam

Power Electronics

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	7	6	15	14	42
Achieved score					

Task 1: Step-up converter **[7 Points]**

In an industrial control system, a stable voltage of 24 V is available. However, some devices require 48 V. Hence, a step-up converter shall be designed for a load current according Tab. 1.

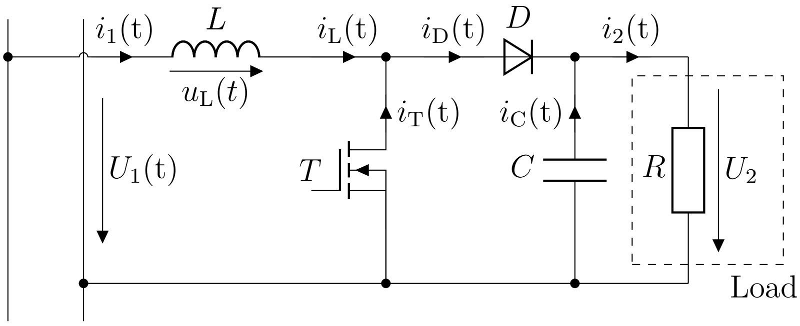

Fig. 1: Step-up converter with filter capacitor.

General parameters:		**IGBT and diode:**	
Input voltage:	$U_1 = 24$ V	Drain-source voltage:	$U_{\mathrm{on,DS}} = 1.2$ V
Output voltage:	$U_2 = 48$ V	Output current range:	$I_2 = 2$ A ... 20 A
Switching frequency:	$f_\mathrm{s} = 100$ kHz	Diode forward voltage:	$U_{\mathrm{D,f}} = 0.81$ V

The switching losses of the semiconductors are negligible.
The filter capacitor C is to be considered only for subtask 1.2.

Tab. 1: Parameters of the circuit.

1.1 Calculate the duty cycle and the minimal inductance in case of ideal components (no voltage drop over transistor and diode), when the converter operates in BCM at minimum load. [2 Points]

1.2 Some devices within the 48 V group tolerate an overvoltage of 5 %. Calculate the capacity of the smoothing capacitor C to keep this limit assuming a constant load current I_2. What is the maximum voltage that can occur at the capacitor? [2 Points]

1.3 Calculate the duty cycle and the minimal inductance in case of ideal components, but consider the voltage drop over the transistor and the diode. The converter shall operates in BCM at minimum load. [2 Points]

1.4 Calculate the efficiency of the step-up converter at maximum load current considering the transistor and diode forward losses. Moreover, sketch the curve of the voltage drop $u_\mathrm{L}(t)$ and the curves of the currents $i_\mathrm{D}(t)$ and $i_\mathrm{L}(t)$ in the diagrams below for this operating point and add the y-labels (assume U_2 as constant). [1 Point]

Fig. 2: Relevant voltage and current signals.

Task 2: Multi-port (flyback) converter for the production area **[6 Points]**

In a modern industrial automation system, a central 12 V DC power supply is used to power distributed sensor units and actuators throughout a production area. While many actuators and some programmable logic controllers (PLC modules) operate directly on 12 V, some sensors (e.g., proximity switches, temperature sensors, camera modules) require a stable voltage of 5 V or 3.3 V. Therefore, a multi-port (flyback) converter with the parameters according Tab. 2 is used.

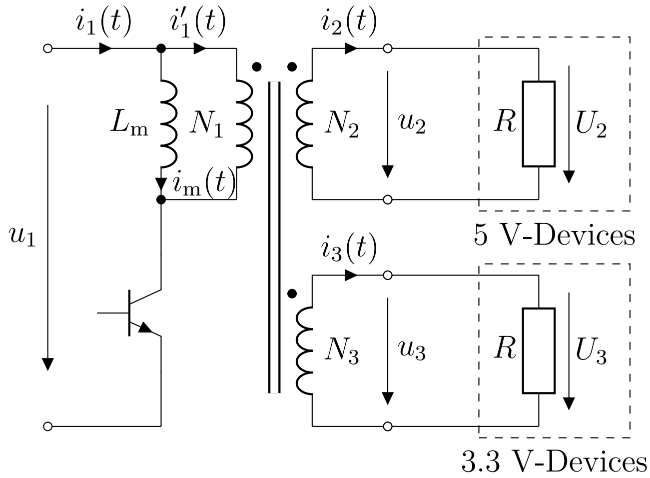

Fig. 3: Multi-port (flyback) converter.

Input voltage:	$U_1 = 12$ V	Switching frequency:	$f_\mathrm{s} = 100$ kHz
Output voltage:	$U_2 = 5$ V	Min. output current:	$I_{2,\mathrm{min}} = 2$ A
Output voltage:	$U_3 = 3.3$ V	Min. output current:	$I_{3,\mathrm{min}} = 3$ A
Duty cycle:	0.2	Primary turns	$N_1 = 2040$
All components are ideal. No losses need to be considered.			

Tab. 2: Parameters of the multi-port flyback converter.

2.1 Calculate the number of turns N_2 and N_3 for the two outputs. [2 Points]

2.2 Calculate the required magnetizing inductance L_m so that the multi-port flyback converter is in BCM at minimum current consumption. [3 Points]
Hint: the input current i_1 is composed of the transformed current components from the 5 V output and from the 3.3 V output according to $i_1 = i_{1,\mathrm{port1}} + i_{1,\mathrm{port2}}$.

2.3 Calculate the output voltage U_2 for the case, that all loads of the 3.3 V-output are disconnected, while minimum current $I_{2,\mathrm{min}}$ at 5 V port. What is the risk in this case? [1 Point]

Task 3: Line-commuted three-phase rectifier [15 Points]

An industrial conveyor system is powered by a DC motor that is supplied via a controlled three-phase midpoint rectifier (M3C). The motor draws a steady current I_2 and operates at a nominal induced motor voltage $U_{\mathrm{mot,ind}}$. The motor has an internal armature resistance R. To smooth the output current, a large inductor ($L \to \infty$) is placed such that CCM is maintained. The input to the rectifier is a symmetrical three-phase grid connected via an ideal transformer. On the secondary side, each phase has an effective voltage of $U_{1,\mathrm{i}} = 200$ V, $\forall i = \mathrm{a, b, c}$. All components (switches, transformer, etc.) are ideal.

Ein industrielles Fördersystem wird von einem Gleichstrommotor angetrieben, der über einen geregelten Dreiphasen-Mittelpunktgleichrichter (M3C) versorgt wird. Der Motor zieht einen konstanten Strom I_2 und weist eine induzierte Spannung $U_{\mathrm{mot,ind}}$ im Nennpunkt auf. Der Motor hat einen internen Ankerwiderstand R. Um den Ausgangsstrom zu glätten, wird eine große Induktivität ($L \to \infty$) so platziert, dass der CCM aufrechterhalten bleibt. Der Eingang des Gleichrichters ist ein symmetrisches Dreiphasennetz, das über einen idealen Transformator angeschlossen ist. Auf der Sekundärseite hat jede Phase eine effektive Spannung von $U_{1,\mathrm{i}} = 200$ V, $\forall i = \mathrm{a, b, c}$. Alle Komponenten (Schalter, Transformator usw.) sind ideal.

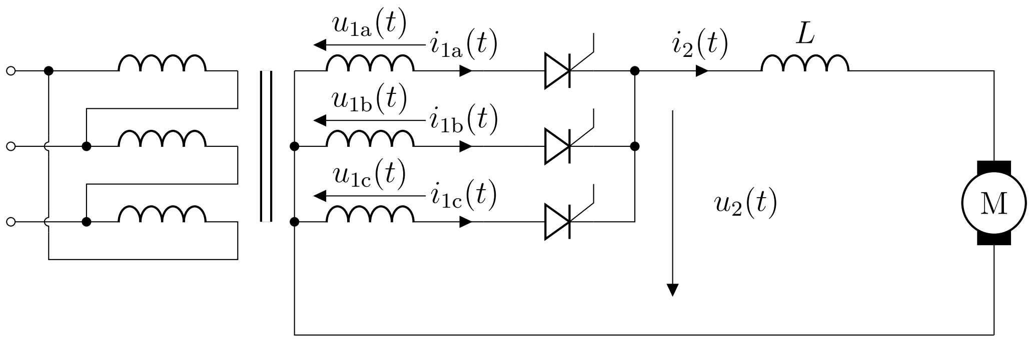

Fig. 4: M3C rectifier used for driving a DC motor.

Input voltages ($i = \mathrm{a, b, c}$):	$U_{1,i} = 200$ V (phase voltage)
	$U_{1,\mathrm{LL},i} = 346$ V (line-to-line voltage)
Nom. motor current:	$I_2 = 50$ A
Nom. motor induced voltage:	$U_{\mathrm{mot,ind}} = 150$ V
Motor internal resistance:	$R_{\mathrm{mot}} = 0.2\ \Omega$
Grid frequency:	$f = 50$ Hz

Tab. 3: Drive parameters

3.1 Calculate the required firing angle α to deliver the specified motor terminal voltage (induced + ohmic). Draw the output voltage signal $u_2(t)$ for this angle into Fig. 5. [3 Points]

3.2 Explain how adjusting α affects the speed of the motor, especially $\alpha = \frac{\pi}{2}$ and $\alpha = 0$. [3 Points]
<u>Hint:</u> the motors' speed is proportional to the back EMF ($\omega \propto U_{\mathrm{mot,ind}}$).

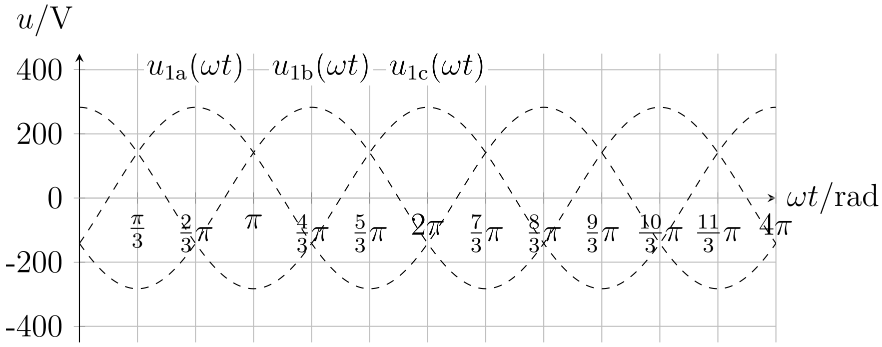

Fig. 5: Output voltage $u_2(t)$ for α.

3.3 Calculate the output power delivered to the motor, the power dissipated in the internal resistance, and the total power drawn from the rectifier output. [3 Points]

3.4 Sketch the input current $i_{1a}(\omega t)$ in Fig. 6, calculate the effective value of the fundamental component $I_{1a}^{(1)}$ and the corresponding total harmonic distortion (THD). [4 Points]
Hint: to calculate the THD, use

$$\mathrm{THD} = \sqrt{\left(\frac{I_{1a}^2}{(I_{1a}^{(1)})^2}\right) - 1},$$

where I_{1a} is the effective value of the phase current.

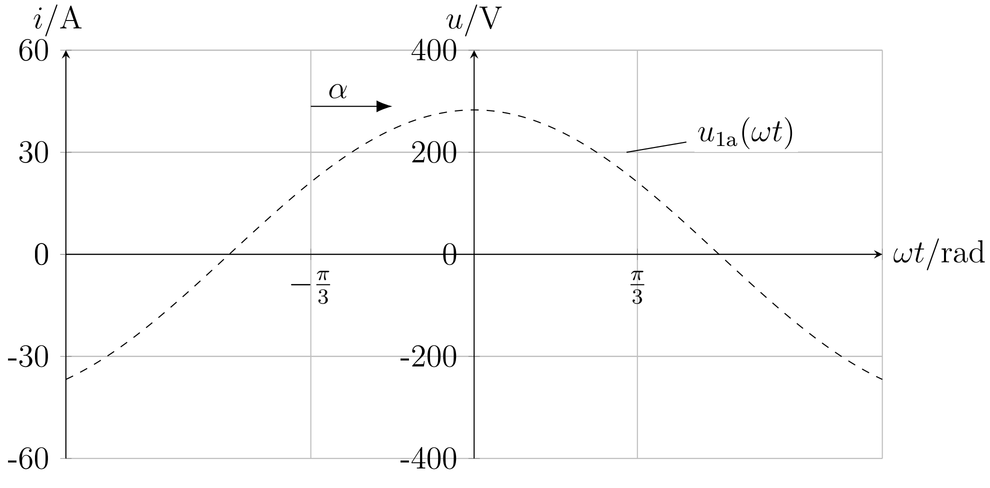

Fig. 6: Input current $i_{1a}(\omega t)$ and $u_{1a}(\omega t)$.

3.5 Suppose the inductance of the inductor is finite and was designed too low. How would that affect the output voltage and current? [2 Points]

Task 4: B6C converter at a motor load **[14 Points]**

An industrial DC motor is used in a rolling mill drive, powered through a B6C six-pulse controlled rectifier, shown in Fig. 7, from a three-phase 480 V, 50 Hz grid. The motor has a rated terminal voltage of 400 V and draws 50 A. A large smoothing inductor ($L \to \infty$) ensures constant output current. The converter is utilized to operate in motoring mode by adjusting the firing angle α.

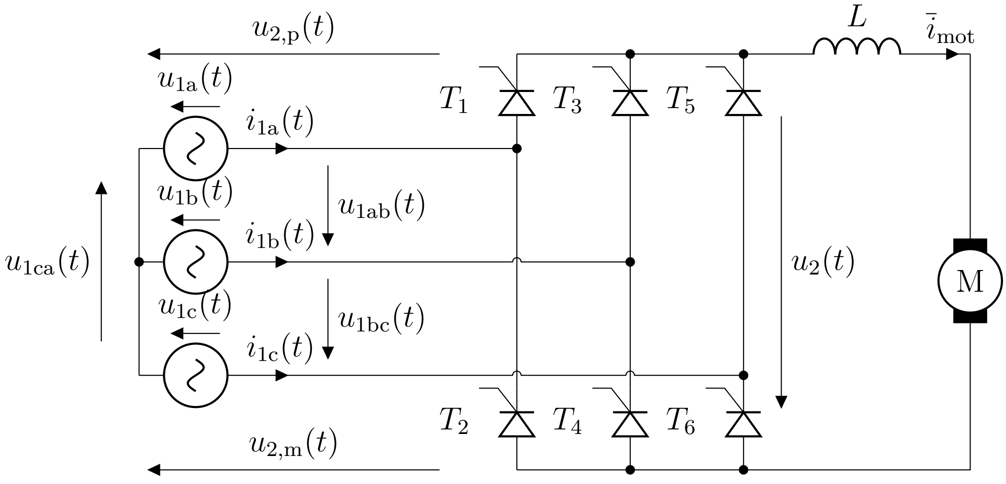

Fig. 7: B6C converter at a motor load.

Input voltages ($i = \mathrm{a, b, c}$):	$U_{1,i} = 277$ V (phase voltage)
	$U_{1,\mathrm{LL},i} = 480$ V (line-to-line voltage)
Nom. motor current:	$I_{\mathrm{mot}} = 50$ A
Nom. motor terminal voltage:	$U_{\mathrm{mot,term}} = 400$ V
Grid frequency:	$f = 50$ Hz

Tab. 4: Drive parameters.

4.1 Calculate the maximum average DC voltage the converter can deliver. In addition, calculate the firing angle α_{mot} to operate the motor at nominal speed. [3 Points]

4.2 Sketch the converter output voltage signal $u_2(t)$ at the firing angle α_{mot} in Fig. 8. [1 Point]
Hint: assume a firing angle $\alpha_{\mathrm{mot}} = 50°$ if, and only if, not calculated in the previous subtask.

4.3 List the thyristor pairs that conduct during each interval over one grid period. For each interval, specify:

- Which thyristors conduct,
- which input line-to-line voltage appears at the converter output.

Add this information to Tab. 5, where already an example for the first interval is given. [3 Points]

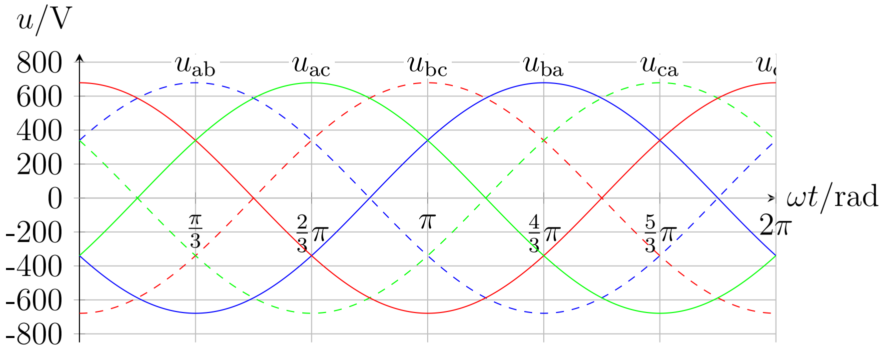

Fig. 8: Output voltage $u_2(t)$ for α_{mot}.

Interval (° electrical)	**Conducting Thyristor Pair**	**Load Voltage** $u_2(t)$
$30+\alpha$	T_1, T_4	u_{ab}

Tab. 5: Switching intervals, conducting thyristor pairs, and corresponding load voltage.

4.4 Given the fundamental input current amplitude $\hat{i}_{1\mathrm{a}}^{(1)} = 55.13$ A and nominal motor current I_{mot}, calculate the average active power supplied to the motor and the fundamental reactive power absorbed from the grid. [3 Points]

4.5 Using the same value for $\hat{i}_{1\mathrm{a}}^{(1)}$ as in the previous subtask, calculate the THD of the phase current $i_{1\mathrm{a}}(\omega t)$. [2 Points]
Hint: use the same THD formula given in the previous task.

4.6 State the effect of changing the number of pulses p (by using other converter topologies) on the maximum achievable voltage and THD of the input current. [2 Points]