Version SMG/3

EGT2
ENGINEERING TRIPOS PART IIA

Tuesday 30 April 2024 14.00 to 15.40

Module 3B3

SWITCHED-MODE POWER ELECTRONICS

Answer not more than ***three*** *questions.*

All questions carry the same number of marks.

The ***approximate*** *percentage of marks allocated to each part of a question is indicated in the right margin.*

Write your candidate number ***not*** *your name on the cover sheet.*

STATIONERY REQUIREMENTS
Single-sided script paper

SPECIAL REQUIREMENTS TO BE SUPPLIED FOR THIS EXAM

CUED approved calculator allowed
Engineering Data Book

10 minutes reading time is allowed for this paper at the start of the exam.

You may not start to read the questions printed on the subsequent pages of this question paper until instructed to do so.

You may not remove any stationery from the Examination Room.

1 (a) Power supplies for latest consumer electronics, such as laptop computers and cell phones, use a very typical structure of a single-phase grid-side passive rectifier and a subsequent fly-back converter. Sketch the schematic for this circuit. Assume the output load to be represented by a resistor and its voltage stabilised with a capacitor. Furthermore, assume a voltage-stabilising capacitor between the rectifier and the fly-back converter. [20%]

(b) Derive the expression of the output voltage of the fly-back converter as a function of the duty ratio D and the input voltage of the fly-back converter. Assume ideal devices and continuous flux of the transformer. [20%]

(c) Sketch the transformer flux ϕ, the transistor current $I_{\mathrm{T,flbck}} = I_{\mathrm{Tfb}}$, and the current of the diode $I_{\mathrm{D,flbck}} = I_{\mathrm{Dfb}}$ over time. [15%]

(d) Explain why operation of the fly-back converter right between the continuous and the discontinuous conduction mode is advantageous. [10%]

(e) Sketch the voltages and currents on the mains and the DC side of the rectifier over time for a large capacitor between the rectifier and the fly-back converter. Briefly discuss the problems this behavior may cause and why modern devices that follow all regulations should not do this. [20%]

(f) To ease this problems of part (e), a different passive filter instead of a large capacitor at the output of the rectifier could be used. Sketch such a filter and the voltage and current traces at the input and the output of the rectifier with this filter. [15%]

2 (a) Inverter circuits allow feeding power into the mains or operating variable-speed motors. Sketch a three-phase inverter with transistors. Mark the fundamental circuit pattern that is repeated in this circuit. [10%]

(b) A three-phase drive inverter for an electrical vehicle should be operated with pulse-width modulation (PWM).

(i) Explain the concept of pulse-width modulation. How many voltage levels can a single phase versus ground use? How many voltage levels can an inverter generate from one phase to another? [10%]

(ii) Sketch the spectrum of the output of the inverter and name key components. [10%]

(iii) Derive a simple expression of the output voltage in dependence of the DC voltage and the modulation depth. Up to which voltage level does this relationship apply? Can the output voltage amplitude exceed this level, and how is this modulation regime called? [15%]

(iv) Explain why there is no third harmonic in the differential output (from phase to phase). [10%]

(v) Show briefly that adding the very same (same phase, same amplitude) third harmonic with a small amplitude (e.g. 10%) to each inverter output can increase the differential, phase-to-phase output voltage for the same DC supply voltage. [10%]

(c) Assume a three-phase inverter with pulse-width modulation for an electric vehicle with an 800 V battery.

(i) Calculate the necessary switching rate for the transistors if the connected motor has an inductance of 500 μH from phase to neutral and if the ripple current should be less than 20 A. For simplicity, isolate a single phase, assume a stable neutral point and study the case of a stand-still motor. [15%]

(ii) The car is now driving and the motor spinning such that it generates a back electromotive force, i.e., an induced no-load generator voltage of 400 V (phase-neutral) and a frequency of 200 Hz. Which modulation depth M is needed to drive 10 A through the motor, in phase with the back electromotive force (for active power). [20%]

3 (a) A tensor processing unit (TPU) for artificial intelligence problems requires a compact step-down converter to supply a variable output voltage from 0.8 V to 1.2 V from a 3 V supply. Sketch the schematic for a simple step-down converter. The required power flow is exclusively unidirectional so that you may use diodes for simplicity. [15%]

(b) Which two operation modes do you know for a unidirectonal step-down converter? Considering that modern high-performance processors are very sensitive and require a very stable voltage, which mode would you recommend in that case? Give a reason for your decision. [20%]

(c) Which duty ratio range is required to cover the entire output voltage range if any losses are ignored? How would that change if the TPU needs up to 100 A of current and the effective resistance of the step-down converter, connectors, etc. may reach 4 mΩ? Assume otherwise ideal components, such as transistors and diodes. [20%]

(d) The step-down converter will use some novel transistors and operate at 5 MHz. Assume that the output capacitor almost perfectly smoothens the voltage. Estimate the current ripple for 1 V output at a 100 A and an inductance of 100 nH. [15%]

(e) Sketch the input current, the inductor current, and the voltage across the diode over time. [20%]

(f) Typically step-down converters for processors do not use diodes. Give two problems real diodes would introduce. [10%]

4 (a) Draw the cross-sectional structure of a double-diffused metal-oxide field-effect transistor (MOSFET). Name the key elements. Indicate in which place or range the highest electric field is reached in the off state for a high positive drain–source voltage. [25%]

(b) Why are such silicon power MOSFETs as you sketched in part (a) only offered up to a certain voltage? Which element has to manage a higher operating voltage and how does it become the limiting element for the static performance in MOSFETs for high voltages? [15%]

(c) What are the key structural differences between an insulated-gate bipolar transistor (IGBT) and a vertical power MOSFET, which would also be visible in the cross-sectional structure? Which of these differences is clearly visible in the device characteristics and where? [25%]

(d) How can wide-bandgap semiconductor materials allow reasonable power MOSFET devices at higher voltage levels, which used to be the exclusive domain of IGBTs? Which material properties are responsible for the fact that devices avoid the problems from part (b)? [15%]

(e) Sketch a typical modern silicon-carbide transistor structure. Silicon carbide has a lower charge carrier mobility than silicon. Which structural design choice is supposed to compensate the lower charge carrier mobility? [20%]

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Short answers:
1(b) $V_{fb,out}/V_{fb,in} = N_2/N_1\, D/(1-D)$
2(c) 25.5 kHz, 0.7
3(c) 0.27...0.533 (d) 4 A