Version SMG/4

EGT2
ENGINEERING TRIPOS PART IIA

Thursday 7 May 2026   9.30 to 11.10

Module 3B3

SWITCH-MODE 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 boost converter has an input voltage V_i, input current I_i, output voltage V_o, and output current I_o. The inductor of this boost converter is L. The transistor of this boost converter has a duty ratio D and the switching frequency is $f_\mathrm{S} = 1/T_\mathrm{S}$. The current conduction coefficient K is given as $K = 2L/RT_\mathrm{S}$.

(a) Sketch the circuit of the boost converter. How many states does the circuit have? Sketch the equivalent circuit of each state. Derive the voltage transfer function $M(D)$ when the boost converter operates in continuous current mode with a load R and state any assumptions. [20%]

(b) For which duty cycles D does the boost converter operate in the discontinuous conduction mode for the same load conditions? Derive an equation or an inequality and sketch the input and output voltages as well as the currents accurately. Name all axes, mark and name characteristic points of the curves. [30%]

(c) Derive an expression of the voltage transfer function $M(D)$ for the discontinuous conduction mode for the same load conditions. [30%]

(d) The boost converter is part of a battery charger that receives 725 V at the input and should deliver low ripple current to the battery at the output of not more than 2 A peak-to-peak. For size and weight reasons, the inductance $L = 1000$ µH is fixed. However, the charger may adjust the switching frequency to trade off losses and ripple. Derive an equation for the ideal switching frequency in Hertz in dependence of the duty cycle. Furthermore, analyse the case of the boundary conduction mode: Derive an expression for the instantaneous power loss $P_\mathrm{L}(t)$ representing the loss of the internal resistance of the inductor R_L, for the instantaneous power loss $P_\mathrm{FET}(t)$ representing the conduction loss of the transistor (assume $R_\mathrm{ds,on}$ as the equivalent on-resistance of the transistor), and instantaneous power loss $P_\mathrm{D}(t)$ representing the diode loss, each as as a function of time. Assume that the diode has a fixed forward-voltage drop V_fd, widely independent of the current. [20%]

2 A single phase, full-wave, diode rectifier is connected to an ideal AC voltage without internal impedance on the input side with a root-mean-square (RMS) value V_{AC} and a frequency of $f = 50$ Hz. The diodes are assumed to be ideal.

(a) The load is a so-called constant-power load without any capacitance or inductance. Thus, no matter which non-zero voltage is connected to it, the load will absorb the same power P_{CPL}. Provide an equation for the current–voltage characteristic of the load and derive explicit equations for the output voltage as a function of the current, $V_{\mathrm{CPL}}(I_{\mathrm{CPL}})$, as well as the voltage-dependent resistance $R_{\mathrm{CPL}}(V_{\mathrm{CPL}})$ for a constant power P_{CPL}. [10%]

(b) Discuss how such a constant-power load could be implemented as a combination of a switched-mode converter with a resistive load. Which switched-mode circuit potentially in combination with electronic control could be used and how would it need to be operated? Derive an expression for the duty cycle of that circuit as a function of the voltage V_{CPL} across the constant-power load and any circuit parameters, such as resistors. [30%]

(c) Derive expressions for the voltages and the currents at the input and the output side of the rectifier. Subsequently sketch the voltage and the current on both the input and the output side of the rectifier over time in a clean sketch. Name all axes, add characteristic time points and explain the shapes. Assume that the constant-power load has a minimum non-zero resistance. Discuss the problems with such a setup as revealed by the shapes of the traces. [30%]

(d) To solve the problems, a second-order filter should be placed between the rectifier and the load. Which two options of a second-order filter are there? Sketch the circuits. [10%]

(e) Sketch the input and output currents and voltages for the preferable case of the two filter options from part (d). Assume that the filter has very large components. [20%]

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3 (a) The circuit schematic of a Flyback converter is shown in Fig. 1. The input voltage of this Flyback converter is V_1 and the output voltage is V_2. The number of turns of the primary and secondary winding is N_1 and N_2, respectively. The magnetising inductance of the transformer is L_m. The duty cycle of the transistor of the Flyback converter is D. The circuit is considered as lossless and all voltage ripples are neglected.

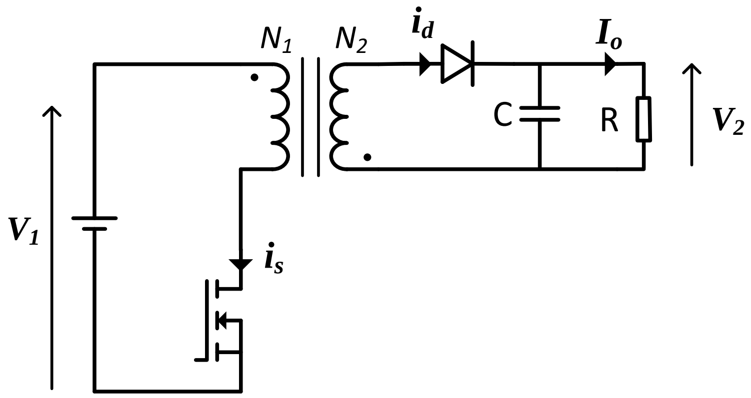

Fig. 1

(i) Derive the expression of the output voltage V_2 when the flux of the transformer core is continuous. [20%]

(ii) The input and output voltages of the Flyback are 400 V and 40 V, respectively. The output current is 10 A. If the transistor of the Flyback converter is required to operate at 100 kHz and a 50% duty ratio, calculate the minimum magnetising inductance of the transformer in this Flyback converter. [30%]

(b) Fig. 2 shows the circuit schematic of a half-bridge LLC converter. The input voltage of this LLC converter is V_i and the output voltage is V_o. The number of turns of the primary and secondary winding is N_1 and N_2, respectively. The magnetising inductance of the transformer is L_m. The duty cycle of the half-bridge is 50%. The resistive load resistance is R. An inductor L_r and a capacitor C_r are used as a resonant tank. The circuit is considered as lossless and all voltage ripples are neglected.

(i) Define the switching frequency of the half-bridge when this LLC converter operates at the resonant frequency. [10%]

(ii) Derive the voltage gain $\frac{V_o}{V_i}$ with respect to the switching frequency when L_m is much larger than L_r (hint: the rectifier side resistance can be taken as equivalent to $\frac{8R}{\pi^2}$). [20%]

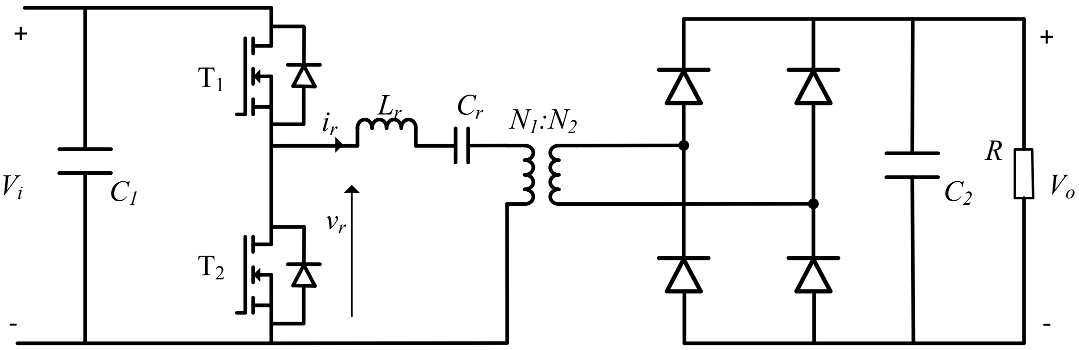

Fig. 2

(iii) Sketch the output voltage waveform of the half-bridge v_r and the current i_r when operating at the resonant frequency. [20%]

4 Two metal–oxide–semiconductor field-effect transistors (MOSFETs) are used in a synchronised boost converter as shown in Fig. 3. The switching frequency is 100 kHz and the output voltage V_o is 100 V. The synchronised boost operates in the continuous conduction mode (CCM), and the duty cycle is 75%. The input power is 250 W and the inductor L has a 40% peak-to-peak current ripple.

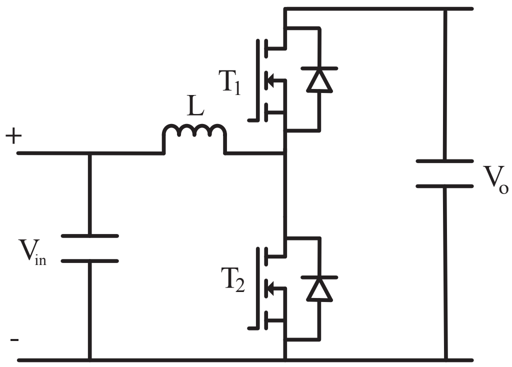

Fig. 3

(a) What is the dead time in the context of the synchronised boost converter? Explain the necessity of the dead time in this circuit. [15%]

(b) Calculate the conduction loss of MOSFET T2. The conduction resistance of the MOSFET R_{ds} in this converter is 50 mΩ. [20%]

(c) Sketch the simplified curve of the gate-to-source voltage V_{GS}, gate current I_G, drain-to-source voltage V_{DS}, and drain current I_D of MOSFET T2 for the switch-on and switch-off event, respectively. Mark on this sketch the switch-on delay time t_{don}, switch-on rise time t_r, switch-off delay time t_{doff}, and switch-off fall time t_f. [25%]

(d) Calculate the switching loss of MOSFET T2 when t_{don} is 14 ns and t_r is 16 ns, assuming the switch-off loss and the switch-on loss to be equal. [20%]

(e) Sketch the current commutating loops in one switching period. Explain why MOSFET T2 has larger switching loss than MOSFET T1. [20%]

END OF PAPER