Version PRP/6

EGT1
ENGINEERING TRIPOS PART IB

Wednesday 1 June 2016 2 to 4

Paper 5

ELECTRICAL ENGINEERING

Answer not more than ***four*** *questions.*

Answer not more than ***two*** *questions from any one section and not more than* ***one*** *question from each of the other two sections.*

All questions carry the same number of marks.

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

Answers to questions in each section should be tied together and handed in separately.

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.

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

SECTION A

1 (a) A battery is used to provide a supply voltage V_{DD} to a mobile phone circuit. A MCP6421 Op-Amp is used in the battery current sensor circuit as shown in Fig. 1 (a). The battery voltage is nominally 3.7 V.

(i) Explain why an Op-Amp is well suited for use in the battery current sensor circuit. [4]

(ii) Assuming the Op-Amp to be ideal, find the output voltage expected for $I_{DD} = 80$ mA and the value of V_{DD} in this condition. [6]

(iii) What will happen to the output voltage as the battery discharges reducing its voltage by 10% assuming that the main phone circuit still draws a current $I_{DD} = 80$ mA? [4]

(b) An Op-Amp is to be used as a buffer to drive a capacitor load, as shown in Fig. 1 (b). The load is C_0.

(i) The Op-Amp has a finite gain A and a finite output resistance R_0. Find an expression for the ratio of output voltage to input voltage. [5]

(ii) The Op-Amp gain at dc is A_0 and its open loop bandwidth is ω_0. Derive a new expression for the ratio of output voltage to input voltage for the circuit and comment on the significance of your answer. [6]

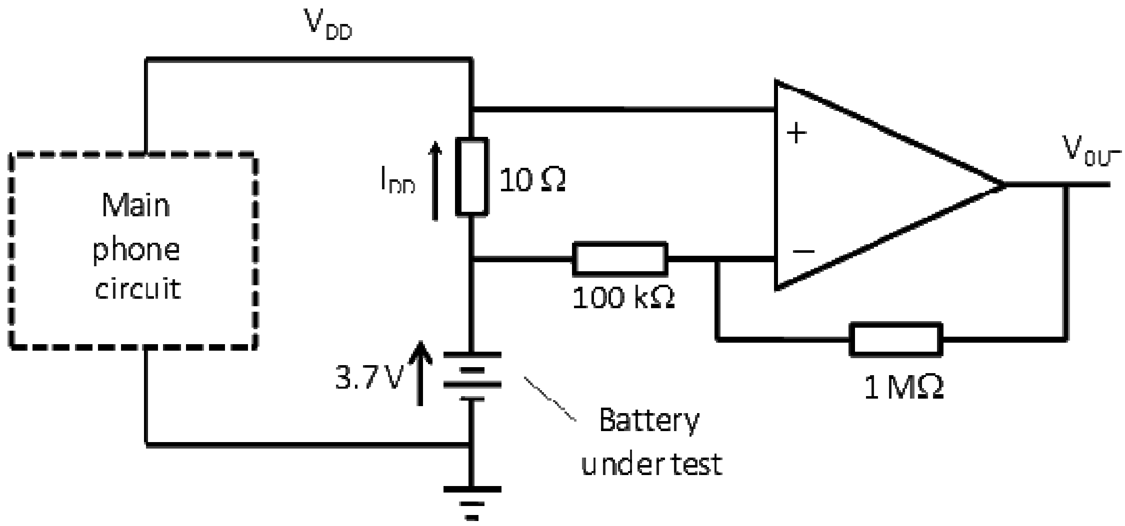
V_DD
Main
phone
circuit
I_DD
10 Ω
100 kΩ
1 MΩ
3.7 V
Battery
under test
+
−
V_OUT

Fig. 1 (a)

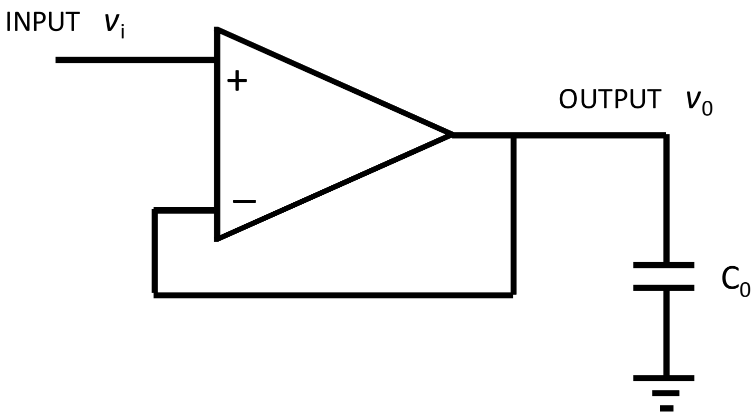
INPUT v_i
+
−
OUTPUT v_0
C_0

Fig. 1 (b)

2 (a) A bipolar transistor amplifier circuit is shown in Fig. 2 (a). The transistor h_{FE} is 100 and with no input signal the collector current is to be 100 mA and the voltage at the output is to be 2.5 V.

(i) Suggest values for the base bias resistor R_B and collector resistor R_C, stating the approximations you used. [5]

(ii) Why is this collector voltage optimal for this type of amplifier? [3]

(iii) Draw an exactly complementary version using a pnp transistor of the circuit in Fig. 2 (a). [3]

(iv) Draw a Class B amplifier by superimposing the circuit in Fig. 2 (a) and its complement from part 2a (iii), eliminating R_C, taking care to label the new output voltage node. Explain how the circuit may be modified to improve its output linearity. [3]

(b) The circuit of Fig 2 (b) is one half of the output stage of a new Op-Amp. Gain compensation of the Op-Amp is provided by the 20 nF capacitor C_C. The transistor characteristics are $h_{fe} = 100$, $h_{ie} = 2.5$ kΩ and h_{oe} and h_{re} may be neglected. I_B is a dc current, and i_{in} is the small signal input.

(i) Draw the small signal equivalent circuit for the circuit of Fig. 2 (b). [5]

(ii) Estimate the 3dB frequency of the Op-Amp due to C_C. State any approximations or assumptions you make. [6]

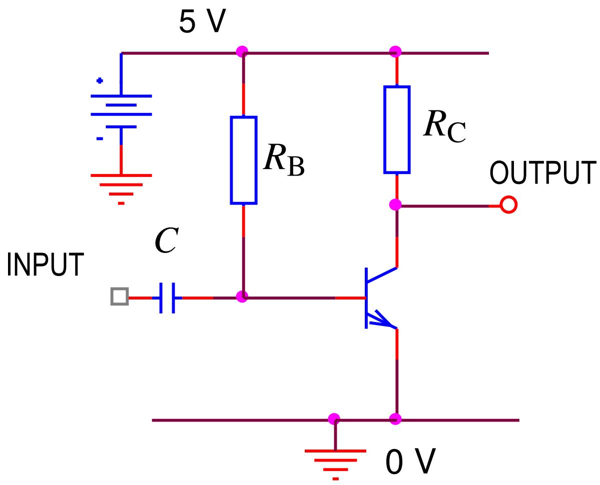

Fig. 2 (a)

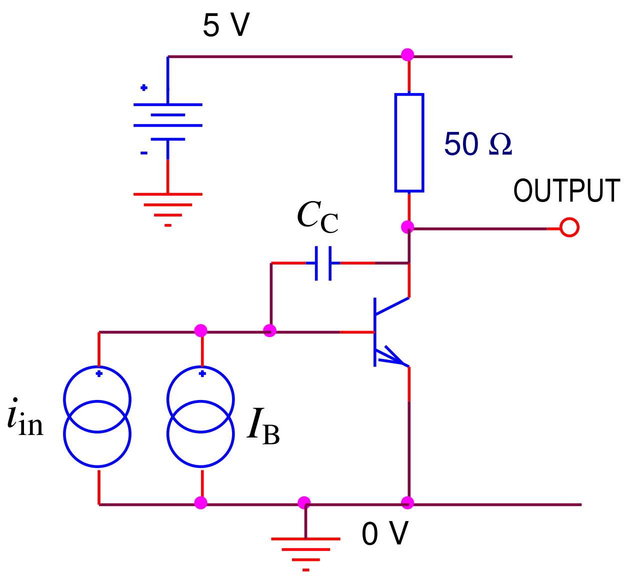

Fig. 2 (b)

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SECTION B

*Answer not more than **two** questions from this section*

3 (a) High voltage transmission pylons have sets of three wires hung on long insulators and one small cable. Suggest why this is the case taking care to mention the use of pure sine wave voltages. [5]

(b) Consider a three phase transmission line with inductance only. Draw a phasor diagram to show that current can flow in the line while the magnitudes of the voltages at each end of the line are the same. [5]

(c) A wind farm in a remote area is 20 km from the nearest town and is connected by a 33 kV three phase line operating at 50 Hz. The 33 kV lines each have a total resistance of 6 Ω and an inductive reactance of 22 Ω . The maximum current in the lines is 260 A.

(i) Assuming that the town remains at 33 kV, what is the maximum power that may be delivered to the town and what is the line voltage at the Wind Farm end? [5]

(ii) Find the star connected capacitance required at the wind farm for maximum power capacity of the 33 kV line, if the wind generators may only produce power at unity power factor and the town remains at 33 kV. [5]

(iii) For maximum current in the line, calculate the required capacitance at the town, to correct the power factor at the wind farm to unity assuming the town remains at 33 kV. [5]

4 (a) Peterhead power station is connected to the high voltage transmission grid in Scotland. The station houses four 300 MW gas turbines all paired with identical synchronous generators. With the increase in Scotland's windpower generation, Peterhead is used for reserve capacity, with a contract specifying normal operation between 240 MW and 400 MW, with an additional 750 MW which may be called on at any time. It is also used to support the grid with reactive power.

(i) Making reference to the load angle, explain carefully why the synchronous machine can be considered to work according to the principles of magnetic attraction. [4]

(ii) The generators are rated at 400 MVA, 33 kV and a power factor of 0.85. Their synchronous reactance is 2 Ω per phase. Find the generated phase emf, when operating at these rated conditions. [6]

(iii) Assuming that the generated phase emf is that found in part a (ii), find the maximum reactive power which can be supplied to the grid, within the terms of the contract. [7]

(b) The 275 kV transmission line from Peterhead to the city is 240 km long. The power station is connected to the transmission line with a 1500 MVA, 33/275 kV transformer with a reactance of 15%. The transmission line has an inductance of 1 mH km^{1}. Find the fault current for a three phase fault to earth on the transmission line at the city end using the per-unit method. [8]

 (TURN OVER

5 (a) A rotating magnetic field can be produced in an induction motor using three phase sinusoidal voltages and currents.

(i) Using a set of three phase ac waveforms and a sketch of the stator coils together with a simple rotor or otherwise, show that a constant torque may be produced. [4]

(ii) Sketch a simple three phase winding for a four pole machine and explain how the number of pole pairs affects the no-load speed. [3]

(iii) Explain why the induction motor is sometimes known as an *asynchronous* motor. [2]

(b) A three phase star connected 460 V, 60 Hz, induction motor has two poles. At rated conditions, it has a slip of 0.03. Its equivalent circuit parameters are: stator resistance of 0.003 Ω; referred rotor resistance of 0.015 Ω; a combined stator and referred rotor leakage reactance of 0.1 Ω. The magnetising reactance may be ignored. The iron losses of 9 kW are referred to the terminals.

(i) Find the torque at *rated* slip and the peak torque. [6]

(ii) Carefully sketch a torque - speed curve for the motor for speeds from zero to synchronous. [4]

(iii) Estimate the efficiency at peak torque. [6]

SECTION C

6 (a) A plane electromagnetic wave is travelling in the z direction, through air.

(i) Sketch the electric and magnetic fields as a function of z for $z = 0$ to 2λ indicating their relative directions. [4]

(ii) Sketch the instantaneous magnitude of the Poynting vector for $z = 0$ to 2λ. What is the physical significance of the time average value? [4]

(b) A laser diode hair removal unit shown in Fig. 3 consists of a laser diode from which light of 800 nm wavelength is emitted. The light passes through a layer of cooling water and then a sapphire window before reaching the skin where hair is to be removed. The relative permittivity of the laser material and the sapphire window is 11, and that of the water is 81. You may assume that skin has the same relative permittivity as water.

The laser produces a 50 ms pulse of light which covers a 1 cm^2 area of the skin. The total energy emitted by the laser in the pulse is 60 J.

(i) Calculate the energy which is reflected back into the laser by the cooling water. [5]

(ii) Estimate the peak electric field at the surface of the skin. [7]

(iii) If the propagation constant of the skin at 800 nm is actually $57(1 + j)\ m^{-1}$, estimate the distance that the light penetrates into the skin, and sketch how the peak electric field varies with distance into the skin. [5]

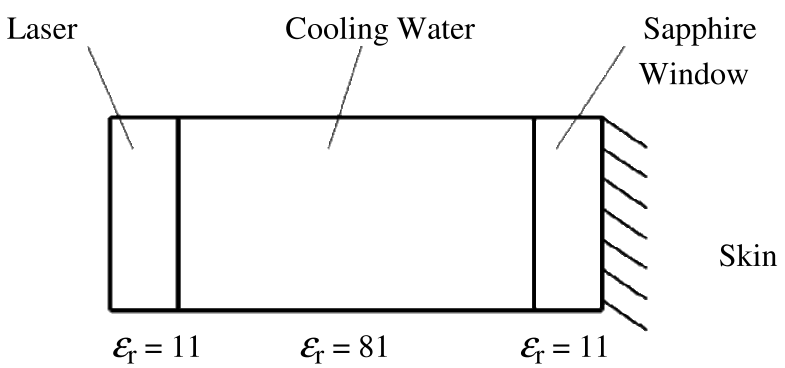

Fig. 3

7 (a) The inductance and capacitance per metre of a twisted pair cable used in a telephone line are 525 nH m^{-1} and 52 pF m^{-1} respectively.

(i) What is the physical meaning of the characteristic impedance? [3]

(ii) Find the characteristic impedance and the wave velocity for the line. [3]

(iii) Which parts of the construction of the cable affect the wave velocity and which affect the characteristic impedance? [5]

(b) A 1300 m length of the twisted-pair cable is used to connect a wireless router in a home to a roadside cabinet. The output impedance of the router and the input impedance of the cabinet are chosen to match the characteristic impedance of the cable. To test the line, the router produces a +24 V square pulse output voltage lasting 5 μs. There is a fault half way along the line which appears as a 200 Ω load, between the two conductors in the cable.

(i) Draw a graph showing how the voltage at the output of the router varies with time for 15 μs starting from when the test pulse is first applied. Mark important times and voltages with quantities on the axes of your graph. [7]

(ii) The router is disconnected from the cable. What is the input impedance of the cable to a 2 MHz sinusoidal signal? [7]

END OF PAPER

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ANSWERS

1.	(a)	(ii)	-5.1 V , 2.9 V	(iii)	-5.47 V		
2.	(a)	(i)	4300 Ω, 25 Ω				
	(b)	(ii)	1000 Hz				
3.	(c)	(i)	14.9 MW , 37.1 kV	(ii)	10.3 μF	(iii)	13.0 μF
4.	(a)	(ii)	29 kV	(iii)	1132 MVAR		
	(b)		1350 A				
5.	(b)	(i)	1080 Nm , 2816 Nm	(iii)	82 %		
6.	(b)	(i)	12.7 J	(ii)	21.9 kVm^{-1}	(iii)	0.0175 m
7	(a)	(ii)	100.47Ω , 1.91×10^8 ms^{-1}				
	(b)	(ii)	136 Ω, -0.26 rad				