ENGINEERING TRIPOS PART IB

Wednesday 3 June 2009 2 to 4

Paper 5

ELECTRICAL ENGINEERING

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

*Answer at least **one** question from each section.*

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.

There are no attachments.

STATIONERY REQUIREMENTS
Single-sided script paper

SPECIAL REQUIREMENTS
Engineering Data Book
CUED approved calculator

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

SECTION A

*Answer at least **one** question from this section.*

1 (a) A bipolar transistor has its d.c. operating point determined by its collector current I_C, base current I_B, base-emitter voltage V_{BE}, and collector-emitter voltage V_{CE}. Under these conditions, the dependence of small variations in collector current and base-emitter voltage about the operating point can be written as

$$\delta I_C = \frac{\partial I_C}{\partial I_B}\delta I_B + \frac{\partial I_C}{\partial V_{CE}}\delta V_{CE}$$

$$\delta V_{BE} = \frac{\partial V_{BE}}{\partial I_B}\delta I_B + \frac{\partial V_{BE}}{\partial V_{CE}}\delta V_{CE}$$

Write these equations in terms of small-signal quantities v_{be}, v_{ce}, i_b, i_c, and small-signal transistor parameters h_{ie}, h_{fe}, h_{oe}, and h_{re}. Hence derive the small-signal equivalent circuit for the bipolar transistor. [4]

(b) The transistor in the common-emitter amplifier of Fig. 1 is to be biased so that $I_C =$ 10 mA, $V_{CE} =$ 15 V and V_{BE} = 0.7 V. The d.c. current gain of the transistor at this operating point is 250. Find suitable values for R_1 and R_C. [4]

(c) Draw a small-signal equivalent circuit for the amplifier, valid at mid-band frequencies. Determine the value of load resistance, R_L, which will maximise the load power, and for this value of R_L, determine the mid-band voltage gain. The small signal parameters for the transistor are: $h_{ie} =$ 800 Ω, $h_{fe} =$ 250, $h_{oe} = 0$ S, $h_{re} = 0$. [6]

(d) An improved model for the transistor at high frequencies includes a parasitic capacitance between base and collector, of value 15 pF. Explain why this attenuates the gain at high frequencies, and find the frequency of the corresponding –3dB point. State and justify any assumptions made. [6]

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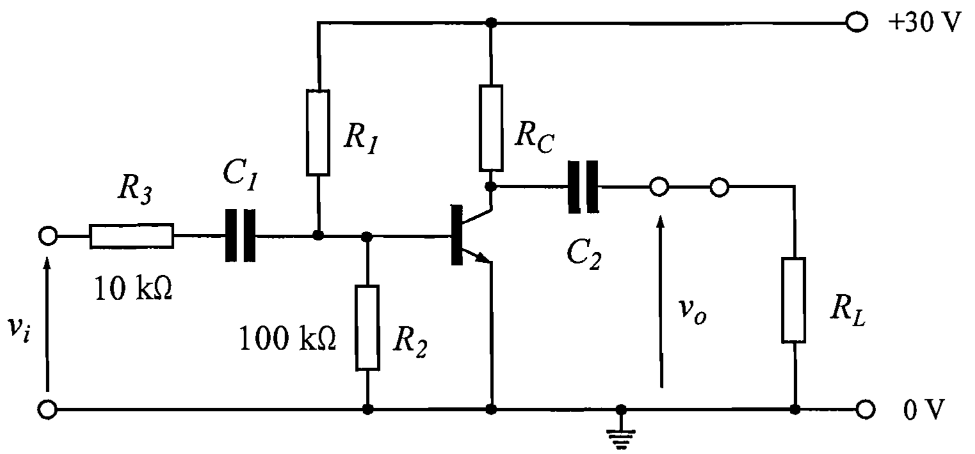

Fig. 1

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2 (a) Discuss briefly the advantages and disadvantages of using negative feedback in circuits based on operational amplifiers. [2]

(b) Consider the op-amp circuit shown in Fig. 2(a). What is the function of this circuit? Using small-signal analysis, derive expressions for the voltage gain v_2/v_1 and input impedance of the circuit in terms of resistors R_1 and R_2. Assume that the open-loop gain A and the input resistance R_i of the op-amp are finite. The output resistance R_O of the op-amp may be taken as zero. Show how the resultant expressions may be simplified for the case of the ideal op-amp. [7]

(c) Now consider the more complicated op-amp circuit shown in Fig. 2(b). Assuming in this case that the op-amp is ideal, show that the closed-loop gain v_4/v_3 is given by:

$$\frac{v_4}{v_3} = -\frac{R_4}{R_3}\left(1+\frac{R_6}{R_4}+\frac{R_6}{R_5}\right)$$ [6]

(d) If $R_3 = R_4 = R_6 = 500\ \text{k}\Omega$, $R_5 = 5.1\ \text{k}\Omega$, determine the voltage gain and input impedance achieved by the circuit of Fig. 2(b). [2]

(e) By comparing the circuit values required in Fig. 2(a) to obtain the same voltage gain and input impedance as in part (d), discuss briefly the advantages of these two approaches to circuit design. [3]

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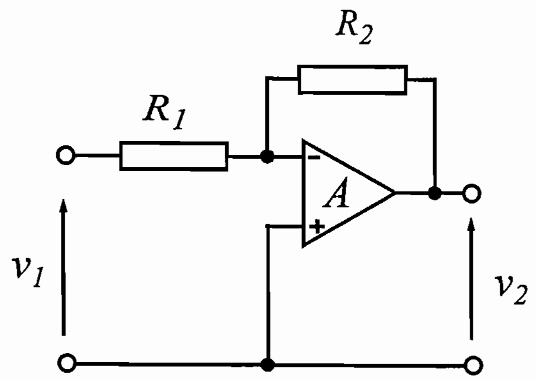

Fig 2(a)

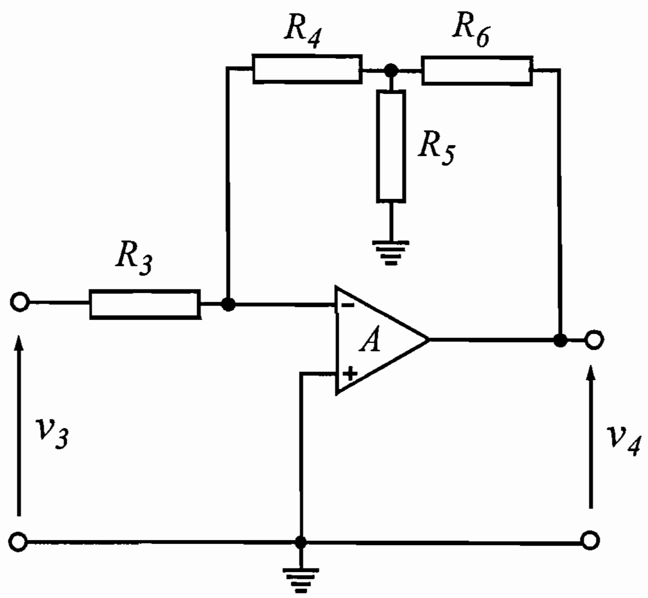

Fig 2(b)

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SECTION B

*Answer at least **one** question from this section.*

3 (a) Give two reasons why electrical power is usually generated in the form of three-phase alternating voltages. [2]

(b) Working from first principles, derive expressions for the real and reactive power consumed by

(i) A delta-connected three-phase load of impedance $Z_1 = R_1 + jX_1$ per phase,

(ii) A star-connected three-phase load of impedance $Z_2 = R_2 + jX_2$ per phase,

when each are connected to a three-phase voltage supply of line voltage V. [6]

(c) Hence show that a delta-connected load of impedance Z_1 per phase may be transformed into a star-connected load of impedance Z_2, where

$$Z_2 = \frac{Z_1}{3}$$ [4]

(d) Figure 3 shows a star-connected load (load 1) consisting of a $50\ \Omega$ resistor in parallel with a $25\ \Omega$ inductive reactance, connected via lines of impedance $(5 + j25)\ \Omega$ to a second load (load 2). Load 2 is a delta-connected and consists of a $150\ \Omega$ resistor in series with a $75\ \Omega$ capacitive reactance. A 415 V three-phase supply is connected to load 1. By transforming load 2 into a star-connected load or otherwise, determine the real and reactive power which is supplied by the 415 V supply. [6]

(e) Determine the value of the delta-connected correction capacitor which, when connected in parallel with load 1, would correct the overall power factor at 50 Hz to 1. [2]

(cont.

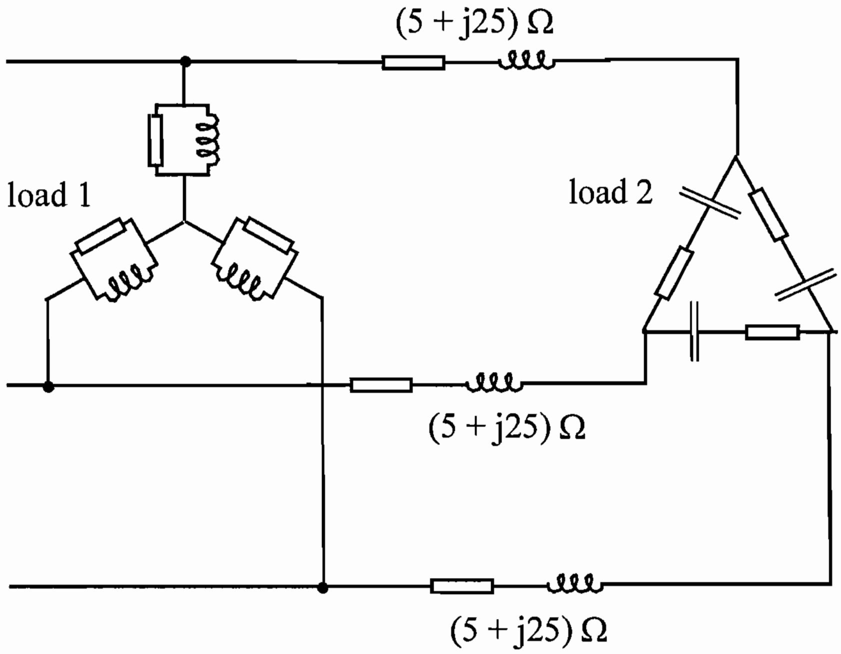

Fig. 3

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4 (a) Explain how the operating chart of a three-phase synchronous generator can be obtained from the voltage phasor diagram for the machine. [4]

(b) A 1000 MVA, 60 kV synchronous generator is star-connected. It has a synchronous reactance of 5 Ω and negligible stator resistance. It is driven by a steam turbine with a rated output of 800 MW. The maximum excitation produces a generated line EMF of 135 kV.

(i) Draw to scale an operating chart for the generator, indicating the various operating limits. [7]

(ii) Explain the physical significance of each of the operating limits [3]

(iii) Calculate numerically the range of power factors at which the rated MVA can be delivered (you must *not* use the scaled drawing produced in part b(i) for this purpose). [6]

(cont.

5 (a) Explain briefly why an induction motor produces torque at all speeds other than the synchronous speed. Make a sketch of a typical torque/speed curve for an induction motor. [4]

(b) Figure 4 shows a simplified equivalent circuit per phase of a 3-phase induction motor, in which the magnetising reactance and iron loss resistance can be ignored. Show that the output torque of the motor is given by

$$T = \frac{3V^2}{(R_1 + R'_2/s)^2 + (X_1 + X'_2)^2} \cdot \frac{R'_2}{s\omega_s}$$

where the symbols have their usual meaning. [6]

(c) Using the maximum power transfer theorem or otherwise, show that the maximum torque developed by the motor occurs at a slip of

$$s = \frac{R'_2}{\sqrt{R_1^{\,2} + (X_1 + X'_2)^2}}$$ [4]

(d) If the induction motor has equivalent circuit parameters of

$R_1 = 5\ \Omega$, $R'_2 = 3.5\ \Omega$, $X_1 = 4\ \Omega$ and $X'_2 = 8\ \Omega$.

and is connected in star to a 3-phase, 50 Hz 415 V supply, determine the speed of rotation of the machine at which the output torque is a maximum and also the net output power at this speed. The number of poles is 6. [6]

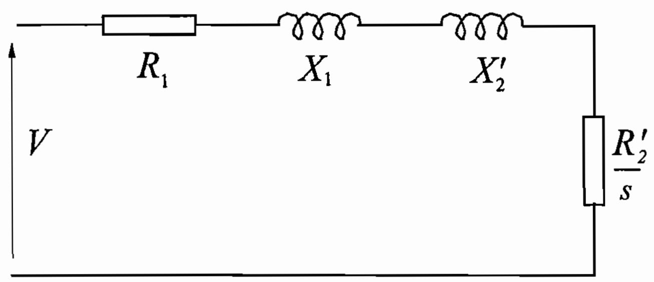

Fig. 4

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SECTION C

*Answer at least **one** question from this section.*

6 (a) Define briefly the characteristic impedance of a transmission line. [2]

(b) A 20 m long coaxial cable has a capacitance per unit length of 80 pF m^{-1}, and an inductance per unit length of 0.2 μH m^{-1}. Calculate the characteristic impedance Z_0 of the cable and the phase velocity. Estimate the transmission frequency at which transmission line effects become significant. [4]

(c) A circuit consists of a 16 V voltage source with internal resistance of 150 Ω, an ideal switch and a 20 m long, loss-free transmission line having a characteristic impedance of 50 Ω. The wave velocity along the line is $v = 2 \times 10^8$ m s^{-1}. The line is terminated by a load impedance Z_L. At time $t = 0$, the switch is closed and remains closed thereafter. Calculate the value of the voltage of the first incident wave that travels from source to load. [4]

(d) Calculate the reflected power from the load, in each of the following cases

(i) $Z_L = \infty$
(ii) $Z_L = 0$
(iii) $Z_L = Z_0$ [6]

For $Z_L = 150\ \Omega$, plot the time variation of the voltage at the midpoint of the transmission line, for up to 0.4 μs after the switch has been closed. Mark on the plot the times and voltages. [4]

(cont.

7 (a) By considering the time harmonic solutions of Maxwell's equations in free-space, determine the speed of propagation of plane electromagnetic waves and comment on your result. Assume that E and H vary only with z and t, and that the only component of E is parallel to the x axis. [4]

(b) If the peak amplitude of the electric field is E_0, obtain the equivalent magnitude of the magnetic field, H_0. Use your results to obtain an expression for the wave impedance of free space. What is the significance of the quantity $\frac{1}{2}E_0H_0$? [4]

(c) A satellite antenna transmits a radio wave through free space, without power loss. The peak power of the wave is 40 W. If the gain of this antenna is 2,000, calculate the peak power intensity at a distance of 25,000 km from the antenna. [6]

(d) A receiving antenna is placed 25,000 km from the satellite. The receiving antenna has an area of $2\ m^2$ and is connected via a $50\ \Omega$ coaxial cable to an amplifier which is perfectly matched to the cable. Calculate

(i) the peak power received by the antenna;

(ii) the RMS current that flows into the receiver. [6]

END OF PAPER