UNIVERSITY OF CAMBRIDGE

ENGINEERING TRIPOS PART IIA

Wednesday 5 May 2004 2.30 to 4

Module 3B4

ELECTRIC DRIVE SYSTEMS

Answer no 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*

There are no attachments

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

(TURN OVER

1 a) An induction motor is wound with a concentrated winding. Assume that the fundamental magnetic field B_g in the airgap varies as the equation

$$B_g(\theta,t) = \sqrt{2}B_{rms}\cos(\omega t - p\theta),$$

where ω is the supply angular frequency and p is the number of pole pairs.

Show that the voltage per phase is directly proportional to the fundamental magnetic field and is therefore given by the following relationship

$$V_{ph} = \left(\frac{ld\omega}{p}\right)NB_{rms},$$

where l is the axial length, d is the diameter of the air-gap and N is the number of turns in the coil. [35%]

b) Using the result from part a) and bearing in mind that the machine rating is an indication of the amount of power that a device can deliver, derive an expression for a three-phase machine's rating in terms of the volume of the airgap, the specific electric loading and the specific magnetic loading. [35%]

c) For the arrangement of teeth shown in Fig. 1, in which the width of the teeth and the slots are the same, produce expressions for the relative magnitudes of the specific magnetic loading $\overline{B}$ and the peak flux density in the teeth $\hat{B}$.

[15%]

d) Give two ways of increasing the specific electrical loading and discuss their relevance to motors of small and large ratings. [15%]

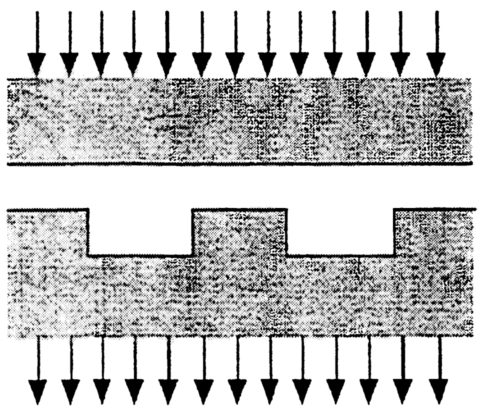


Figure 1

2 a) The 'brushless' dc motor is, in reality, a variable-frequency synchronous machine in which there is an emf $\overline{E}$ induced in the stator by the rotor magnets. Draw an equivalent circuit and write down an expression for the stator supply voltage $\overline{V}_o$. [20%]

b) If you assume that the rotor magnets produce an airgap flux density that is a square wave of magnitude B_m show that the peak induced emf in the stator is given by

$$\hat{e} = \omega_r B_m d N_{ph} l ,$$

where d is the diameter of the airgap, l is the rotor length, N_{ph} is the number of turns per phase and ω_r is the rotor angular velocity. [20%]

c) By considering that the **power flow** in a three-phase brushless dc motor is controlled by an ideal current pulse which is 120 electrical degrees wide, show that the torque is given by

$$T = \phi k I ,$$

where ϕ is the flux per pole and $k = {4pN_{ph}}/{\pi}$ and p is the number of pole pairs. [20%]

d) The motor is run with a duty cycle in which it heats from 80 to 100 °C during four minutes use. The thermal loss during this time is 200 watts. It is then turned off and the temperature returns to 80 °C after a further 90 seconds. The ambient temperature is 20 °C. Calculate the dissipation coefficient k_d and the thermal capacity c of the motor. [40%]

3 a) A vehicle may use either, relative position measurement or, absolute position measurement. Compare and contrast various methods of position measurement. In your answer include at least one method of relative position measurement and up to three absolute position measurement methods. [30%]

b) A vehicle in which the orientation of the wheels is fixed uses differential steering to round a corner. Show that the radius of the motion of the mid-point of the vehicle's axle is given by the formula

$$\frac{b(v_R + v_L)}{2(v_R - v_L)},$$

where v_L and v_R are the velocities of the left and right wheels respectively and b is the wheelbase.

Fig. 2 shows the wheels of a typical train bogey. Calculate the minimum turn radius of a train track which can be rounded without derailing, or the wheels slipping. Assume that the train is travelling at 180 km/hr and that $b = 143.5$ cm , $t = 10$ cm , $r = 60$ cm , $\theta = 2°$ and that both wheels have the same angular velocity. [30%]

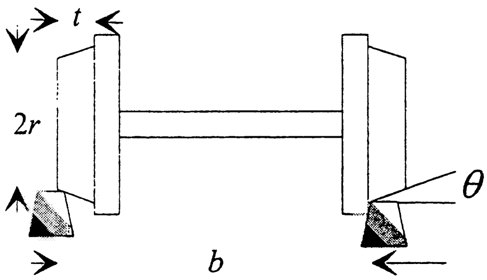
c)

(i) A designer wishes to use the Zeigler-Nichols method to calculate the parameters necessary for PID control of a particular device. He measures the response of the device to a step change and obtains the results given in Table 1.

Plot the data given and mark on your plot the relevant quantities which can be used to estimate the parameters required for PID control. [20%]

(ii) An alternative form of the Zeigler-Nichols method looks at the closed loop response. Describe how this is performed and explain the meaning of the parameters P_u , K_u, K_c , T_d and T_i . [20%]

(Cont.



Note:
r is the radius of left hand wheel at the point of contact.
b is the lateral distance (relative to each wheel) between the point of contact of the left hand wheel and that of the right hand wheel.

Figure 2

Time(s)	**Normalised Response**
1	2.718282
2	7.389056
3	20.08554
4	54.59815
5	148.4132
6	245.4018
7	279.9145
8	292.6109
9	297.2817
10	300

Table 1

(TURN OVER

4 a) The static torque T_A produced by a multi-stack variable reluctance motor with phase A energised is given by

$$T_A = -\frac{1}{2} N_S I_A^2 L \sin(N_S \theta),$$

where N_S is the number of stator teeth, I_A is the phase current and L and θ have their usual meanings.

Given that the minimum torque T_{min} is equal to half of the maximum torque T_{peak}, calculate the maximum average torque for a motor with six teeth and three stacks, in terms of T_{peak}. [25%]

b) By considering the response of a stepper motor to a small excitation show that the natural angular frequency of response is given by

$$\omega = \sqrt{\frac{N_S \hat{T}}{J}},$$

where J is the polar moment of inertia.

[25%]

c) Fig. 3 shows the variation of inductance with θ for a simple two-pole switched reluctance motor. Given that the torque produced is given by

$$T = \frac{1}{2} I^2 \frac{dL}{d\theta},$$

explain why it is important that the voltage is switched on before the inductance starts increasing and sketch curves of the variation of flux linkage, current and torque given a typical voltage waveform. [25%]

d) Given that the current and the inductance are varying simultaneously, derive an equation for the power developed by a typical switched reluctance machine and explain which terms relate to mechanical and which to electrical power. [25%]

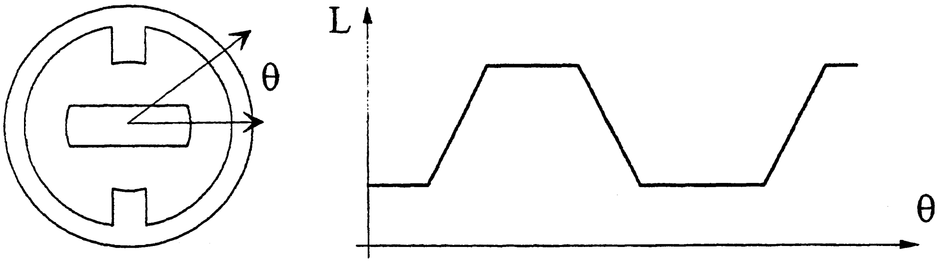


Figure 3

END OF PAPER