EGT2
ENGINEERING TRIPOS PART IIA

Monday 27 April 2015 2 to 3.30

Module 3B4

ELECTRIC DRIVE SYSTEMS

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.

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

1 (a) Briefly describe the main constructional differences between a *trapezoidal* brushless DC motor (BLDCM) and a *sinusoidal* BLDCM. Give two advantages and two disadvantages of a sinusoidal BLDCM compared to a trapezoidal BLDCM. [25%]

(b) For a *trapezoidal* BLDCM, sketch waveforms on the same axes for:

(i) the phase A current; [5%]

(ii) the phase A back-emf; [5%]

(iii) the applied phase A voltage. [5%]

Explain how *Hall-effect* sensors may be used to determine the switching instants of the applied voltages. [10%]

(c) Sketch a phasor diagram for a sinusoidal BLDCM operating with a torque angle of 90° and show that for this case the motor torque is given by:

$$T = 3kI$$

in which k is the emf constant defined as E/ω_s and ω_s is the synchronous speed of the motor . [20%]

(d) A 4-pole, three-phase, star-connected sinusoidal BLDCM has an emf constant of 1.2 $Vsrad^{-1}$ and its rated phase current is 40 A. Its phase inductance is 8 mH and its phase resistance may be neglected. The motor is used within a drive system that maintains the torque angle at 90^0 up to its rated speed, and then operates at the maximum possible load angle for speeds above its rated speed. The system includes an inverter with maximum output frequency and line-line voltage of 80 Hz and 415 V respectively.

(i) Find the rated torque, speed and power of the drive. [10%]

(ii) Find the maximum speed of the drive, and the maximum torque that it can deliver at this speed. [20%]

2 (a) Sketch a cross-sectional view of a two phase, two stack, 4 pole hybrid stepper motor showing the arrangement of the rotor and stator teeth. Explain why the two rotor wheels are offset by half a rotor tooth pitch, and how the two phases are sequentially excited so that the step size is one quarter of a rotor tooth pitch. Show that the full step size for this type of motor is 1.8° if the number of rotor teeth on each rotor wheel is 50. [25%]

(b) Derive the equations for the oscillatory motion about an equilibrium position for a stepper motor and show that the natural frequency f_0 is given by:

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{N_t \hat{T}}{J}}$$

and give the meaning of N_t, $\hat{T}$ and J. [25%]

(c) The stepper motor of part (a) has a peak restoring torque of 0.1 Nm at its rated current. It is to be used to drive the paper feed mechanism of an inkjet printer via a speed reduction gearbox. The paper feed mechanism may be modelled as a pure inertia of 2×10^{-5} kgm^2, with the combined moment of inertia of the rotor with the gearbox being 0.1×10^{-5} kgm^2. Assume that the stepper motor is driven in full-stepping mode and never misses a step.

(i) Find the gearbox ratio required to give a maximum angular position error at the paper feed mechanism of 0.6°. [5%]

(ii) Find the combined moment of inertia of the load, gearbox and rotor, and hence determine the natural frequency of oscillation of the system. [10%]

(iii) Find the motor speed which corresponds to the natural frequency of oscillation, and explain the possible consequence of operating the motor at this speed. [15%]

(d) Determine the maximum required stepper motor excitation frequency if the maximum angular speed of the paper feed mechanism is to be 100 rpm. Give two strategies for attaining this speed without incurring problems due to the natural resonance of the drive system. [20%]

3 (a) Explain what is meant by the terms *specific electric loading* and *specific magnetic loading* in the context of an electrical machine and explain what physical factors limit their values. [10%]

(b) A design for a 22 kW 4-pole delta connected three-phase induction motor for use on a 400 V, 50 Hz supply is required. The expected power factor is 0.8. The machine is to use standard laminations with 48 slots and the air-gap diameter is 175 mm. The allowable specific magnetic and electric loadings are 0.55 T and 30 kA/m respectively.

(i) Calculate a suitable stack length. [5%]

(ii) Design a suitable single layer winding for this machine. [25%]

(iii) What conductor diameter is needed assuming the allowable current density is 5 $\mathrm{Amm^{-2}}$. Comment on this value. [10%]

(iv) Why might a double layer winding be preferred instead? [10%]

The following may be quoted without proof: $\bar{J} = \dfrac{6N_{ph}k_w}{\pi d} I_{ph}$ $\bar{B} = \dfrac{2\sqrt{2}}{\pi} B_{rms}$

$$k_w = \frac{\sin(mp\beta/2)}{m\sin(p\beta/2)}\cos(p\alpha/2) \qquad E_{rms} = \frac{l\omega}{p} d N_{ph} k_w B_{rms} \qquad S = \frac{\pi}{\sqrt{2}}\pi\left(\frac{d}{2}\right)^2 l \frac{\omega}{p}\bar{B}\bar{J}$$

(c) Tests on the machine show that losses of 3 kW in the machine at full load result in a steady state temperature rise of 120 K. Further tests at full load show that a temperature rise of 90 K occurs after 30 minutes.

(i) Find the *dissipation coefficient k* and the *thermal capacity c* of the machine. [15%]

(ii) In an application 50% additional output power is needed when the motor is started. For how long can this level of overload be tolerated? State any assumptions made. [20%]

(iii) What precautions could be taken to prevent damage to the machine if the overload were sustained? [5%]

4 (a) Explain the operating modes of an induction motor drive which uses a variable voltage, variable frequency inverter. What is meant by the terms *constant flux operation* and *field weakening*? [15%]

(b) Sketch the variation of maximum output torque with speed for the drive of part (a). [10%]

(c) Give the assumptions made in deriving the simplified formula for torque T:

$$T = \frac{3V_1^2 s}{\omega_s R_2'}$$ [10%]

(d) A drive uses a star-connected 2.2 kW 4-pole induction motor for use on a 400 V, 50 Hz supply. Rated stator current is 4 A. The machine parameters (measured at 50 Hz) are:

Stator resistance $R_1 = 3.4\ \Omega$

Stator leakage reactance $X_1 = 3.5\ \Omega$

Referred rotor resistance $R_2' = 2.7\ \Omega$

Referred rotor leakage reactance $X_2' = 3.5\ \Omega$

Magnetizing reactance $X_m = 120\ \Omega$

(i) Determine the rated torque for the drive. [15%]

(ii) Find the maximum speed and the corresponding inverter output frequency at which rated torque can be delivered. [10%]

(iii) What excitation frequency is required to get full torque at zero speed? Estimate the terminal voltage required to achieve this. [20%]

(iv) What is the maximum speed in the reverse direction at which full torque can be obtained? [5%]

(e) Why are encoderless motion control systems attractive? Describe one encoderless method of speed control suitable for an inverter-fed induction motor drive. [15%]

END OF PAPER

Numerical answers

1. d) (i) T_{rated} = 144 Nm N_{rated} = 1682 rpm P_{rated} = 25.3 kW (ii) N_{max} = 2400 rpm

T_{max} = 115 Nm

2. c) (i) 3:1 speed reduction (ii) $J_{tot} = 3.22\times10\text{-}6\ kgm^2$ f_0 = 198 Hz (iii) N = 59.5 rpm

d) f = 1 KHz

3. (b) (i) 199 mm (ii) 128 turns per phase (2 phase belts, 4 coils each of 16 turns)
(iii) 2.4 mm   (c) (i) 25 W/K, 32.5 kJ/K   (ii) 765 s

4. (d) (i) 15.5 Nm (ii) 1439 rpm, 50 Hz (iii) 2.05 Hz, 23.1V (iv)1439 rpm

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