ENGINEERING TRIPOS PART IIA

Wednesday 9 May 2012 2.30 to 4

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.*

There are no attachments.

STATIONERY REQUIREMENTS
Single-sided script paper

SPECIAL REQUIREMENTS
Engineering Data Book
CUED approved calculator allowed

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

FINAL version

1 (a) Explain what is meant by the terms *specific magnetic loading* and *specific electrical loading*, and why their values are physically limited. Show that the specific magnetic loading is related to the rms airgap flux density of an electrical machine by:

$$\overline{B} = \frac{2\sqrt{2}}{\pi} B_{rms}$$ [15%]

(b) A 200 kW, 3.3 kV, 50 Hz, star-connected 3-phase induction motor is to be designed with an assumed power factor of 0.8 lagging when operating at rated output power. The motor is to be used to drive a mechanical load at a fixed speed of approximately 300 rpm. The specific magnetic and electrical loadings are to be 0.4 T and 25000 $\mathrm{Am^{-1}}$ respectively. The axial length of the motor is to be twice its airgap diameter.

(i) Find the number of pole-pairs of the motor, its full-load output torque, its airgap diameter and axial length.

(ii) Find the same quantities in (b) part (i) but assuming that a gearbox is fitted between the shaft of the motor and the load with a motor:load speed ratio of 5:1.

(iii) Use your answers to (i) and (ii) to explain why it can be advantageous to use a gearbox in low-speed, high-torque drive applications. [35%]

(c) The motor of (b) part (ii) is to have its stator wound with a balanced three-phase winding in 48 slots. The winding is to be double-layered and short-pitched by two slots. Find the winding factor and the number of turns per phase of the winding. [25%]

(d) If the peak flux density in the stator teeth is limited to 1.8 T, and the maximum allowable current density in the stator winding is 5 $\mathrm{Amm^{-2}}$, estimate the stator tooth width, slot width and slot depth. Assume a slot fill factor of 70%. [25%]

The following may be quoted without proof: $S = \frac{\pi}{\sqrt{2}} \times \pi \left(\frac{d}{2}\right)^2 l \times \frac{\omega}{p} \times \overline{B} \times \overline{J}$

$$k_w = \frac{\sin(mp\beta/2)}{m\sin(p\beta/2)}\cos(p\alpha/2) \qquad E_{rms} = \frac{l\omega}{p} d N_{ph} k_w B_{rms}$$

2 (a) Explain why variable voltage, variable frequency (VVVF) control of induction motors is the preferred method of control in high-performance induction motor drives. Contrast the performance of VVVF induction motor drives with

(i) speed control by varying the rotor resistance and

(ii) speed control by varying the magnitude of the stator voltage only. [25%]

(b) Assuming that a VVVF induction motor drive is controlled so that $V_1 = k\omega$ in which V_1 is the stator phase voltage and ω is the angular supply frequency, derive an expression for the motor torque, T. You should ignore the voltage drop across the stator series impedance, $R_1 + jX_1$. Show that your expression for small slip simplifies to

$$T = 3pk^2\, s\omega / R_2$$

To what part of the torque-speed curve does this correspond, and what is the typical extent of the validity of this simplification? [25%]

(c) A three-phase VVVF induction motor drive uses a delta-connected, 415 V, 50 Hz, 6 pole induction motor with the following parameters (at 50 Hz):

$$R_1 = 2.2\ \Omega;\ X_1 = 0.9\ \Omega;\ R_2 = 1.4\ \Omega;\ X_2 = 4.1\ \Omega;\ X_m = 90\ \Omega.$$

The rated stator current is 20 A. The motor is connected to an inverter with a maximum output voltage of 415 V and maximum output frequency of 100 Hz.

(i) Determine the maximum torque of the drive, and the maximum speed at which this torque can be delivered.

(ii) Determine the maximum unloaded speed of the drive, and the maximum speed at which the drive can deliver 80% of its maximum torque.

(iii) Determine the voltage boost required when operating at rated magnetising current and delivering 10% of the maximum torque at a stator frequency of 2 Hz. [50%]

3 (a) Describe the construction of the three-phase permanent magnet synchronous machine (PMSM). Explain why these machines have negligibly small reluctance torque and small values of synchronous reactance. Also explain why V/ω should be kept constant in PMSM variable speed drives except at very low speeds. [20%]

(b) (i) Draw a phasor diagram for a PMSM motoring at a leading power factor, marking on the load angle δ, the torque angle β, and the angle φ from which the power factor may be found as $\cos\varphi$. You may ignore the effect of the stator winding resistance.

(ii) Using your phasor diagram, and assuming that $V/\omega = E/\omega = k$, show that the torque may be expressed as

$$T = k'I \sin\beta$$

Find the value for k' in terms of other PMSM parameters.

(iii) Explain how the control of the torque angle β may be implemented so that the PMSM behaves like a dc motor. [25%]

(c) An 8-pole, three-phase, star-connected PMSM variable-speed drive has an emf constant k (so that $V/\omega = E/\omega = k$) of 0.3 Vsrad^{-1}, synchronous inductance of 5 mH and phase resistance of 0.2 Ω. The motor has a rated phase current of 50 A. The motor is used within a control system which maintains the torque angle so that the PMSM behaves like a dc motor. This system includes an inverter with maximum output frequency and voltage of 80 Hz and 415 V respectively.

(i) Determine the maximum torque and speed of the drive.

(ii) Determine the inverter frequency and voltage, phase current, load angle and motor power loss when the drive is delivering 50% of its maximum torque at a speed of 600 rpm. [30%]

(d) Radially-magnetised permanent magnets made of N44H (page 7 of the Electrical and Information Data Book) are to be designed to produce a rotor-driven flux density in the airgap of peak value 0.65 T. The airgap length is to be 1.5 mm. Estimate the required thickness of the magnets, stating any assumptions made. [25%]

4 (a) A 2-pole single-phase concentrated winding of N turns produces an mmf distribution around the airgap of a single-phase induction motor as shown in Fig. 1 below when carrying a current of I amps.

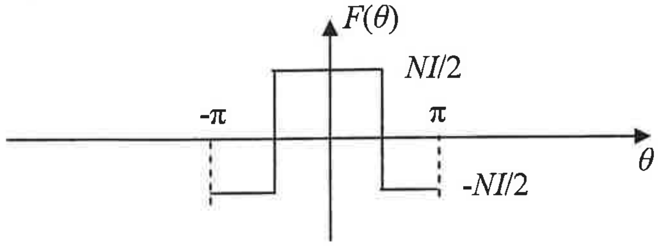

Fig. 1

(i) Show that the fundamental component of this mmf distribution is

$$F(\theta) = \frac{2NI}{\pi}\cos\theta$$

(ii) Assuming that the winding current is given by $I(t) = \hat{I}\cos\omega t$, derive an expression for the mmf as a function of θ and t, and hence show that a single-phase induction motor produces two counter-rotating mmf waves of equal amplitude. [20%]

(b) By considering a single-phase induction motor as the superposition of two induction motors, one with a forwards-rotating mmf wave and the other with a backwards-rotating mmf wave, draw the equivalent circuit of the single-phase induction motor and sketch a typical torque-speed curve. [20%]

(c) A 240 V, 50 Hz, 6 pole, single-phase induction motor has the following parameters: R_1 = 3.0 Ω; $X_1 = X_2$ = 5.0 Ω; R_2 = 4.0 Ω; X_m may be ignored. The motor runs at a speed of 900 rpm. Determine the slip, input current, torque, stator and rotor power loss, output power and efficiency of the motor. [35%]

(d) Explain the principles of using a starter winding to provide a starting torque. Show that if the starter winding is displaced by 90° to the main winding, and its current lags the main winding current by 90°, then the rotating mmf wave produced by the superposition of the main and starter windings may consist only of a forwards-rotating component. [25%]

END OF PAPER

3B4 Electric Drive Systems 2012 Short Answers

1 (b) (i) p = 10, T = 6.37 kNm, d = 0.611 m, l = 1.22 m (ii) p = 2, T = 1.27 kNm, d = 0.357 m, l = 0.715 m (c) k_w = 0.925, N_{ph} = 128 (d) Tooth width = 8.15 mm, slot width = 15.25 mm, slot depth = 13.1 mm

2 (c) (i) Rated torque = 231 Nm, speed = 934 rpm (ii) Maximum unloaded speed = 2000 rpm, maximum speed at 80% rated torque = 1169 rpm (iii) Voltage boost = 6.6 V.

3 (c) Maximum torque = 180 Nm, speed = 1200 rpm (ii) Inverter frequency = 40 Hz, voltage = 283 V line, load angle = 22.6^0, power loss = 375 W (d) Magnet thickness = 1.49 mm

4 (c) Slip = 0.1, input current = 5.04 A, torque = 9.23 Nm, stator loss = 76.2 W, rotor loss = 203 W, output power = 870 W, efficiency = 75.7%