ENGINEERING TRIPOS PART IIA

Friday 26 April 2013 9.30 to 11

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 why electrical machines have a volt-amp rating and show that the volt-amp rating of a three-phase electrical machine may be expressed as

$$S = \frac{\pi}{\sqrt{2}}\pi\left(\frac{d}{2}\right)^2 l\frac{\omega}{p}\overline{B}\overline{J}$$

and define all the terms in this expression. [30%]

(b) A 100 kW, 6.6 kV, 50 Hz, star-connected, 3-phase, 10 pole induction motor is to be designed with a specific magnetic loading of 0.5 T and a specific electric loading of 20 kAm^{-1}. When operating at rated output power, the power factor is 0.8 lagging and the efficiency is 92%. The airgap diameter of the motor is to be four times its axial length. The stator is to be wound with a single-layer balanced three-phase winding in 60 slots. The peak stator tooth and stator core flux densities are to be 1.57 T and 1.4 T respectively. The rms stator winding current density is to be 6 Amm^{-2} and the stator slot-fill factor is to be 70%.

(i) Find the airgap diameter and axial length of the motor. [10%]

(ii) Find the winding factor and the number of turns per phase of the stator winding. [15%]

(iii) Derive expressions for the stator tooth width and the stator core thickness in terms of their respective peak allowable flux densities. [15%]

(iv) Hence find the stator tooth width and core thickness. [10%]

(v) Find the stator slot depth. [10%]

(vi) Hence estimate the total volume of the machine. [10%]

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

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

Final version

2 (a) Sketch a set of torque-speed curves for a three-phase induction motor for the following three cases:

(i) fixed voltage and frequency, variable rotor resistance speed control; [5%]

(ii) variable voltage, fixed frequency speed control; [10%]

(iii) variable voltage, variable frequency (VVVF) speed control. [10%]

Use your sketches to explain the advantages of VVVF speed control for three-phase induction motor drives.

(b) Stating the assumptions made, show that the steep part of the torque-speed characteristic of a three-phase induction motor can be expressed as

$$T = \frac{3V_1^2 s}{\omega_s R_2}$$

Derive an expression for the slope of the steep part of the torque-speed characteristic and hence show that for VVVF speed control in which $V_1 = k\omega$ that this slope is fixed. [25%]

(c) A three-phase VVVF induction motor drive uses a star-connected, 415 V, 50 Hz, 8 pole induction motor with the following parameters (at 50 Hz):

$$R_1 = 1.5\ \Omega;\ X_1 = 1.0\ \Omega;\ R_2 = 1.2\ \Omega;\ X_2 = 0.8\ \Omega;\ X_m = 100\ \Omega.$$

The rated stator current is 15 A. The motor is connected to an inverter with a maximum output voltage of 415 V and maximum output frequency of 150 Hz.

(i) Determine the maximum unloaded speed of the drive, the rated torque of the drive, and the maximum speed at which rated torque can be delivered. [30%]

(ii) Determine the voltage boost required when operating at rated magnetising current and delivering 50% of the rated torque at a stator frequency of 1 Hz. [20%]

3 (a) Describe the key features of a three-phase permanent magnet synchronous machine (PMSM). Why are rare earth magnets normally used in these machines and what precautions are needed to avoid inadvertent permanent demagnetization? [30%]

(b) Draw a phasor diagram for the machine under conditions which give maximum torque per Ampere, ignoring stator resistances. [20%]

(c) (i) Explain how a simple model with a thermal capacity C and a dissipation co-efficient k can be used to predict the temperature of a motor during operation.

Derive an expression for the temperature of a motor after time t when dissipating a power P in an ambient temperature of Θ_o. [20%]

(ii) An excavator for quarry use is fitted with drive motors with a thermal capacity of 5000 J/Kg and a dissipation co-efficient of 10 W/K. When driving into the quarry face, the motor losses are 3.6 kW. Find the temperature rise if the duration of excavation period is 100 s. The ambient temperature is 40 °C. [10%]

(iii) In practice, the excavator is operated repetitively such that the motor cools to 90 °C before the next drive in the quarry face. What is the motor's peak temperature under these conditions? [10%]

(iv) The motor insulation is rated to 125 °C. If the motor exceeds this temperature, what measures should the designer take? [10%]

4 (a) Comment on the relative advantages and disadvantages of hybrid stepper motors and brushless dc motors for small automation applications. [25%]

(b) Why do some small hybrid stepper motors have bifilar windings?

Sketch circuits for exciting one phase of a standard hybrid stepper motor and a bifilar want hybrid stepper motor. [25%]

(c) By considering a small displacement about a step position show that a stepper motor exhibits a natural resonant frequency f_o of

$$f_o = \frac{1}{2\pi}\sqrt{\frac{N_s\hat{T}}{J}}$$

where N_s is the number of steps per revolution, J is the combined moment of inertia of the rotor and load and $\hat{T}$ is the peak torque at a given level of excitation.

How can microstepping be used to reduce the onset of oscillations? [35%]

(d) According to a patent, the torque exerted by a stepper can be deduced from the mean current drawn from the DC supply, assumed to be at fixed voltage. Explain why this is possible, and why this scheme cannot work at zero speed. [15%]

END OF PAPER