Version TJF/4

EGT2
ENGINEERING TRIPOS PART IIA

Monday 18 April 2016 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.*

*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) Give three advantages and three disadvantages of the sinusoidal brushless DC motor compared to the trapezoidal brushless DC motor in the context of electric drive systems. Assuming that the stator winding resistance may be ignored, draw and label a phasor diagram for a sinusoidal brushless DC motor operating at a general torque angle β, and show that the torque may be expressed as

$$T = 3kI\sin\beta \quad .$$

Hence explain why this type of motor is typically operated in a drive application with a torque angle of 90° where possible. Outline the principles of operation of the drive system which ensures this, assuming that the application requires speed control only. [30%]

(b) A 6-pole, three-phase, star-connected sinusoidal brushless DC motor has an emf constant of 0.8 Vs rad^{-1} and its rated phase current is 50 A. Its phase inductance is 4 mH and its phase resistance may be neglected. The motor is used within a drive system that maintains the torque angle at 90° up to rated speed. The system includes an inverter which is matched to the motor and has a maximum output frequency and line-line voltage of 150 Hz and 415 V respectively.

(i) Define and determine the rated speed and rated torque of the drive. [20%]

(ii) Determine the maximum speed of the drive at 50% of rated torque assuming that the torque angle is maintained at 90°. [15%]

(iii) Explain the principle of field-weakening as a means of obtaining speeds greater than rated speed. [10%]

(iv) Determine the maximum speed of the drive at 50% of rated torque assuming that the torque angle is not required to remain at 90°. [25%]

2 (a) Explain the advantages of distributing and short-pitching the stator windings of three-phase induction motors. [10%]

(b) A 6.6 kV, 4 pole, 50 Hz, star-connected three-phase induction motor is to have its stator wound with a balanced three-phase winding in 48 slots. The airgap diameter is 0.4 m, the axial length is 0.8 m and the rms airgap flux density is to be 0.5 T. The winding is to be double-layered and short-pitched by two slots. Draw a diagram to show how the phases of the winding are arranged in the slots of the stator, and find the winding factor and the number of turns per phase of the winding.

The following may be quoted without proof:

$$k_w = \frac{\sin(mp\beta/2)}{m\sin(p\beta/2)}\cos(p\alpha/2) \quad , \qquad E_{rms} = \frac{l\omega}{p} dN_{ph} k_w B_{rms} \quad .$$ [40%]

(c) Explain carefully why variable voltage, variable frequency (VVVF) control is the preferred method of producing variable speed operation with three-phase induction motors. [10%]

(d) 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, $R_1 + jX_1$. Explain the conditions under which the expression simplifies to:

$$T = 3pk^2 s\omega / R_2 \quad .$$ [20%]

(e) A three-phase VVVF induction motor drive uses a star-connected, 415 V, 50 Hz, 4-pole induction motor with the following parameters (at 50 Hz):

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

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 120 Hz. Estimate the rated torque and speed of the drive, and the maximum unloaded speed of the drive. [20%]

3 (a) Give two advantages and one disadvantage of permanent magnet (PM) brushed DC motors compared to their field-wound counterparts. [10%]

(b) A PM brushed DC motor has the cross-section shown in Fig. 1 below. The pole-piece width is 90 mm, the inner radius of the pole-pieces is 100 mm and the airgap length at the pole-pieces is 3 mm. The reluctance of the soft iron may be assumed to be negligible. The PM material used to provide the field is Neodynium-Iron-Boron (NdFeB). The NdFeB magnets have a linear B-H characteristic in the second quadrant, with B_r = 1.25 T and H_c = -940 kAm^{-1}. Determine the length of the NdFeB magnets if the airgap flux density at the pole-pieces is to be 0.8 T. State any assumptions. [30%]

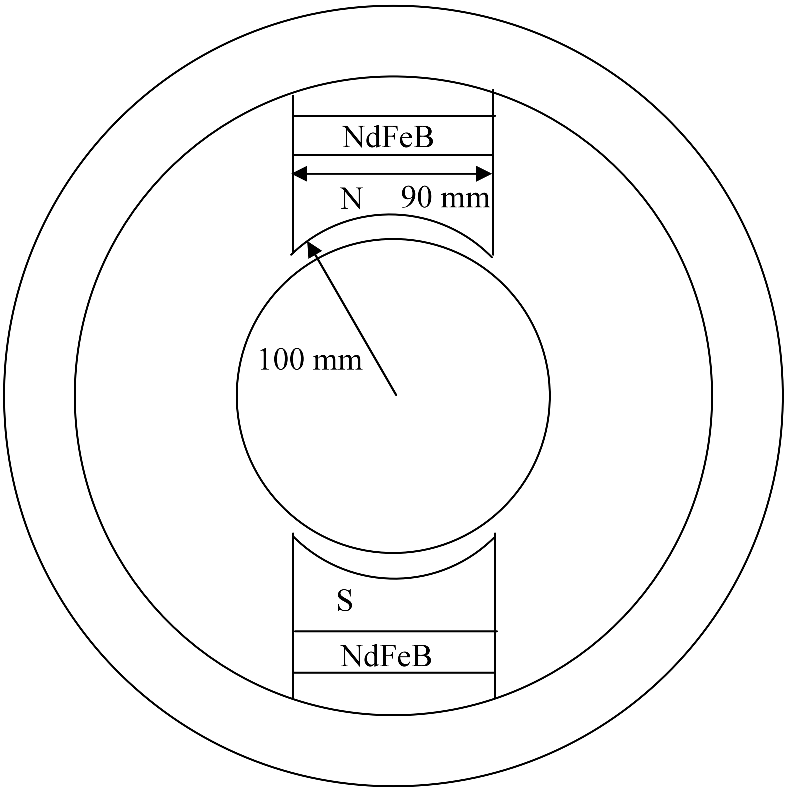

Fig. 1

(c) Explain what is meant by four quadrant drive control, and give an application, with reasons, where this type of control would be appropriate. Draw a full H-bridge circuit to show how this type of control may be implemented, and show the sequence of transistor switching in order to provide forward and reverse motoring with speed control. [20%]

(d) A permanent magnet brushed DC motor produces an open-circuit voltage of 180 V when driven at a speed of 1000 rpm. The motor has an armature resistance of 8 Ω and a rated current of 20 A. It is driven by an H-bridge circuit which is supplied by a 400 V DC power supply. Determine:

(i) the rated torque and speed of the drive; [15%]

(ii) the duty ratio of the H bridge transistors required for the drive to deliver 50% of its rated torque when motoring at a speed of 500 rpm. [15%]

(e) Owing to the cost of NdFeB, a manufacturer of PM brushed DC motors proposes to replace the NdFeB with Ferrite, but without making any other changes to the motor or the drive design. Without performing any calculations, explain how this change will affect the rated torque and rated speed of the drive. [10%]

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4 (a) Give three reasons why single-phase induction motors are frequently found in mass-produced domestic appliances, and give one example of such an appliance. [15%]

(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 its equivalent circuit and sketch a typical torque-speed curve. [15%]

(c) A 240 V, 50 Hz, 8-pole, single-phase induction motor has the following parameters: $R_1 = 2.0\ \Omega$, $X_1 = X_2 = 3.0\ \Omega$, $R_2 = 2.5\ \Omega$. X_m may be ignored. At rated load the motor runs at a speed of 700 rpm. Find the slip, input current, torque, stator and rotor power loss, output power and efficiency of the motor. [35%]

(d) The motor of part (c) is operated at rated load until it reaches thermal steady-state, at which point the motor temperature is 80°C with a 20°C ambient temperature. The motor is then switched off and takes 10 minutes to cool down to 50°C. Find:

(i) the heat capacity and dissipation coefficient of the motor; [15%]

(ii) the minimum and maximum motor temperatures when the motor is run under a periodic duty cycle in which it is operating at rated load for 20 minutes and then switched off for 5 minutes. State any assumptions made. [20%]

END OF PAPER