EGT2
ENGINEERING TRIPOS PART IIA

Tuesday 23 April 2019 2 to 3.40

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
Engineering Data Book
CUED approved calculator allowed

10 minutes reading time is allowed for this paper at the start of the exam.

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 reasons why the Brushless DC Motor (BLDCM) has largely replaced the brushed DC motor for drive applications up to around 200 kW. [10%]

(b) Describe the basic construction of the sinusoidal BLDCM. Draw its per-phase equivalent circuit and the corresponding phasor diagram assuming operation with a 90^{o} torque angle. Explain what is meant by the terms *rated speed* and *rated torque*. Referring to your phasor diagram, explain why Variable Voltage, Variable Frequency (VVVF) control is required if the drive is to maintain rated torque up to rated speed. [20%]

(c) A three-phase, 4 pole, star-connected sinusoidal BLDCM has an emf constant of 2.2 V s rad^{-1} and its rated current is 200 A. The motor is part of an electric drive system and it is supplied from an inverter which is matched to it. The rated line voltage of the motor is 415 V and its phase inductance is 3.2 mH.

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

(ii) Explain how field-weakening can be used to obtain greater speeds at the expense of torque, and find the maximum speed of the drive when delivering 50% of rated torque. Find also the corresponding output power, load angle, torque angle and power factor. [25%]

(d) The rotor-driven flux is provided by surface-mounted permanent magnets made of N44H (see page 7 of the Electrical Engineering Data book). The air gap length is 1 mm and the magnet thickness is 1.5 mm. Estimate the peak air gap flux density, stating any assumptions made. [20%]

(e) Explain in principle how the iron losses of the BLDCM could be estimated at its rated speed and at 50% of its rated speed, assuming VVVF operation at rated flux. [15%]

2 (a) Explain the principle of operation of the *hybrid stepper motor*, making reference to the standard 2-phase, 2-stack hybrid stepper motor with 50 teeth on each of the two rotor wheels. Determine the step angle assuming operation in full-stepping mode. [20%]

(b) A 2-phase, 2-stack hybrid stepper motor with 50 teeth on each of the two rotor wheels has a rated phase current of 4 A and a peak static torque $T = (20 + 50I)$ mN m, where I is the magnitude of the phase current in one of the two phases of the motor.

(i) Explain why there is a static torque even when the phase current is zero, and give an example of why this can be a useful feature of the hybrid stepper motor. [5%]

(ii) Labelling the axes carefully, and on the same axes, sketch graphs of static torque vs rotor position for the cases of zero phase current, 50% rated current and rated current. [15%]

(c) Explain what is meant by full-stepping, half-stepping and micro-stepping. For the case of half-stepping write down the excitation sequence of the two phases of the stepper motor. Determine the peak phase current for half-stepping in terms of the rms rated current, and hence sketch graphs of the phase currents of the two phases vs time for the stepper motor of part (b), on the same axes, assuming a rotational speed of 60 rpm. [20%]

(d) The stepper motor of part (b) is wound with standard single-wire phase windings. Draw a circuit diagram of the drive circuit used in this case assuming that MOSFETs are used as the switches, and explain its operation. If the phase resistance of the stepper motor of part (b) is 0.1 Ω determine the power loss of the stepper motor when operating at rated rms current in full-step mode with one phase excited at a time. Also find the peak value of the MOSFET currents. [20%]

(e) Draw the drive circuit for a stepper motor with a bifilar winding and explain its operation. Explain why bifilar windings are commonly used in low power applications. If the standard winding of the stepper motor of part (d) was replaced with a bifilar winding, resulting in a reduced fill factor of 0.4 compared to 0.6 for the standard winding, estimate the power losses of the motor under the same conditions of part (d) above, stating your assumptions. [20%]

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

(b) A 400 V, 4 pole, 50 Hz, star-connected three-phase induction motor is to have its stator wound with a balanced three-phase winding in 36 slots. The airgap diameter, d, is 0.4 m, the axial length, l, is 0.8 m and the rms airgap flux density, B_{rms}, is to be 0.2 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, N_{ph}. [40%]

The following equations may be quoted without proof:

$$k_w = \frac{\sin\left(\frac{mp\beta}{2}\right)}{m\sin\left(\frac{p\beta}{2}\right)}\cos\left(\frac{p\alpha}{2}\right)$$

$$E_{rms} = \frac{l\omega}{p} d N_{ph} k_w B_{rms}$$

(c) Derive the torque-slip expression for the three-phase induction motor assuming that the stator resistance and stator leakage reactance are small enough to be ignored. Give the names of all symbols used in your expression. [15%]

(d) Assume Variable Voltage, Variable Frequency control of the three-phase induction motor.

(i) Derive the requirements for speed control with constant torque and with constant power, respectively. [20%]

(ii) In motoring operation, sketch the torque-slip characteristic curves to explain how speed changes occur at rated torque. Comment on the changes to the values of the airgap magnetic field and the torque when the required speed is larger than rated speed. [15%]

4 A 1.5 kW, 230 V, 50 Hz, 4 pole single-phase induction motor has been situated for a long time in a space where the ambient temperature is 20 °C. The motor starts running with the following duty cycle:

Run for 10 minutes at half power and full speed, at the end of this period the temperature of the motor has risen to 70 °C;

Rest for 2 minutes, during which time the temperature falls to 40 °C;

Run for 3 minutes at full power and full speed, during which time the temperature rises to 80 °C.

(a) Draw the equivalent circuit for the motor, including both the forward and backward rotor branches. Label all of the components, and the voltages and currents in the circuit, and list the full names and meanings of those labels. [25%]

(b) Determine the heat capacity of the motor, C, assuming that the dissipation coefficient k is equal to 1.2 W K^{-1}. [20%]

(c) Derive an expression for the total mechanical output power, and an expression for the power dissipated in the rotor winding, assuming all leakage reactances and the stator resistance are negligible. The magnetising reactance may be assumed to be very large. [25%]

(d) By considering the last period of the duty cycle, determine the power dissipated in the rotor winding under full load conditions. Hence find the rated slip of the motor. [30%]

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