Version TJF/3

EGT2
ENGINEERING TRIPOS PART IIA

Monday 23 April 2018 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
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 two advantages and one disadvantage of permanent magnet brushed DC motors compared to their field-wound counterparts. Explain what is meant by the term *armature reaction*. [20%]

(b) Sketch the circuit for a DC chopper and explain the principle of the DC chopper for enabling variable-speed operation of brushed DC motors. [20%]

(c) A permanent magnet brushed DC motor has an armature resistance of 3 Ω, a rated current of 15 A and develops an open-circuit voltage of 200 V when driven round at a speed of 1200 rpm. The armature is supplied from a 500 V DC power supply via a DC chopper. Find:

(i) the rated torque of the drive, and the maximum speed that the drive can deliver its rated torque; [15%]

(ii) the maximum speed at which the drive can deliver 50% of its rated torque, and the efficiency of the drive at this torque-speed point; [15%]

(iii) the duty ratio of the DC chopper for the drive to deliver its rated torque at a speed of 500 rpm. [15%]

(d) Explain what is meant by the *electrical time constant* and the *electromechanical time constant* of a DC motor. Explain how these quantities are used in assessing the transient behaviour of an electric drive system based on DC motors. [15%]

2 (a) Explain the principles of operation of the *trapezoidal* Brushless DC Motor (BLDCM) by sketching waveforms showing the current, back emf and applied voltage of one of the phases. Describe the main constructional differences between the trapezoidal and the sinusoidal BLDCM. [25%]

(b) An 8-pole trapezoidal BLDCM is driven round at a speed of 1000 rpm and the measured open-circuit line voltage is 20 V. The phase resistance is 1 Ω and the rated motor current is 5 A. The motor is supplied from an inverter of maximum output frequency 175 Hz, which in turn is supplied from a 40 V DC power supply. Find:

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

(ii) the maximum speed that the drive can attain whilst delivering 25% of its rated torque. [15%]

(c) The drive of part (b) is used to accelerate a mechanical load consisting of a total moment of inertia of 20×10^{-3} kg m^2 and a viscous load. The torque required to drive the viscous load is proportional to its speed, and at a speed of 800 rpm is 0.4 N m. The drive is operated so that the motor is always drawing 4 A from the inverter. Find:

(i) the motor torque and the final speed of the drive; [10%]

(ii) an expression for the drive speed as a function of time; [25%]

(iii) the time taken for the drive to accelerate to 63% of its final speed. [15%]

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3 (a) Derive the torque-slip expression for the three-phase induction motor assuming that the stator resistance and leakage reactance are small enough to be ignored. Sketch the *torque-speed* characteristic for values of slip *s* between 0 and 1. [10%]

Using your torque-slip expression, determine expressions for:

(i) the starting torque; [5%]

(ii) the maximum torque, and its corresponding value of slip. [15%]

Explain how the starting torque can be increased to the peak motor torque. [10%]

(b) When a three-phase induction motor is operated in its normal operating region,

(i) indicate the region on the torque-speed curve, giving a typical slip value; [5%]

(ii) derive a simplified torque-slip expression, stating your assumptions, and determine the slope of the torque-speed curve in the normal operating region; [15%]

(iii) assuming Variable Voltage, Variable Frequency (VVVF) control, give the requirements for speed control with constant torque and with constant power. [15%]

(c) An inverter with maximum output voltage and frequency of 415 V and 150 Hz respectively is used to feed a three-phase, star-connected, 8-pole induction motor. At the rated line voltage of V_1 = 415 V, 50 Hz, the parameters of the motor have been measured as stator resistance $R_1 = 1.5\ \Omega$, stator leakage reactance $X_1 = 1\ \Omega$, referred rotor resistance $R_2 = 1.2\ \Omega$, referred rotor leakage reactance $X_2 = 0.8\ \Omega$, and the magnetising reactance $X_m = 100\ \Omega$. Stating any assumptions find:

(i) the maximum unloaded speed in rpm; [5%]

(ii) the rated speed in rpm and the rated stator current if the rated torque is known to be 136 N m; [10%]

(iii) the voltage boost requirement, including the phase angle with respect to the magnetising voltage, when operating at the rated magnetising current and delivering 50% of the rated torque at a stator frequency of 1 Hz. [10%]

4 A three-phase induction motor is driving a spinning load at the rated output power P_{out} = 9.6 kW at 1458 rpm. The motor has 4 poles and the stator is delta connected. The rated stator voltage is 380 V, 50 Hz. At the rated voltage, the parameters of the motor are: stator resistance R_1 = 1.375 Ω, stator leakage reactance X_1 = 2.43 Ω, referred rotor resistance R_2 = 1.047 Ω, referred rotor leakage reactance X_2 = 4.4 Ω, and the magnetising reactance X_m = 82.6 Ω.

(a) Ignoring only the iron losses of the motor find:

(i) the power factor; [20%]

(ii) the efficiency; [15%]

(iii) the mechanical output power. [15%]

(b) If the thermal capacity of the motor is C and the dissipation coefficient is k,

(i) derive an expression for the temperature of the motor after time t when dissipating a loss power P in an ambient temperature Θ_0; [15%]

(ii) if C = 5000 J kg^{-1} and k = 10 W K^{-1} determine the temperature of the motor after 100 s when operated as described above in part (a). Assume that the starting motor temperature is the ambient temperature of 40 °C; [10%]

(iii) if the motor is operated as described in part (ii), then stopped and allowed to cool to 50 °C before repeating this cycle, determine the peak temperature of the motor; [15%]

(iv) the maximum temperature allowed for the motor is 50 °C. If the motor exceeds this temperature, what measures should be taken? [10%]

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Short answers

1. (c) (i) 23.9 Nm; 286 rads^{-1} (ii) 300 rads^{-1}; 95.6% (iii) 25.6%

2. (b) (i) 0.955 Nm; 157 rads^{-1} (ii) 196 rads^{-1} (c) (i) 0.764 Nm; 160 rads^{-1} (iii) 4.19 s

3. (c) (i) 2250 rpm (ii) 683 rpm; 15.8 A (iii) $11.7\angle -18^0$ V

4. (a) (i) 0.845 lagging (ii) 92.3% (iii) 9645 W (b) (ii) 54.5 ^{0}C (iii) 55.5^{0}C