Version TJF/6

EGT2
ENGINEERING TRIPOS PART IIA

Monday 10 May 2021 9 to 10.40

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 and at the top of each answer sheet.*

STATIONERY REQUIREMENTS
Write on single-sided paper.

SPECIAL REQUIREMENTS TO BE SUPPLIED FOR THIS EXAM
CUED approved calculator allowed.
You are allowed access to the electronic version of the Engineering Data Books.

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

The time taken for scanning/uploading answers is 15 minutes.

Your script is to be uploaded as a single consolidated pdf containing all answers.

1 (a) Describe three advantages and two disadvantages of a brushed DC motor with radially-magnetised permanent magnets, in comparison to its field-wound counterpart. [10%]

(b) Give three reasons why the sinusoidal Brushless DC Motor (BLDCM) would be a preferred choice for an all-electric passenger vehicle. Give two reasons why, for other applications, the trapezoidal BLDCM would be a preferred choice. [10%]

(c) A four-pole trapezoidal BLDCM is driven round at 2000 rpm and the measured open-circuit voltage is 24 V. The per phase resistance is 1.5 Ω and the rated motor current is 4 A. The motor is supplied by a voltage-fed inverter that has a DC supply voltage of 48 V. Find:

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

(ii) the maximum speed of the drive while delivering 50% of its rated torque; [5%]

(iii) the corresponding duty cycle of the inverter transistors when operating at 10% and 50% of the maximum speed in (ii). [5%]

(d) The drive in (c) is used to accelerate a mechanical load consisting of a total moment of inertia of 20×10^{-3} kg m^2 and a fan such that the load torque due to the fan varies with its angular speed squared. The torque due to the fan is 0.15 Nm at 1500 rpm. The drive is always operated so that the motor draws 3 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 95% of its final speed. [10%]

(e) Explain, using a sketch of the waveforms of the applied phase and sensor voltages, the operating principle of a sensored BLDCM drive system. Describe a situation for which a sensored BLDCM drive would be preferred over a sensorless one. [15%]

2 (a) A standard two-phase, two-stack hybrid stepper motor with 50 teeth on each of the rotor wheels has a peak restoring torque of 600 mN m at its rated current of 1 A. The total combined moment of inertia of the purely inertial load and the rotor is 3.2×10^{-5} kg m^2.

(i) Derive the equation for the oscillatory motion about an equilibrium position for the stepper motor and show that the natural frequency f_0 is given by:

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{N_t \hat{T}}{J}}$$

defining all of the terms N_t, $\hat{T}$ and J. [25%]

(ii) Assuming full-stepping operation, one phase excited at a time, determine the stepper motor speed at which the oscillation frequency coincides with the stepping frequency. [5%]

(iii) Explain what problem might occur if the stepper motor was operated at this speed for a long time and describe two methods that could be used to avoid this problem. [10%]

(iv) Sketch the phase current waveform for one of the phases, assuming full-stepping, and determine the maximum amplitude of the phase current in this mode of excitation. [10%]

(v) Give the excitation sequence if the motor were operated in half-stepping mode, sketch the phase current waveform for one of the phases in this case, and determine the maximum amplitude of the phase current. [15%]

(b) (i) Draw a phasor diagram, clearly labelling all quantities and angles, of the hybrid stepper motor when operating at speed in full-step mode, taking into account only the fundamental frequencies of all electrical quantities. [15%]

(ii) The motor has phase resistance 1.6 Ω, phase inductance 4.8 mH and an emf constant of 1.4 V s rad^{-1} . The motor is controlled so that it operates at its rated current (see (a)) at a lagging power factor of 0.9, and at a speed of 150 rpm, with a load angle of 10 degrees. Find the excitation frequency, phase voltage, input power, power loss, output power and torque. [20%]

3 A 690 V, 4 pole, 50 Hz, 13.8 kW, star-connected three-phase induction motor has a laminated stator with 48 slots. The airgap diameter d is 0.3 m, the axial length l is 0.5 m, the stator diameter is 0.5 m, and the specific magnetic loading $\bar{B}$ is to be 1.1 T. The winding is to be double-layered and short-pitched by two slots. The flux density at the knee point of the $B-H$ curve of the silicon steel used in the laminated stator is 2.2 T.

(a) Draw a diagram to show how the phases of the winding are arranged in the slots of the stator, and find the RMS flux density, B_{rms}, the winding factor, k_w, the number of turns per phase, N_{ph}, and the number of turns per coil, N_{coil}. The following equations may be quoted without proof:

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

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

[40%]

(b) Calculate the specific electric loading, $\bar{J}$, of the machine. State the unit of $\bar{J}$. Also give the physical meanings of the specific electric loading and specific magnetic loading. [20%]

(c) Determine whether it is sensible to design the slot width, w_s, and the tooth width, w_t, to be identical for the stator of this machine. Justify your answer by giving your calculation and explanation. [20%]

(d) Calculate the peak value of the flux density in the yoke of the stator core if the stator slots have a depth of 3 cm. Determine whether the power rating of this machine can be further increased by increasing the specific electric loading. Show your calculations and explanation. [20%]

4 A 2 kW single-phase induction motor is used for a pump. The efficiency of the motor is 90%.

(a) The thermal capacity of the motor, C, is 1000 J kg^{-1} and its dissipation coefficient, k, is 2.5 W K^{-1}. Determine the temperature rise when operating at the rated power for 100 s. The motor is initially at the ambient temperature of 40 °C. [20%]

(b) If the motor is operated at the rated power for 100 s, then stopped and allowed to cool to 50 °C before repeating this cycle, determine the peak temperature of the motor. [20%]

(c) Draw the equivalent circuit for the machine, including both the forwards and backwards 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. [20%]

(d) Sketch the forward, backward and overall torque-slip characteristic curve of the single-phase machine. State both the forward and backward slips. Comment on the starting torque of the single-phase machine. [20%]

(e) In order to maximise the starting torque, an additional winding can be used. State and explain the requirements of this additional winding and its current for achieving the maximum starting torque. Sketch the schematic circuit of the capacitor starting method, and draw the phasor diagram of the applied voltage, main winding current and the capacitor current when starting a single-phase induction machine. [20%]

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Short answers
1 (c) (i) 0.458 N m, 3000 rpm (ii) 3500 rpm (iii) 25.6%, 78.1%
(d) (i) 0.344 N m, 2271 rpm (ii) 25.3 s
2 (a) (ii) 46.2 rpm (iv) 1.414 A (v) 1.115 A
(b) (ii) 125 Hz, 26.1 V, 47 W, 3.2 W, 43.8 W, 2.79 N m
3 (a) 1.22 T, 0.925, 15, 1 (b) 1009 A m^{-1} (d) 1.3 T
4 (a) 19.64 °C (b) 67.3 °C