Version TJF/4

EGT2
ENGINEERING TRIPOS PART IIA

Thursday 2 May 2024 9.30 to 11.10

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 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.

You may not remove any stationery from the Examination Room.

1 (a) Sketch the per-phase equivalent circuit of a three-phase induction machine under variable-voltage, variable-frequency (VVVF) control, and name all the elements. Split the rotor resistance into two components, one that represents power loss and one that represents the power transfer to mechanical power. [10%]

(b) Derive an expression for the torque as a function of slip. You may simplify the equivalent circuit if you state your assumptions. Sketch an equivalent circuit that reflects your assumptions. [20%]

(c) What are the control parameters of a VVVF induction motor drive? Explain how they are used to vary the torque-speed characteristic of the drive. [10%]

(d) Geometrically identical rotors are available in two versions, one with copper, the other one with aluminium conductors in the rotor. When used within the same stator, discuss how you would expect the maximum torque to differ. How would the slip at maximum torque quantitatively change for the same load torque? Which of the two rotors would spin up faster? Take the conductivity of copper to be $\approx 5.5 \times 10^7$ S m^{-1} and that of aluminium $\approx 3.5 \times 10^7$ S m^{-1}. [20%]

(e) A VVVF inverter (0 - 450 V line voltage, 0 - 500 Hz) drives an induction machine of an electrical vehicle. The electrical machine has a three-phase stator winding with star configuration and four poles. The stator resistance R_1 = 100 mΩ, stator leakage inductance L_1 = 50 µH, referred rotor resistance R_2' = 100 mΩ, referred rotor leakage inductance L_2' = 30 µH, and the magnetising inductance L_m = 3 mH.

(i) Estimate the maximum speed in rpm. [10%]

(ii) The car should be marketed as a sports car. Find the maximum torque at stand-still for this motor assuming that the inverter would use $50\sqrt{3}$ V (line voltage) and 15 Hz. [10%]

(iii) Estimate the slip, the speed and the stator current magnitude at a load torque of 25 N m at 200 V (line voltage) and a frequency of 100 Hz. [20%]

2 (a) Multiphase electric machines typically generate a rotating magnetic field with their stator winding. Two different winding concepts are concentrated and distributed windings. Explain each winding concept and compare them. [10%]

(b) Explain the role of the phase band number m of a winding. Why would a designer increase the phase band number? What disadvantage can a high phase band number have? [20%]

(c) Describe the concept of short-pitching. Why do motor designers short-pitch windings? What changes on the stator slot level? [20%]

(d) Briefly explain the concept of magnetic loading. What typically limits the magnetic loading? The same motor is operated at two different mechanical operating points, one with higher magnetic loading than the other one. What does this indicate about torque and speed at these two operating points? [20%]

(e) Briefly discuss how doubling the air gap length might affect a motor that is operated notably below its rated load. Also explain how doubling the air gap length affects the parameters in the equivalent circuit models of brushless DC motors and induction motors, quantifying your answers where possible. [15%]

(f) Explain the trend for high-performance motors, for example in electric cars, towards higher rotational speeds. Which elements of a motor typically limit the speed? [15%]

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3 (a) Explain the main constructional differences between a sinusoidal brushless DC motor (BLDCM) and a trapezoidal BLDCM. Sketch a cross sectional view of a trapezoidal BLDCM with 12 stator poles and 8 rotor poles. Label your sketch to show the orientation of the permanent magnets and the layout of the stator windings. [15%]

(b) A trapezoidal BLDCM with 12 stator poles and 8 rotor poles has phase resistance of 0.5 Ω, phase emf constant 0.4 V s rad^{-1} and rated current of 8 A. Its phase inductance may be neglected.

(i) If the motor rotates at 400 rpm and is operating at its rated current, sketch graphs of the phase A back emf, phase A applied voltage and phase A current as functions of time, all on the same axes. Pay careful attention to the peak values and time periods of all quantities. [15%]

(ii) The motor is required to accelerate a purely inertial load with combined moment of inertia of the rotor and load of 0.1 kg m s^{-2}. The motor is supplied by a voltage-fed inverter which has a DC supply voltage of 100 V. If the motor is controlled to operate at rated current for the entire acceleration, find the time taken to accelerate the load from 0 to 1000 rpm, and the overall efficiency of the drive when performing this operation. Assume that the inverter is 95% efficient at all loadings. [15%]

(iii) Explain, with the aid of a sketch, how Hall effect sensors may be utilised in a sensored BLDCM drive system to determine the switching instants for the applied phase voltages. Also explain the principles of operation of sensorless drives based on the trapezoidal BLDCM, and give two situations where a sensored drive would give improved performance compared to a sensorless one. [15%]

(c) A 3-phase, delta-connected, 6 pole, sinusoidal BLDCM has the following parameters: emf constant of 2 V s rad^{-1}, rated phase current of 35 A and phase inductance of 10 mH. Its phase resistance may be neglected. It is supplied by an inverter with maximum frequency and line-line voltage of 120 Hz and 400 V, respectively.

(i) Draw a general phasor diagram for the sinusoidal BLDCM, and show that its torque is given by $T = 3kI \sin\beta$, defining all terms. [10%]

(ii) Find the rated torque, speed and power of the drive. [10%]

(iii) Find the maximum speed of the drive, the maximum torque it can provide at this speed, and the corresponding torque and load angles. [20%]

4 (a) Give two reasons why field-wound brushed DC motors are still found in low power mass-produced goods. Give one advantage of replacing the field winding with permanent magnets. [15%]

(b) A field-wound brushed DC motor has a separate voltage supply for its field and armature windings. The field winding supply uses a DC chopper circuit whereas the armature voltage supply is a full H-bridge. The H-bridge and the DC chopper are both supplied from a 50 V DC power supply.

(i) Draw the circuit of the DC chopper and explain its principle of operation. [10%]

(ii) Draw the circuit of the full H-bridge, and explain how its transistors are controlled to achieve variable speed forward and reverse motoring operation. [10%]

(c) The motor of part (b) has the following specifications: field winding resistance and rated field current (rated field current produces rated flux) are 40 Ω and 1 A, respectively; armature resistance and rated armature current are 0.5 Ω and 20 A, respectively. When driven round at 1000 rpm, the measured open-circuit armature voltage with the field winding supplied at its rated current is 25 V. The motor's field and armature windings are supplied as detailed in part (b) to form a drive system.

(i) Find the rated torque and rated speed of the drive, and the corresponding duty ratio of the DC chopper transistor. [15%]

(ii) Find the maximum speed of the drive when delivering a torque of 10% of rated torque, and the corresponding duty ratio of the DC chopper transistor. [10%]

(d) In order to reduce costs, it is proposed to replace the motor of part (c) with a permanent magnet equivalent. The replacement motor utilises the same armature design, and the permanent magnets are such that the rated field flux is unchanged. Determine the torque-speed characteristic of the replacement motor, and explain why it may not be able to function effectively as a replacement motor. Also explain how the drive based on the replacement motor could be modified so that it becomes a viable replacement. [20%]

(e) Explain the significance of the electromechanical time constant when determining the transient behaviour of electrical drive systems based on DC motors. Derive an expression for the electromechanical time constant of a permanent magnet brushed DC motor with back emf constant k, armature resistance R_a and armature moment of inertia J. Assume that the armature inductance is negligible. [20%]

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Short answers

1 (e) (i) 15000 rpm (ii) 400 N m (iii) 0.02, 2940 rpm, 63.1 A

3 (b) (ii) 1.6 s, 80% (c) (ii) 210 N m, 1690 rpm, 37.2 kW (iii) 2400 rpm, 165 N m, β=128°, δ=31.4°

4 (c) (i) 4.77 N m, 1600 rpm, 0.8 (ii) 16000 rpm, 0.08