Version TJF/2

EGT2
ENGINEERING TRIPOS   PART IIA

Monday 9 May 2022   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) Describe the main constructional differences between a trapezoidal brushless DC motor (BLDCM) and a sinusoidal BLDCM. [10%]

(b) A three-phase, 6-pole, star-connected sinusoidal BLDCM has an emf constant of 1.8 V s rad^{-1} and its rated current is 150 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, its phase inductance is 2.8 mH and its phase resistance is negligibly small.

(i) Assuming that the BLDCM is controlled so that its torque angle is maintained at 90°, find the rated speed and the rated torque of the drive. [10%]

(ii) Find the maximum speed of the drive with a load torque of 70.7% of rated torque, assuming that the torque angle remains at 90°. [10%]

(iii) Explain the term 'field-weakening', and by use of a phasor diagram, show how field-weakening can be used to obtain greater speeds at the expense of torque. Find the maximum speed of the drive when delivering 70.7% of rated torque assuming now that the torque angle is no longer contrained to 90°. Find also the corresponding output power and load angle. [30%]

(c) A trapezoidal BLDCM is driven round at 800 rpm and the measured open-circuit line-line voltage is 30 V. A measurement of the resistance between two of the stator terminals (the neutral is not available) gives 1.2 Ω. The inverter driving the motor is supplied from a 48 V DC power supply, and the maximum inverter frequency is 175 Hz. The rated drive current (meaning the DC current drawn from the power supply) is 5 A. Determine:

(i) the emf constant of the motor; [5%]

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

(iii) the rms phase current of the motor when delivering rated torque; [10%]

(iv) the maximum speed that the drive can attain whilst delivering 50% of rated torque, and the overall drive efficiency assuming that the inverter is 95% efficient at this torque-speed point. [15%]

2 (a) Permanent magnet brushed DC motors, and stepper motors, are often found in low-power, lost-cost consumer products. By detailing the characteristics of these motors, give an example of a typical application area in each case. [10%]

(b) A permanent magnet brushed DC motor is driven round at 1000 rpm, and its open-circuit voltage is measured to be 12 V. Its rated current is 3 A, and its armature resistance is 2 Ω.

(i) Find the emf constant of the motor, its rated torque, rated speed and maximum speed when connected to a 20 V DC power supply. Asssume that the load torque on the motor is zero, and that you can ignore any loss torque. [20%]

(ii) Hence sketch a torque-speed characteristic of the motor, assuming that it is incorporated into a drive system which limits the armature current to its rated value up to rated speed, and thereafter limits the armature voltage to 20 V. [10%]

(c) The drive system of part (b) is used to accelerate an inertial load of 0.05 kg m^2 from rest up to a speed of 1400 rpm. By considering the torque-speed characteristic of the drive, determine the time taken for the acceleration. Explain why a field-wound DC motor might be a better option if a significantly greater range of speeds was required. [30%]

(d) A standard two-phase, two-stack hybrid stepper motor with 50 teeth on each of the two rotor wheels has a rated current of 2 A. At rated current, with one phase excited, its peak static torque is 250 mN m. It is proposed for use in an application which requires accurate position control.

(i) Explain the term 'position error' as applied to stepper motors, and sketch a graph of static torque against rotor position. [10%]

(ii) Determine the angular position error when one phase of the motor is excited with a current of 1.5 A and a load torque of 100 mN m is applied. [5%]

(iii) The manufacturer of the motor states that when the motor is unloaded and tested at rated current in full-stepping mode, the speed of 5 rpm should be avoided. Explain why the manufacturer states this, and give two ways that the problem can be avoided. Use this information to estimate the moment of inertia of the stepper motor. [15%]

You may quote $f_0 = \frac{1}{2\pi}\sqrt{\frac{N_t\hat{T}}{J}}$ without proof.

3 (a) State the meaning of the terms 'specific electric loading' and 'specific magnetic loading' when applied to motor design. [10%]

(b) An electrical machine has p pole-pairs, axial length l and air gap diameter d. The rms value of the fundamental component of the air gap magnetic field is B_{rms} and the specific electric loading is $\overline{J}$. Assuming a three-phase concentrated winding with N_{ph} turns per phase derive, from first principles, expressions for:

(i) the specific magnetic loading, $\overline{B}$, in terms of B_{rms}; [5%]

(ii) the induced voltage in the stator winding; [10%]

(iii) the rated VA of the machine in terms of its specific magnetic and electric loadings, its volume and its angular speed. [10%]

You may quote the result $\overline{J} = \frac{6N_{ph}I_{ph}}{\pi d}$ for a three-phase concentrated winding with rms phase current I_{ph}.
Comment on the harmonic content of the air gap magnetic field in the case of a concentrated winding compared to a distributed winding. [5%]

(c) A three-phase motor is required for an electric vehicle. The desired continuous peak output power of the motor is 50 kW. The efficiency and power factor at the peak output power are 80% and 0.85 respectively. The rotational speed of the motor is 6000 rpm. Assuming a specific electrical loading of 30000 A m^{-1} and a specific magnetic loading of 0.5 T, estimate the volume of the rotor required. [30%]

(d) The stator winding of this motor needs to be designed. The rotor diameter chosen is 240 mm and the air gap length is negligible. The winding is delta-connected and the line voltage is 260 V. The motor has 8 poles and the stator has 48 slots. The winding is short pitched by one slot. Determine the number of turns per coil, the number of turns per stator slot, and the number of turns per phase. [30%]

The following equations for the distribtion and pitch factors may be quoted without proof:

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

4 (a) Sketch the torque-speed characteristic curve of a three-phase induction machine for each of following control methods:

(i) varying the rotor resistance; [5%]

(ii) varying the magnitude of the stator voltage only; [5%]

(iii) variable voltage, variable frequency (VVVF) control. [5%]

Referring to the torque-speed characteristic curves, give two advantages of using VVVF control for induction machine drives. [5%]

(b) Draw the equivalent circuit of a three-phase induction machine, labelling each element of the equivalent circuit with the appropriate symbol. Write down a list of all of the circuit elements, including the appropriate frequency in the case of inductances. Explain the stator voltage and frequency relationship for applying VVVF control. [20%]

(c) A universal series motor is connected to a variable DC source voltage, and a variable mechanical load for testing. Measurement from the tests are recorded in the table below.

Test	Input voltage [V]	Input current [A]	Rotational speed [rpm]
Test 1	7	2	60
Test 2	14.3	3	90

The same motor is now connected to a single-phase AC supply of 110 V, 60 Hz and is driving a pump. The input current is 8 A and the rotational speed is 270 rpm. If the mechanical friction loss of the motor is negligible, determine:

(i) the average torque; [20%]

(ii) the power factor and the efficiency of the motor at this operating point. [20%]

(d) A different electrical machine has a rated output mechanical power of 1 kW. The efficiency of this motor is 90% at half-load. The motor is run as follows:
run for 10 minutes at half-load, and the temperature rises from the ambient temperature of 20 °C to 70 °C;
rest for 2 minutes and the temperature falls to 40 °C.
Determine the dissipation coefficient and the heat capacity of the motor. [20%]

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Short answers

1 (b) (i) 1041 rpm, 810 N m (ii) 1139 rpm (iii) 1798 rpm, 108 kW, 44.4°

(c) (i) 0.179 V s rad^{-1} (ii) 1.79 N m, 1120 rpm (iii) 4.08 A (iv) 1200 rpm, 89.1%

2 (b) (i) 0.115 V s rad^{-1}, 0.344 N m, 1167 rpm, 1667 rpm

(c) 22.5 s (d) (ii) 0.64° (iii) 0.00114 kg m^2

3 (c) 0.00373 m^3 (d) 3, 6, 48

4 (d) 0.794 W K^{-1}, 104 J K^{-1}