EGT2
ENGINEERING TRIPOS PART IIA

Tuesday 09 May 2023   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) Name four electrical machine types and their respective magnetic principles of torque generation. Name at least one such electrical machine design and briefly explain how the two principles of torque generation work. Explain one key difference between these two torque-generating principles. [20%]

(b) Why do electrically excited DC machines and brushless DC machines differ with respect to the power density? Give at least three reasons. [20%]

(c) Explain the major trend towards higher speeds in variable speed drives. Discuss two major limitations for this effort. [20%]

(d) The torque in brushless DC and synchronous machines has a strong dependence on the angle between the stator and the rotor poles, also called the torque angle. Sketch a diagram for the torque angle and indicate in which range the brushless DC machine is typically operated. Mark the section for motoring and generating, respectively. How does the curve change if the voltage amplitude is increased? [20%]

(e) Discuss the requirement of permeability of the permanent magnet used in electrical machines. Compare the soft magnetic ferrite materials and silicon-steel in terms of magnetic properties. [20%]

2 The air intake of a future hydrogen ship uses a compressor with an air-cooled three-phase permanent-magnet motor with $k_V = 1900\,\mathrm{V^{-1}min^{-1}}$. The phase voltage is 48V and the continuous phase current is 200A. The phase current can reach 450A for 10 seconds.

(a) Calculate the maximum torque the motor can generate at 200A. [20%]

(b) Assume that the motor has relatively simple thermal behaviour and the dominant loss is the winding loss and the short-term overloading starts from room temperature. The power rating of this motor is only limited by heat dissipation. Estimate the maximum current for operating 30 seconds and 60 seconds, respectively. [30%]

(c) Describe the speed change with respect to the torque. Calculate the speed of the motor limited by the voltage supply? [20%]

(d) A voltage drop could be generated to partially compensate the back EMF, thus allowing the use of a lower supply voltage to drive the motor beyond the voltage limitation. Explain how this compensation works using an equivalent circuit. Give the phase relationship between the AC current and the back EMF. [30%]

3 (a) Give the definition of the electrical loading and the magnetic loading used in describing the power rating of an electrical machine. Derive the power of a three-phase electrical machine as

$$S = \left(\frac{\pi}{\sqrt{2}}\right)\left(\frac{l\pi d^2}{4}\right)\left(\frac{\omega}{p}\right)\bar{B}\bar{J}$$

and define all the terms in the expression. [40%]

(b) A $100kW$, $6.6kV$, $50Hz$, star-connected, three-phase, 10 pole induction motor is to be designed with a specific magnetic loading of $0.5T$ and a specific electric loading of $20\text{kA} \cdot m^{-1}$. When operating at the rated output power, the power factor is 0.8 lagging and the efficiency is 92%. The air gap diameter of the motor is four times its axial length. The stator is to be wound with a single-layer balanced three-phase winding in 60 slots. The peak stator tooth and stator core flux densities are to be $1.57T$ and $1.4T$, respectively. The RMS stator winding current density is to be $6\text{A} \cdot mm^{-2}$ and the stator slot-fill factor is to be 70%.

(i) Find the airgap diameter and axial length of the motor. [10%]

(ii) Find the stator winding factor and the number of turns per phase. [15%]

(iii) Find the width and depth of the stator tooth and the core thickness. [25%]

(iv) Estimate the total volume of the machine. [10%]

The following may be quoted without proof

$$\bar{J} = \frac{6N_{ph}k_w}{\pi d}I_{ph}$$

$$\bar{B} = \frac{2\sqrt{2}}{\pi}B_{rms}$$

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

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

4 (a) Sketch a set of torque-speed curves for a three-phase induction motor for the following two cases:

(i) variable voltage, fixed frequency speed control;

(ii) variable voltage, variable frequency (VVVF) speed control.

Use your sketches to explain the advantages of VVVF speed control for three-phase induction motor drives. [30%]

(b) Derive the expression of the torque-speed characteristic of a three-phase induction motor as

$$T = \frac{2{V_1}^2 s}{\omega_s {R_2}'}$$

For VVVF speed control, derive the expression $V_1 = k\omega$. State all the assumptions made. [20%]

(c) A three-phase VVVF induction motor drive uses a star-connected, $415V$, $50Hz$, 8-pole induction motor with the following parameters (at $50Hz$):

$$R_1 = 1.5\ \Omega;\ X_1 = 1.0\ \Omega;\ {R_2}' = 1.2\ \Omega;\ {X_2}' = 0.8\ \Omega;\ X_m = 100\ \Omega.$$

The rated stator current is $15A$. The motor is connected to an inverter with a maximum output voltage of $415V$ and maximum output frequency of $150Hz$.

(i) Determine the maximum unloaded speed of the drive, the rated torque of the drive, and the maximum speed at which the rated torque can be delivered. [20%]

(ii) Determine the voltage boost required when operating at the rated magnetising current and delivering 50% of the rated torque at a stator frequency of $1Hz$. [30%]

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