Data Provided: Two sheets of linear-linear graph paper

The University Of Sheffield.

DEPARTMENT OF ELECTRONIC AND ELECTRICAL ENGINEERING

Spring Semester 2010-2011 (2 hours)

EEE6120 Modelling of Electrical Machines 6

Answer **THREE** questions. **No marks will be awarded for solutions to a fourth question.** Solutions will be considered in the order that they are presented in the answer book. Trial answers will be ignored if they are clearly crossed out. **The numbers given after each section of a question indicate the relative weighting of that section.**

1. a. Draw the Kron primitive equivalent circuit of a series universal motor and derive the form of the governing terminal voltage equations which are applicable to its operation on a sinusoidal AC supply. **(3)**

b. A domestic washing machine is driven by a 2-pole universal series motor which is connected to a 230Vrms, 50Hz, sinusoidal AC mains supply. The drum of the washing machine is connected to the shaft of the motor via a belt drive, such that the motor shaft rotates at 14 times the rotational speed of the drum. The motor has a measured resistance between its two terminals of 3.9Ω.

During the high-speed spin cycle of the washing machine, the motor produces a mechanical output torque of 0.51Nm at a speed of 17,200rpm. The copper loss in the motor windings at this operating point is 323W.

i) Calculate the magnitude of the current at this high-speed spin operating point. **(2)**

ii) Calculate the efficiency at this high-speed spin cycle operating point (you may assume that the iron losses in the stator and rotor cores are negligible when compared to the copper losses). **(2)**

iii) Calculate the total self-inductance of the motor between its two terminals. **(4)**

iv) Calculate the power factor at this high-speed spin cycle operating point. **(2)**

c. During the low-speed main wash cycle of the machine, an electronic controller reduces the effective voltage applied to the machine to a 92Vrms, 50Hz, sinusoidal AC waveform. The torque produced by the motor during this wash cycle is 0.1Nm

i) Calculate the speed of the washing machine drum during this low-speed wash cycle. **(3)**

ii) Calculate the power factor of the motor during this low speed wash cycle. **(2)**

iii) Calculate the efficiency (again you may neglect iron losses in the motor). **(2)**

2. **a.** Starting from the Kron primitive equivalent of a non-salient three-phase, squirrel cage induction motor, derive the voltage equations and a corresponding exact equivalent circuit for steady-state operation with a sinusoidal AC supply. **(8)**

b. A coolant circulation pump on a nuclear power plant is driven from a two-pole, star-connected, three-phase induction machine. The machine has no saliency and is connected to a 3300V (rms line to line) 50Hz three-phase sinusoidal AC mains supply. The motor has the following per-phase equivalent circuit parameters:

Stator resistance= 0.09Ω	Stator leakage reactance = 0.26 Ω
Referred rotor leakage reactance = 0.24Ω	Referred rotor resistance = 0.16 Ω

In order to account for the core losses, the per-phase equivalent circuit derived from the Kron primitive is enhanced by including a resistor across the stator terminals which dissipates the corresponding real power. During initial commissioning, the machine is tested on no-load at full rated voltage. For this operating point, the machine draws a no-load per phase current of $20\angle\text{-}85°$A. When pumping at rated load the machine draws a phase current of $400\angle\text{-}27°$A.

i) Calculate the magnetising reactance per phase of the machine (you may assume that the magnetising current is small in comparison with the total input current drawn at rated load). **(2)**

ii) Calculate the resistance per phase which is incorporated into the equivalent circuit to represent the core loss. **(2)**

iii) Calculate the no-load core losses. **(1)**

iv) Calculate the speed at which the machine is rotating at rated load. **(4)**

v) Calculate the rated torque of the machine. **(3)**

3. A 3-phase switched reluctance (SR) machine has 6 stator teeth and 4 rotor teeth. Each phase consists of two series connected coils. Figure 3 shows the measured variation in the flux-linkage of one phase with current at a series of discrete rotor angular displacements ***which correspond to the normal stroke during which the phase is normally excited*** to produce torque. (Note: An angular displacement of 30° on the scale of Figure 3 corresponds to the rotor being fully-aligned with stator teeth of the phase).

a. Calculate the average torque produced by the machine over the 30° angular excursion to the aligned position for currents of 5A and 12.5A. **(7)**

b. The machine has an airgap between the rotor and stator of 0.5mm in the aligned position. Estimate the number of series turns per phase if the stator and rotor core material begin to saturate at ~1.5T. **(3)**

c. Calculate the maximum and minimum value of the phase self-inductance, taking care to define the rotor angle and current at which you calculate these two values. **(3)**

d. Calculate the peak induced phase emf when operating with a current of 12.5A at a constant speed of 3000 rpm (you **need not** plot the variation in flux-linkage versus rotor angular displacement unless you wish to do so to calculate the emf). **(3)**

e. In practice, the SR machine whose flux-linkage versus current characteristic is shown in Figure 3 is operated from a constant voltage source. Sketch a typical dynamic flux-linkage versus current characteristic for the period up to commutation and a separate characteristic following commutation. **(3)**

f. List any factors which influence the selection of the commutation angle for dynamic operation. **(1)**

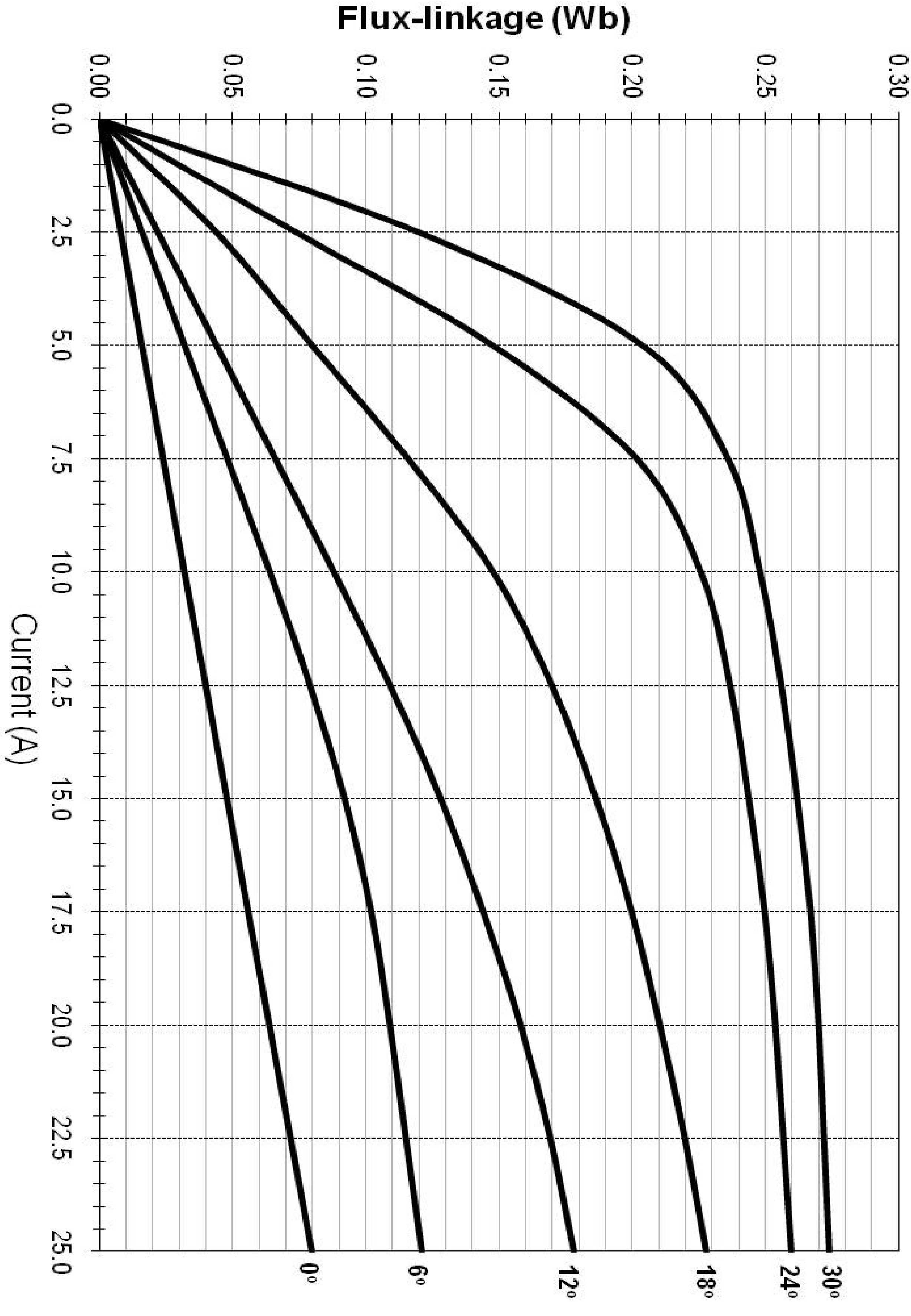

Figure 3 Measured flux-linkage versus current characteristics for one phase of a three-phase switched reluctance machine with 6 stator teeth and 4 rotor teeth

4. Figure 4a shows a schematic of a low-cost, single-phase, two-pole brushless permanent magnet motor which is used in a rechargeable shaver. The machine is driven from a 12V battery supply via a power electronic converter. Under normal operating conditions, the motor is driven by the power electronic converter in a mode that produces a 180°(elec) wide square-wave currents of alternating polarity which are synchronised to the rotor angular position.

The stator consists of a single coil with N turns which is wound on a Silicon Iron laminated core. The rotor consists of a two-pole magnet ring of wall thickness 3mm which is mounted on a cylindrical Silicon Iron core. The length of airgap between the outer surface of the rotor magnets and the stator core is 0.5mm. The measured variation in the coil flux-linkage with rotor angular displacement for a series of different DC bias currents is shown in Figure 4b.

a. Calculate the number of turns N on the coil given that the Silicon Iron used in the stator core begins to magnetically saturate at a flux density of 1.6T (You may assume that the permanent magnet has a relative permeability of 1.0). **(6)**

b. In order that the motor remains under full control from the 12V supply, the maximum allowable value of instantaneous induced emf is 8V. Calculate the maximum rotational speed in rpm at which this condition is satisfied. **(4)**

c. By plotting the appropriate flux-linkage versus current characteristics, calculate the average torque produced by the motor when supplied with 180°(elec) wide square-wave currents of 0.5A and 2.0A. **(7)**

d. Calculate the absolute values of phase inductance for currents of 0.5A and 2.0A at rotor angular displacements of -90° and +90° (i.e. 4 values in total) and comment on any differences between the values calculated. **(3)**

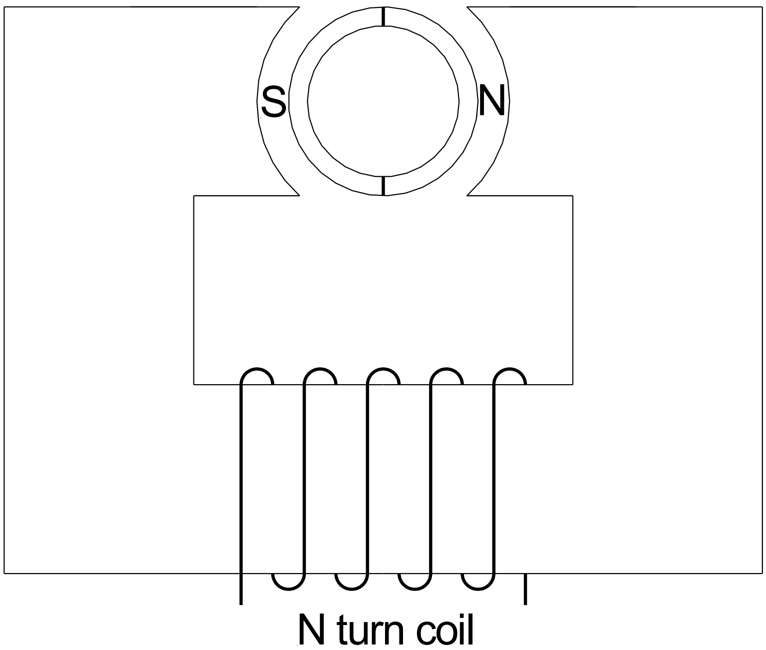

Figure 4a Schematic of a single-phase permanent magnet brushless machine

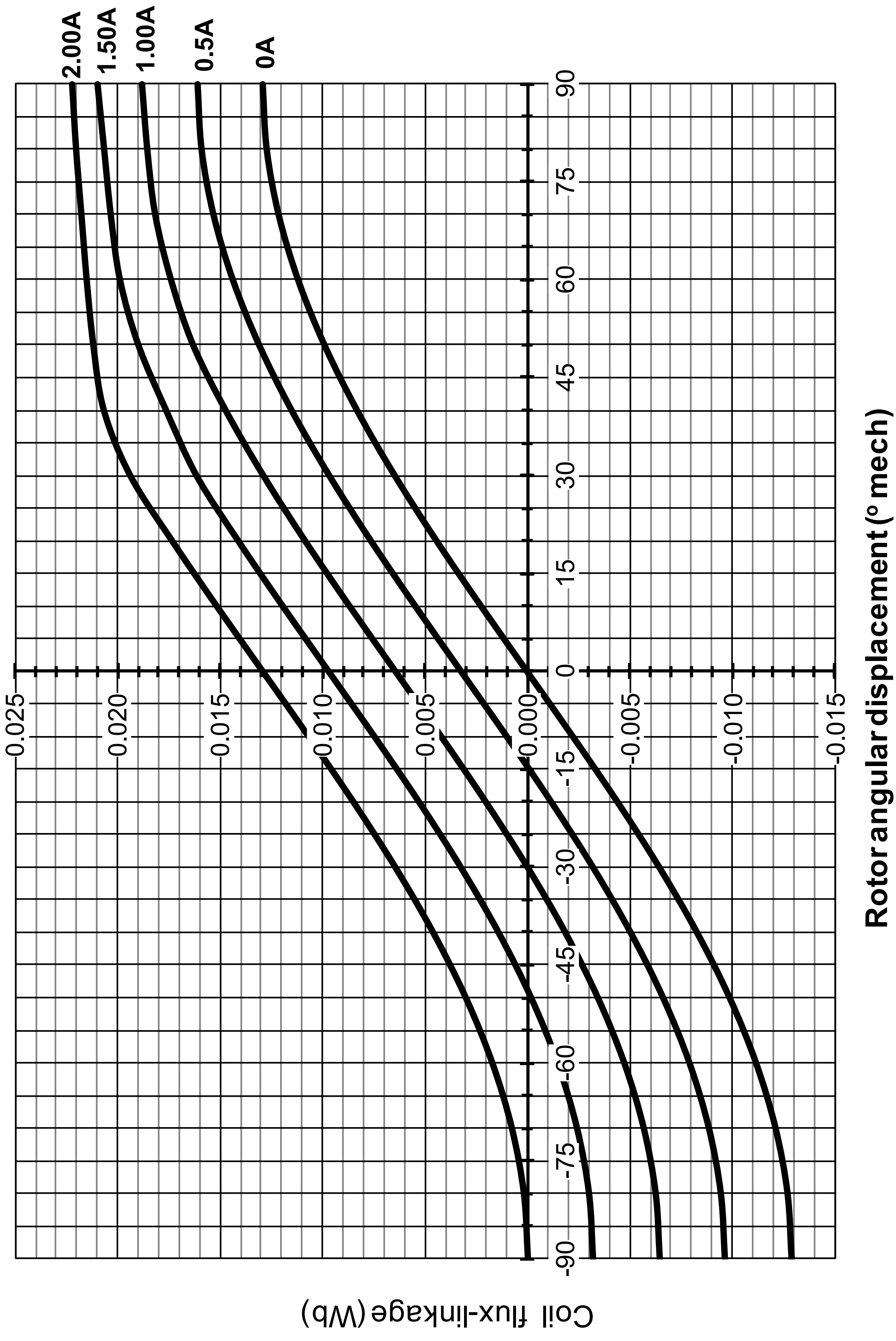

Figure 4b – Measured variation in coil flux-linkage with rotor angular displacement for the motor of Figure 4a

GWJ