Data Provided:
Slot diagram for Questions 1 and 2
Linear-linear graph paper for Question 4

The University Of Sheffield.

DEPARTMENT OF ELECTRONIC AND ELECTRICAL ENGINEERING

Spring Semester 2015-16 (3.0 hours)

EEE6200 AC Machines

Answer **FOUR** questions. **No marks will be awarded for solutions to a fifth 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 3-phase synchronous machine has the following dimensions and design features:

- 30 stator slots
- 10 rotor slots
- 10 rotor poles
- Rotor outer diameter = 450 mm
- Radial airgap length = 1.0 mm
- Axial length of stator and rotor = 500mm
- Stator slot openings that span an angle of 2° (mechanical)
- A rotor tooth pitch : slot pitch ratio of 0.9
- The stator is equipped with a single-layer, integer slot winding with 10 conductors per slot
- The rotor is equipped with a simple series wound field winding in which each rotor slot contains 200 conductors

a. Complete the slot diagram provided to show the layout of the stator winding, taking care to indicate the direction of the winding in each slot (e.g. upper and lower case, plus and minus etc). **Ensure that you attach the slot diagram to your answer book.** **(4)**

b. By calculating the Carter coefficients which account for slotting in **both** the stator and rotor, calculate the effective magnetic airgap between the stator and rotor. **(6)**

c. Calculate the airgap flux density in the machine when the rotor current is 8.5A. **(3)**

d. Calculate the peak stator flux-linkage in one phase of the machine. **(3)**

e. If the stator is star-connected, calculate the **rms** magnitude of the line to line induced emf in the machine when rotating at 1,000rpm. You may assume that the flux-linkage variation with rotor angular position is a good approximation to being sinusoidal. **(4)**

2. **a.** A 24 slot stator core is to be wound with a **single-layer**, 3-phase, 4 pole winding. Complete the slot diagram provided to show the layout of this winding, taking care to indicate the direction of the winding in each slot (e.g. upper and lower case, plus and minus etc). **Ensure that you attach the slot diagram to your answer book.** **(4)**

b. Calculate the overall winding factor for the fundamental, the 5^{th} harmonic and the 7^{th} harmonic. **(5)**

c. The same 24 slot stator core is to be re-wound with a **double-layer**, 3-phase, 4-pole winding in which the coil span is short-pitched by 2 slots. Complete the slot diagram provided to show the layout of this winding, taking care to indicate the direction of the winding in each slot (e.g. upper and lower case, plus and minus etc). **Ensure that you attach the slot diagram to your answer book.** **(4)**

d. Calculate the overall winding factor for the fundamental and the 5^{th} harmonic of this new double-layer winding. **(5)**

e. List the other pole numbers which could be realised in this stator core with integer slot windings. **(2)**

3. A three-phase, star-connected, 8-pole, non-salient synchronous generator supplies power to a 50Hz network at 3.3kVrms (line to line voltage). Figures 3.1 and 3.2 show the measured short-circuit and open-circuit characteristics for one phase of the machine.

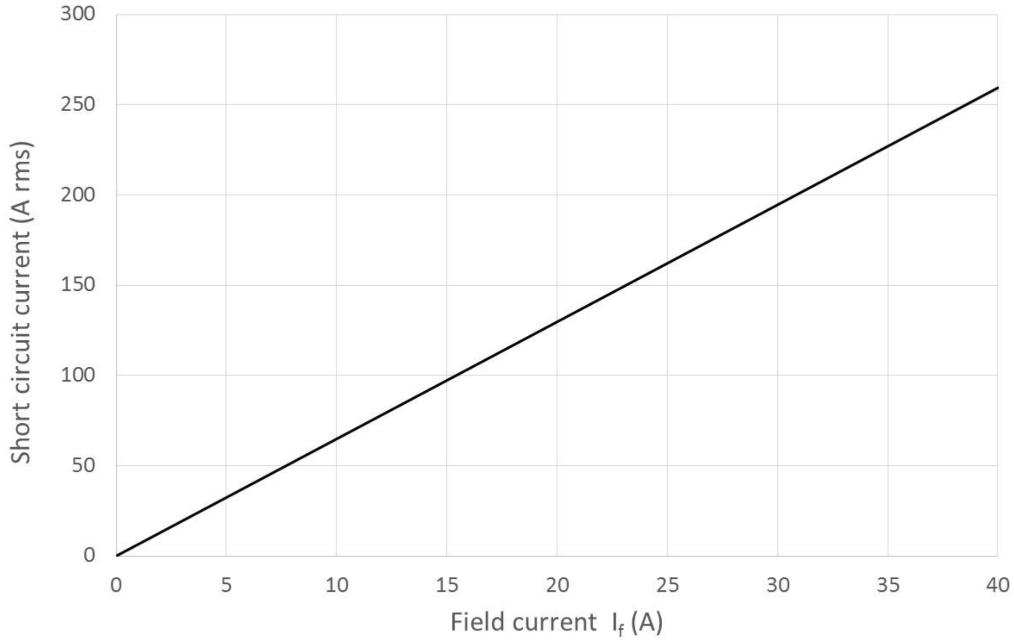

Figure 3.1 Short-circuit characteristic for one-phase

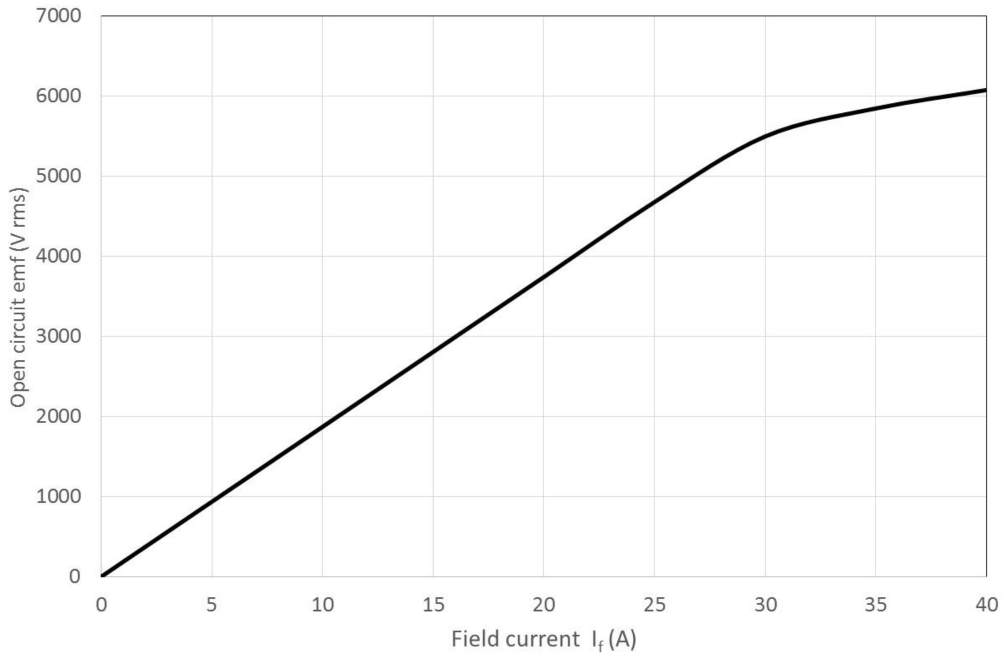

Figure 3.2 Open-circuit characteristic for one-phase

a Calculate the load angle and hence the field current when the generator is delivering a total power of 510kW into the network if the effective power factor of the network is 0.8 lagging.

(Hint: You may assume that the field current required is lower than the level at which any saturation of the open-circuit characteristic occurs) **(8)**

b. Calculate the maximum power that can be delivered to the network with a field current of 40A, and discuss why it would not be regarded as good practice to operate at this generating point. **(4)**

c. The machine is operating at the same steady state operating point of 510kW with at a power factor of 0.8 lagging as calculated in part (a). Starting from this operating condition and assuming that the field current does not change, calculate using an ***iterative approach*** the maximum change in load which can occur if stability of the generator is to be maintained (you need only iterate until the accelerating and decelerating areas agree within 5% of the decelerating area). **(8)**

4. **a.** Figure 4.1 shows the measured variation of coil flux linkage with phase current for one phase of a three-phase switched reluctance rotating machine. The characteristics are measured at equal 6° (mech) increments of angular displacement over the normal torque stroke. This machine has 6 stator teeth (each equipped with a concentrated coil having 127 turns) and 4 rotor teeth. The coils of a given phase are connected in series. The stator and rotor cores are manufactured from silicon iron.

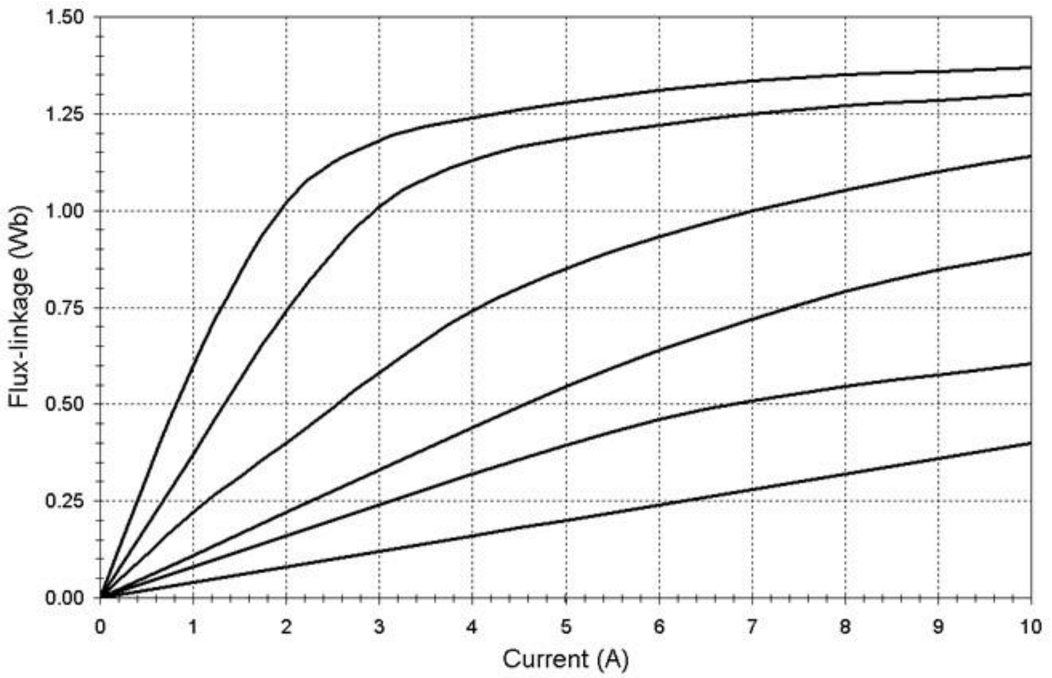

Figure 4.1 Measured flux-linkage versus current characteristic for one phase of a 3-phase 6-4 switched reluctance machine

a. Calculate the number of torque strokes per mechanical revolution for this machine. **(2)**

b. Estimate the average torque produced per phase in moving from the un-aligned to the aligned position for a phase currents of 2A and 5A. **(5)**

c. The stator and rotor core materials saturate at a flux density of approximately 1.6T. Using the flux-linkage versus current characteristic for the **fully aligned** position, estimate the length of the airgap in the machine. **(4)**

d. Use the graph paper provided to plot a corresponding flux-linkage versus rotor angular displacement characteristic for a current of 3A. Estimate the magnitude of the instantaneous induced phase emf at a rotor angular displacement midway between the un-aligned and aligned positions a rotational speed of 200 rpm. **(5)**

e. By reference to the flux-linkage versus current characteristics of the machine, describe two design changes that could be made to the machine to enhance its torque capability. In each case, ***sketch*** representative flux-linkage characteristics in the un-aligned and aligned positions for the original design and the improved design, taking care to label any significant features. **(4)**

5. The equivalent circuit parameters of a single-phase induction motor are given in Table 5.1. The motor has 2 poles and is supplied from a sinusoidal AC supply with voltage V=120Vrms and frequency f=60Hz.
The bearings of the motor produce a constant drag torque of 20 mNm, and the cooling fan produces a drag torque proportional to the square of the speed of the rotor. At a speed of 3,600 rpm, the drag torque from the fan is 50 mNm.

$R_1 = 3.5\Omega$	$R'_2 = 3.2\Omega$	$jX_m = j\,80\Omega$
$jX_1 = j\,4.1\Omega$	$jX'_2 = j\,4.1\Omega$	
Table 5.1 Equivalent circuit parameters		

a. If the motor is operated at a slip s=0.05, and neglecting the iron losses:

(i) Sketch the equivalent circuit of the motor. **(2)**

(ii) Calculate the input current and the power factor of the motor. **(4)**

(iii) Calculate the electromagnetic torque of the motor. **(3)**

(iv) Calculate the losses and the efficiency of the motor. **(4)**

b. To determine the parameters of the single-phase induction motor given in Table 5.1, a locked rotor test was undertaken at V=42 V and a no-load test was undertaken at V=120Vrms:

(i) Calculate the measured current and power factor during the locked rotor test. **(2)**

(ii) Calculate the measured current and the power factor during the no-load test. **(2)**

c. Describe the permanent split capacitor method employed to produce starting torque in a single-phase induction motor. Include in your answer a sketch. **(3)**

6. a. A large load is driven by a star-connected, three-phase induction motor. The number of poles of the motor are $2 \times p = 4$, and connected to a supply with a phase voltage V=1,500V_{rms} . The synchronous speed is 1,500 rpm, and the per-phase equivalent circuit parameters are given in Table 6.1.

R_1 = 0.8Ω	R'_2 = 0.3Ω	R_m = 400Ω
jX_1 = j 1.2Ω	jX'_2 = j 0.6Ω	jX_m = j 60Ω

Table 6.1 Per-phase equivalent circuit parameters

(i) Sketch the approximate per-phase equivalent circuit of the induction machine. **(1)**

(ii) Show that the electromagnetic torque T of the induction motor is a function of slip s, and is given by:

$$T = \frac{3\,V^2}{\omega_s} \times \frac{R'_2/s}{\left(R_1 + R'_2/s\right)^2 + (X_1 + X'_2)^2}$$

(4)

(iii) Calculate the pull-out torque of the induction motor. **(3)**

(iv) Calculate the efficiency of the motor at a speed ω_r=1,485rpm. **(4)**

b. The induction motor is now supplied from an inverter, operated under constant flux, and used to drive a large fan. The torque and speed of the fan are related by:

$$T_f = C_f\,\omega_f^2$$

Where $C_f = 0.155\ \frac{N.m.s^2}{rad^2}$ is constant.

(i) Calculate the electromagnetic torque of the induction motor for a slip s=0.03 and a supply frequency f = 40Hz. **(3)**

(ii) Assuming the iron loss varies linearly with frequency, calculate the power factor of the motor when operating at slip s=0.03, and frequency f = 40Hz. **(3)**

(iii) When driving the fan, will the motor be operating at a slip s smaller or larger than 0.03? **(2)**

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