Loughborough University

ELECTRICAL POWER AND MACHINES

22WSB045

Semester 2 2023 In-Person Exam paper

This examination is to take place in-person at a central University venue under exam conditions. The standard length of time for this paper is **2 hours**.

You will not be able to leave the exam hall for the first 30 or final 15 minutes of your exam. Your invigilator will collect your exam paper when you have finished.

Help during the exam

Invigilators are not able to answer queries about the content of your exam paper. Instead, please make a note of your query in your answer script to be considered during the marking process.

If you feel unwell, please raise your hand so that an invigilator can assist you.

You may use a calculator for this exam. It must comply with the University's Calculator Policy for In-Person exams, in particular that it must not be able to transmit or receive information (e.g. mobile devices and smart watches are **not** allowed).

ELECTRICAL POWER AND MACHINES

(22WSB045)

Semester 2 2023 2 Hours

Answer **ALL FOUR** questions.

Each question carries a total of 25 marks.

Any University-approved calculator is permitted.

A formulae sheet is provided at the rear of the paper.

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1. A single-phase induction motor, driving a water pump, has the following specifications:

- Shaft power 1.1 kW
- Voltage 230 V
- Power factor 0.77
- Efficiency 71%

a) Estimate the current and state one major assumption. [7 marks]

b) The pump has a 25 metre cable with copper conductors of cross-section 1 mm^2.

Take the conductivity of copper to be 58.0 MS/m. Ignore temperature and skin effect.

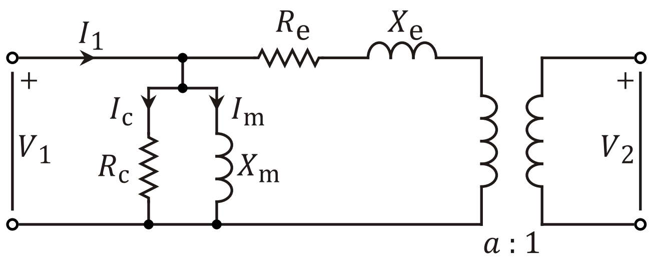
Estimate the power loss in the cable, when the pump is running. [5 marks]

c) Describe how power-factor correction (PFC) could be applied and estimate its effect on power loss in the cable. [7 marks]

d) Additional to the PFC, re-estimate the power loss in the cable if its cross-section were increased to 1.5 mm^2. [2 marks]

e) Estimate the combined effect of PFC and the larger cable on annual running costs, using an electricity price of 40 p/kWh and state one major assumption. [4 marks]

2. A single-phase distribution transformer is to be modelled with the following equivalent circuit.



It is rated at 50 kVA

- Primary voltage 11 kV
- Secondary voltage 240 V

a) Calculate the primary current I_1 at full load, neglecting losses and inductances within the transformer (assuming it to be ideal). [2 marks]

b) The primary current at no load (nothing connected to secondary) is 1.2% of full load.

Calculate the primary current I_1 in amps at no load. [2 marks]

c) The standing loss of the transformer at no load is 135 W.

State where and how this loss occurs. [3 marks]

d) Calculate the current I_c and show that resistance R_c is approximately 896, giving its correct units. [3 marks]

e) Calculate the current I_m and show that magnetising reactance X_m is approximately 207, giving its correct units. [3 marks]

f) Combine R_c and X_m into a single complex impedance and use this to calculate the no-load current as a complex value, treating the primary voltage as the zero-angle reference. [4 marks]

g) Calculate the complex power consumed by the transformer at no-load. [2 marks]

h) The loss of the transformer at full load is 500 W.

Calculate the copper loss and R_e [2 marks]

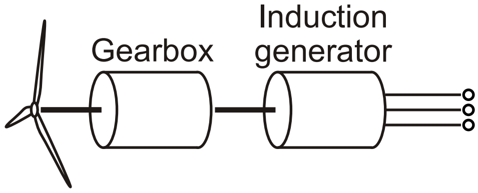
i) The short-circuit impedance of the transformer is quoted as 4.5%

This is the percentage of rated primary voltage that would be needed to reach rated current with the secondary short circuited.

Convert this into an impedance in ohms. [2 marks]

j) Calculate X_e [2 marks]

3. A small grid-connected wind turbine on a site near Loughborough, comprises a three-bladed horizontal-axis aerodynamic rotor, a gearbox to increase the speed and a three-phase induction motor, which has been repurposed as a generator.



a) Describe the rotor of the induction machine and any changes needed to allow operation as a generator. [5 marks]

b) The turbine data sheet says 56 rpm and the gearbox ratio is 27.5

Meanwhile, the motor nameplate says 1460 rpm.

Explain how these numbers might not immediately seem to match up. Then go on to show that they are in fact consistent with expectations. [5 marks]

c) The design includes capacitors exactly as recommended by the motor manufacturer assuming operation as a motor.

Now that the motor is operating as a generator, should these capacitors be removed? Should they be replaced by something else? Explain your answer. [3 marks]

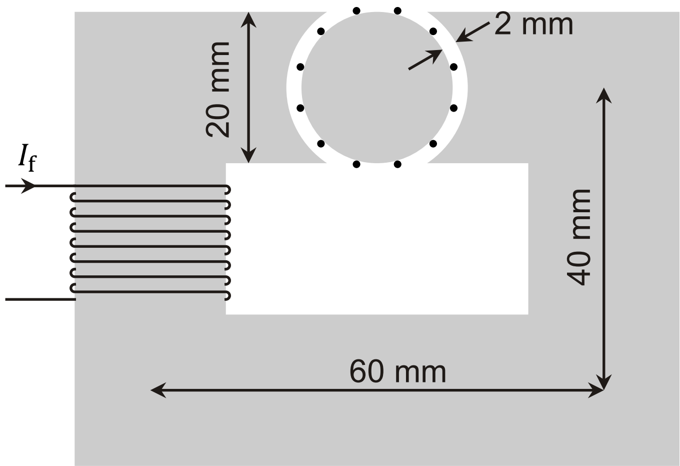
d) The turbine manufacturer would like to enhance the design by allowing it to operate at variable rotational speed.

Explain how this could be achieved with power electronics. [6 marks]

e) The turbine manufacturer is excited to hear that power electronics can allow the generator to operate at any speed from zero to 1540 rpm, and asks if they could get rid of the gearbox by operating the generator directly from the aerodynamic rotor at 56 rpm and below.

Respond to this suggestion.
Hint: Consider the torque. [6 marks]

4. A simple DC motor is illustrated below.



The grey is steel with a relative permeability of 500.

The 3rd dimension (depth into the page) is 30 mm.

The axial length of the rotor is the same 30 mm.

a) Estimate the reluctance of the magnetic circuit. [10 marks]

b) The field winding carries 5 A and has 210 turns. (The diagram only shows a few turns.)

Estimate the MMF, the flux and the flux density. [6 marks]

c) State the direction of the flux. [1 mark]

d) The black dots in the diagram are the rotor conductors. They are made of insulated copper wire of 1 mm diameter, and are glued on to the steel rotor. The interconnections at the ends of the rotor and the commutator are not shown.

The four conductors on the right of the rotor each carry 7 A out of the page. The four on the left each carry 7 A into the page. The two at the top and two at the bottom are commutating and not in the magnetic field.

Estimate the force on a single conductor. [3 marks]

e) Estimate the torque and torque constant. [4 marks]

f) State the direction of the torque. [1 mark]

M. Thomson

Formula Sheet

$$v = iR \qquad V = IR \qquad R = \frac{l}{\sigma A} \qquad \boldsymbol{Z}_\mathrm{R} = R$$

$$p = vi \qquad P = VI \qquad P = I^2 R \qquad P = \frac{V^2}{R}$$

$$V_\mathrm{rms} = \sqrt{\frac{1}{T}\int_0^T v^2 \, \mathrm{d}t} \qquad I_\mathrm{rms} = \sqrt{\frac{1}{T}\int_0^T i^2 \, \mathrm{d}t} \qquad V_\mathrm{rms} = \frac{V_\mathrm{peak}}{\sqrt{2}} \qquad P = \frac{1}{T}\int_0^T p \, \mathrm{d}t$$

$$\mathcal{F} = \phi \mathcal{R} \qquad \mathcal{F} = NI \qquad \mathcal{R} = \frac{l}{\mu A} \qquad H = \frac{\mathcal{F}}{l}$$

$$\phi = BA \qquad F = BIl \qquad B = \mu H$$

$$e = N\frac{\mathrm{d}\phi}{\mathrm{d}t} \qquad L = \frac{N^2}{\mathcal{R}} \qquad \mu = \mu_\mathrm{r}\mu_0 \qquad \mu_0 = 4\pi \times 10^{-7}\,\frac{\mathrm{H}}{\mathrm{m}}$$

$$v = L\frac{\mathrm{d}i}{\mathrm{d}t} \qquad E_\mathrm{L} = \frac{1}{2}Li^2 \qquad X_\mathrm{L} = \omega L \qquad \boldsymbol{Z}_\mathrm{L} = \mathrm{j}X_\mathrm{L}$$

$$i = C\frac{\mathrm{d}v}{\mathrm{d}t} \qquad E_\mathrm{C} = \frac{1}{2}Cv^2 \qquad X_\mathrm{C} = \frac{1}{\omega C} \qquad \boldsymbol{Z}_\mathrm{C} = -\mathrm{j}X_\mathrm{C}$$

$$v = V_\mathrm{peak}\cos\omega t \qquad \omega = 2\pi f$$

$$\boldsymbol{A} = A\,(\cos(\omega t + \alpha) + \mathrm{j}\sin(\omega t + \alpha)) \qquad a = \sqrt{2} \times \mathrm{Re}(\boldsymbol{A}) \qquad \mathrm{e}^{\mathrm{j}x} = \cos x + \mathrm{j}\sin x$$

$$\boldsymbol{V} = \boldsymbol{IZ} \qquad \boldsymbol{Z} = R + \mathrm{j}X \qquad \boldsymbol{Z} = \boldsymbol{Z}_1 + \boldsymbol{Z}_2 + \cdots \qquad \frac{1}{\boldsymbol{Z}} = \frac{1}{\boldsymbol{Z}_1} + \frac{1}{\boldsymbol{Z}_2} + \cdots$$

$$\boldsymbol{S} = \boldsymbol{VI}^* \qquad \boldsymbol{S} = P + \mathrm{j}Q \qquad S = VI \qquad P = S\cos\phi$$

$$a = \frac{N_1}{N_2} = \frac{\boldsymbol{V}_1}{\boldsymbol{V}_2} = \frac{\boldsymbol{I}_2}{\boldsymbol{I}_1} \qquad \boldsymbol{Z}_1 = a^2\boldsymbol{Z}_2$$

$$V = \sqrt{3}V_\mathrm{ph} \qquad n_\mathrm{s} = \frac{120f}{p} \qquad s = \frac{n_\mathrm{s} - n}{n_\mathrm{s}} \qquad T = k_\mathrm{T}I_\mathrm{a}$$