UNIVERSITY OF TASMANIA

EXAMINATIONS FOR DEGREES

ENJ231 Electric Machines and Transformers

Example Paper B

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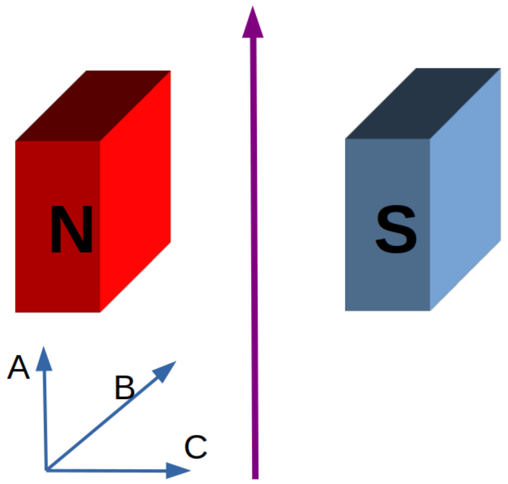
SECTION 1 – Multi-Choice Answer Questions

*Answer **all** TEN (10) Questions. Each question is worth 2 marks. This section is worth 20 marks, or 20% of the examination.*

Question 1.

A wire conducting current is place in a uniform magnetic field. What is the direction of the force acting on the wire?



a. Up
b. Into the page
c. Right
d. There is no force in this case

[Correct answer: b]

Question 2.

Magnetic flux density describes the component of the magnetic field that:

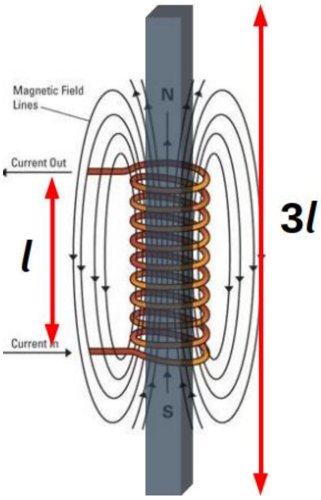
a. is induced by the electric current
b. is induced both by the electric current and magnetisation
c. is induced by magnetisation

[Correct answer: c]

Continued...

Question 3.

When applying the Ampere's law, what is the "mean length"?



- **a.** *l*
- **b.** *2l*
- **c.** *3l*
- **d.** *4l*

[Correct answer: c]

Question 4.

An iron rod is placed inside a coil (as in Question 3). Which statement is correct?

a. As you increase the current, the magnetic permeability increases
b. Even if you increase the current to very large values the magnetisation increases as you increase the current
c. Even if you increase the current to very large values the magnetic flux intensity increases as you increase the current
d. All of the above.

[Correct answer: D]

Question 5.

If the developed torque of an induction motor at a given speed machine is larger than the torque required to drive the load at that speed, then:

a. the motor will remain at the same speed
b. the motor will decelerate (slow down)
c. the motor will accelerate (speed up)

[Correct answer: c]

Question 6.

A three-phase 50 Hz transformer is constructed from three identical single-phase transformers which are connected in Δ-Y configuration. The primary (Δ-connected side) line-line voltage is nominally 22 kV and the secondary line-line voltage is 3.3 kV.

What should the turns ratio, N_1/N_2 of the single-phase transformers be?

a. 3.8
b. 6.7
c. 11.5
d. 120

[Correct answer: c]

Question 7.

In a synchronous machine the angle δ is known as the

a. Rotor angle
b. Power angle
c. Torque angle
d. All of the above

[Correct answer: d]

Question 8.

An 8-pole, 50 Hz Y-connected squirrel-cage induction motor is running at a speed of 700 rpm. What is the slip frequency (frequency of electrical current in the rotor windings) for this machine?

a. 2.5 Hz
b. 46.7 Hz
c. 3.3 Hz
d. 50 Hz
e. 47.5 Hz
f. 0 Hz

[Correct answer: c]

Continued...

Question 9.

An 2-pole, 50 Hz Y-connected squirrel-cage induction machine has the per-phase Thevenin equivalent circuit parameters shown below. The motor is running at a slip of 5%, and rotational losses can be ignored.

$$V_{th} = 600\ \mathrm{V} \quad R_{th} = 3\ \Omega \quad X_{th} = 5\ \Omega \quad R_2' = 2\ \Omega \quad X_2' = 2\ \Omega$$

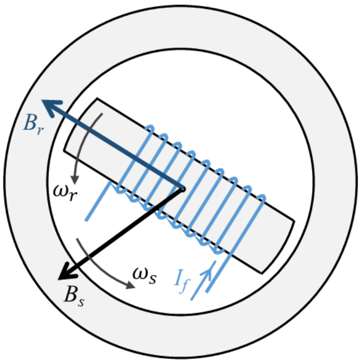
What is the output torque of the motor?

a. 125 Nm
b. 42 Nm
c. 24 Nm
d. 72 Nm
e. 3.6 Nm

[Correct answer: d]

Question 10.

An AC machine is represented by the figure below, which shows the rotor and stator fields and their direction of rotation. The machine is operating at steady state.



Which of the following is true for the operation of this machine?

a. An external counter-torque is applied in the ***opposite*** direction to rotation and the machine is operating as a ***motor***
b. An external counter-torque is applied in the ***opposite*** direction to rotation and the machine is operating as a ***generator***
c. An external counter-torque is applied in the ***same*** direction to rotation and the machine is operating as a ***motor***
d. An external counter-torque is applied in the ***same*** direction to rotation and the machine is operating as a ***generator***

[Correct answer: a (1 mark for answer c)]

SECTION 2 – Fill-In The Blank Questions

*Answer **all** FIVE (5) Questions. Each question is worth 2 marks. This section is worth 10 marks, or 10% of the examination.*

Question 1.

Magnetic flux is proportional to the …...... passing through the surface.

[Answer: magnetic field]

Question 2.

Before reaching saturation, the value of the ...... is constant

[Answer: magnetic susceptibility or magnetic permeability]

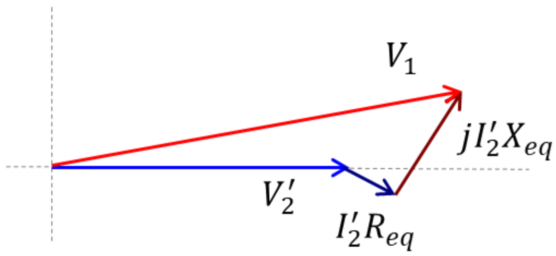
Question 3.

In a synchronous machine, the angle δ is the physical angle between the …………………….………

[Answer: rotor magnetic field (or rotor axis) and the net rotating magnetic field in the machine]

Question 4.

The phasor diagram for a transformer supplying power to a load is shown below.



The load is …………….. reactive power and the transformer output voltage is ……..….. than its input voltage.

[Answer: consuming or absorbing or using AND smaller or lower or less]

Question 5.

In the transformer equivalent circuit, the components R_c and X_m represent ……………………………………………………..

[Answer: core power losses and core magnetizing reactance]

Continued...

SECTION 3 – Short Answer Questions

Answer ***all*** *FOUR (4) Questions. Each question is worth 2.5 marks. This section is worth 10 marks, or 10% of the examination.*

Question 1.

A current is flowing through a coil. Initial the coil is empty. You then put an iron rod inside the coil. Explain what will happen to the magnetic flux inside the coil. Will it change or remain the same? Explain why.

[Correct answer: Magnetic flux will increase. The reason is that there is additional magnetic field induced via the process of magnetization, thus the total magnetic flux is larger than in the case when the coil is empty (i.e. no magnetization).

Question 2.

How can you reduce losses in transformers due to eddy currents?
[Correct answer: Use materials of low conductivity (such as silicon iron) or use lamination.]

Question 3.

Transformer are normally designed so that the iron core is in saturation when operated normally. Describe what this means for the time-varying magnetic flux in the core and for the magnetising current that must be supplied to the transformer?

[Correct answer: The time-varying flux is sinusoidal, since voltage is sinusoidal, but magnetizing current is non-sinusoidal and/or contains 3^{rd} harmonics]

Question 4.

Sketch a torque-speed curve for a typical induction motor, indicating on your sketch the normal range of operation, starting torque and synchronous speed.

[Correct answer: well-labelled T-s curve of IM, with synch speed, starting torque, pull-out torque and normal operating range clearly shown]

SECTION 4 – Calculation Questions

*Answer **all** THREE (3) Questions. Each question is worth 20 marks. This section is worth 60 marks, or 60% of the examination.*

Question 1.

A toroidal coil has a core made out of two materials. One half of the core is made out of an iron alloy (soft ferrite) which has a relative magnetic permeability of $\mu_r = 1000$ and the saturation magnetisation of 1.4 MA/m. The other half is made out of a nickel alloy (hard ferrite) which has a relative magnetic permeability of $\mu_r = 200$ and the saturation magnetisation of 0.3 MA/m. The radius of the coil is r = 25cm, and the cross section is 0.0015 m^2.

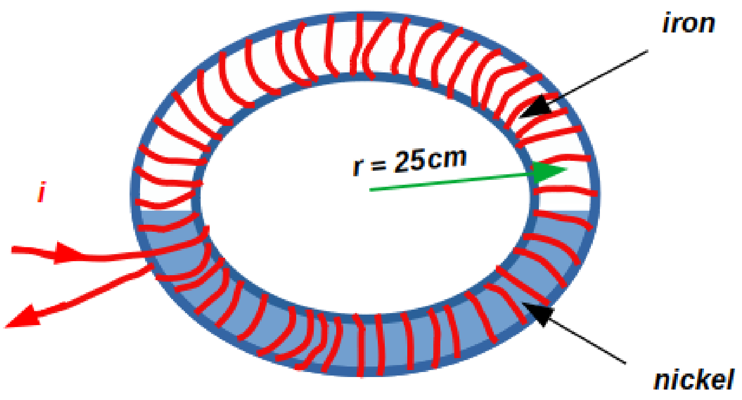


Figure 1: A toroidal coil of radius 25 cm.

a) Assuming that the magnetic flux within the coil is 0.0003 Wb, calculate the magnetic flux density inside the coil.

[2 marks]

Answer: $B = \varphi/A = 0.2$ T

b) What is the magnetic flux intensity inside the iron part?

[2 marks]

Answer: $H = B /(\mu_0 . \mu_r) = 159.16$ [A/m]

c) What is the magnetic flux intensity inside the nickel part?

[2 marks]

Answer: $H = B /(\mu_0 . \mu_r) = 795.78$ [A/m]

d) If the number of turns is N = 50, then what is current?

[6 marks]

$i = (H_{fe}\, l_{fe} + H_{ni}\, l_{ni})/ N = 15$ [A]

e) Has the coil reached the saturation magnetisation (in any of its parts)?

[8 marks]

Expected magentisation at i = 16A
Nickel: $M = (\mu_r - 1) H_{ni} = 0.158$ MA/m, this is less than 0.3 MA/m so Nickel part is not saturated.
Iron: $M = (\mu_r - 1) H_{fe} = 0.159$ MA/m, this is less than 1.4 MA/m so Iron part is not saturated.
The coil is not saturated.

Question 2.

A single-phase 50 Hz 22 kV / 2200 V transformer has the following equivalent circuit parameters:

$$R_c = 300\ \text{k}\Omega,\ X_m = 50\ \text{k}\Omega,\ R_1 = 25\ \Omega,\ X_1 = 100\ \Omega,\ R_2 = 0.25\ \Omega,\ X_2 = 1\ \Omega$$

Use the *approximate equivalent circuit* of the transformer when performing calculations for this question.

a) A load of 130 kW at 0.9 lagging power factor is connected to the secondary side. If the load voltage is 2200 V, calculate the current I_2 in the secondary winding of the transformer?

[4 marks]

Answers: $I_2 = 65.7\angle -25.8°$ A

b) What is the transformer's primary voltage V_1?

[6 marks]

Answers: $I_2' = 6.57\angle -25.8°$ A , $Z_{eq1} = 50 + j200\ \Omega$ → $V_1 = 22890\angle 2.6°$ V

c) What is the voltage regulation for this operating point of the transformer?

[2 marks]

Answers: Voltage regulation = 4.05%

d) Determine the efficiency of this transformer?

[6 marks]

Answers: $P_{Cu} = 2155$ W, $P_c = 1745$ W → $P_{in} = 133902$ W → Eff = 97.1%

e) If the load was increased would the efficiency of the transformer increase or decrease, and why?

[2 marks]

Answers: Efficiency would decrease because $P_{Cu} > P_c$ and hence load is higher than max efficiency point

Question 3.

A 50 Hz, 3-phase, 4-pole Δ-connected synchronous generator has negligible armature resistance and a synchronous reactance of 4 Ω. The generator output terminals are connected to a 3-phase load at a line-line voltage of 22 kV, and the generator is producing 120 MW real power and -80 MW reactive power (that is, the generator is absorbing reactive power)

a) Determine the magnitude and phase angle of the induced stator winding voltage owing to field flux, $|E_f|$ and δ?

[6 marks]

Answers: $|E_f|$ = 18.6 kV , δ = 23.0°

b) Based on the machine's open-circuit characteristics shown in the figure below, determine the required rotor winding current I_f ?

[4 marks]

Answers: → I_f = 31 A

c) Calculate the torque that is being applied by the prime mover to the machine rotor?

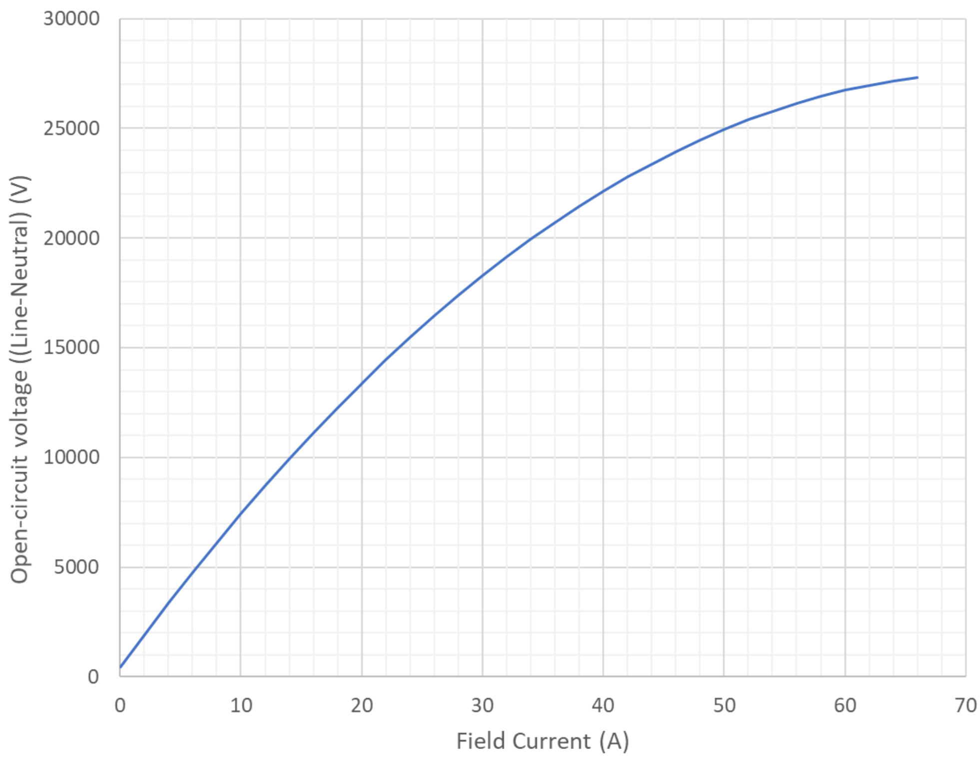
[4 marks]

Answers: w_s = 157.1 rad/s → T = 7.64 x 10^6 Nm

d) What machine input would you need to change and to what new value would you need to change it to make the machine now operate at power factor = 1?

[6 marks]

Answers: Rotor winding current needs to be increased so that |Ef| increases: → $|E_f|$ = 23.2 kV → I_f = 44 A



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Formula Sheet

Constants

$\mu_0 = 4\pi \times 10^{-7}$ H/m

Magnetic Fields and Circuits

Electromotive force, emf $\varepsilon = \oint \vec{E} \cdot d\vec{l}$

Motional emf $\varepsilon = \oint (\vec{v} \times \vec{B}) \cdot d\vec{l}$

Ampere's Law $\oint \vec{H} \cdot d\vec{l} = i_{enc}$

Faraday's Law: emf, $\varepsilon = -\frac{d\phi}{dt}$

Lorentz force

Flux density $B = \mu H = \mu_0(H + M) = \frac{\phi}{A}$

Permeability $\mu = \mu_r \mu_0$

Magnetomotive force: MMF, $F = Ni = Hl$

Reluctance $\mathcal{R} = \frac{l}{\mu A}$

Flux $\phi = \frac{F}{\mathcal{R}}$

Induced emf $e = N\frac{d\phi}{dt}$

Flux linkage $\lambda = N\phi$

Faraday's Law for coil $\varepsilon = -\frac{d\lambda}{dt} = -N\frac{d\phi}{dt}$

Inductance $L = \frac{\lambda}{i}$

Stored energy $E = \frac{1}{2}Li^2$

Induced rms voltage $e_{rms} = 4.44 N_1 \phi_m f$

Transformers

Turns ratio $a = \frac{N_1}{N_2}$

$\frac{Z_1}{Z_2} = \left(\frac{N_1}{N_2}\right)^2$

Voltage Regulation $= \frac{|V_2|_{NL} - |V_2|_L}{|V_2|_L} \times 100\%$

$\eta = \frac{output\ power}{input\ power} = \frac{P_{out}}{P_{out} + losses} = \frac{P_{out}}{P_{out} + P_c + P_{cu}}$

DC Machines

Armature emf $E_a = K_a \Phi \omega_m$

Developed torque $T_m = K_a \Phi I_a$

$\Phi = K_f I_f$ (for unsaturated)

Separately excited: $\mathrm{T} = \frac{K_a \Phi V_t}{R_a} - \frac{(K_a \Phi)^2}{R_a}\omega_m$

Shunt: $T = \frac{K_a K_f V_t^2}{R_a R_{fw}}\left(1 - \frac{K_a K_f}{R_{fw}}\omega_m\right)$

Series: $T = \frac{K_{sr} {V_t}^2}{\left(R_a + R_{ae} + R_{fw} + K_{sr}\omega_m\right)^2}$, $K_{sr} = K_a K_f$

Synchronous Machines

$n_s = \frac{120f}{P}$ rpm

$E_f = V_t + I_a R_a + I_a jX_s = \left|E_f\right| \angle \delta$

$P_{in} = T_{applied} \times \omega_m$

Power (3-phase) $P = \frac{3|V_t||E_f|}{|X_s|}\sin\delta$

Reactive power (3-phase) $Q = \frac{3|V_t||E_f|}{|X_s|}\cos\delta - \frac{3|V_t|^2}{|X_s|}$

Induction Machines

$n_s = \frac{120f}{P}$ rpm

$slip = s = \frac{(n_s - n_m)}{n_s} = \frac{\omega_s - \omega_m}{\omega_s}$

Rotor frequency $f_2 = s f_1$

Stator copper loss $P_1 = 3I_1^2 R_1$

Rotor copper loss $P_2 = 3I_2^2 R_2 = sP_{ag}$

$P_{mech} = P_{ag}(1 - s)$

Output Torque $T = \frac{P}{\omega_m}$

Thevenin equivalent $V_{th} = \frac{V_1}{\sqrt{R_1^2 + (X_1 + X_m)^2}} \times X_m$

$$Z_{th} = \frac{jX_m(R_1 + jX_1)}{R_1 + j(X_1 + X_m)} = R_{th} + jX_{th}$$

Torque equation

$$T_{mech} = \frac{3}{\omega_s} \frac{V_{th}^2}{\left(R_{th} + \frac{R_2'}{s}\right)^2 + (X_{th} + X_2')^2} \frac{R_2'}{s}$$

Slip at max torque $s_{T_{max}} = \frac{R_2'}{\sqrt{R_{th}^2 + (X_{th} + X_2')^2}}$

Max torque $T_{max} = \frac{3}{2\omega_s} \frac{V_{th}^2}{R_{th} + \sqrt{R_{th}^2 + (X_{th} + X_2')^2}}$