THE UNIVERSITY OF ZAMBIA

SCHOOL OF ENGINEERING

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING

UNIVERSITY EXAMINATIONS

TERM III – 29 JULY 2016

EEE 3352 TEST

EEE3352: ELECTROMECHANICS AND MACHINES

TIME:	Two (2) hours
INSTRUCTIONS:	Answer all four (4) questions, each question has 25 Marks
ADDITIONAL INFORMATION:	*permeability of free space* $\mu_0 = 4\pi \times 10^{-7}$ H/m *permittivity of free space* $\varepsilon_0 = 8.85\times 10^{-12}$ F/m

1.

(a) Three charged particles are located at the corners of an equilateral triangle as shown in Fig. Q1(a) below. Calculate the total electric force on the 7.00 μC charge. **[8 marks]**

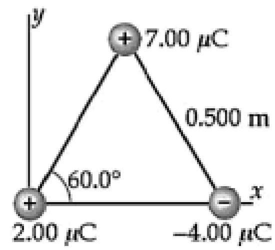


Fig. Q1(a)

(b) Five identical capacitors of capacitance C_0 are connected in a so-called bridge network as shown in Fig. Q1(b) below.

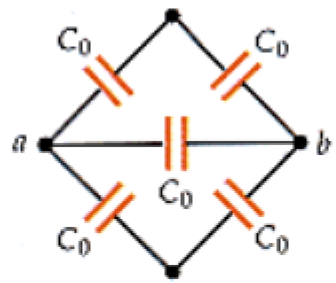


Fig. Q1(b)

(i) What is the equivalent capacitance between points *a* and *b*?

(ii) Find the equivalent capacitance between points *a* and *b* if the capacitor at the center is replaced by a capacitor that has a capacitance of $10C_0$.

[3+2 marks]

(c) The breakdown field strength at which dry air loses its insulating ability and allows a discharge to pass through is $E_b = 3\times10^6$ V/m. Determine the electric energy density at this field strength.

[2 marks]

(d) For a single-core cable, determine the value of conductor radius *r* which gives the minimum voltage gradient for fixed values of applied voltage *V* and sheath radius *R*. Calculate the optimum value of *r* if *V* is 100 kV and the maximum permissible gradient is 55 kV/cm.

[10 marks]

2.

(a) What is hysteresis and mention its importance.

[5 marks]

(b) The core of Fig.**Q2** is cast steel whose B-H curve can be found in the graph just below it. Determine the current required to establish an air-gap flux of $\varphi_g=6\times10^{-3}$ Wb. Neglect fringing.

[20 marks]

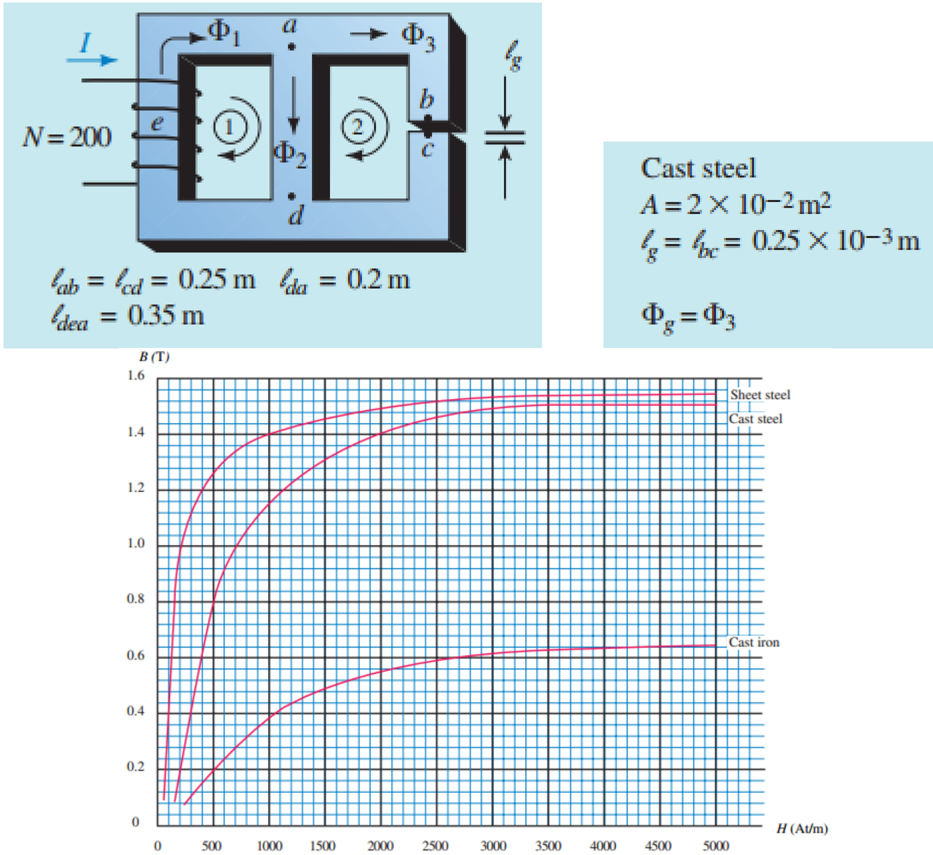


Fig. Q2

3.

Consider a 25 kVA, 2300/230 V, 50 Hz single phase distribution transformer with the following parameters:

$$Z_{eq,H} = 4 + j5\ \Omega$$
$$R_{c,L} = 450\ \Omega$$
$$X_{m,L} = 300\ \Omega$$

Note that the series and shunt parameters are referred to high and low voltage sides of the transformer respectively.

a) With the aid of appropriate diagrams, briefly explain how open circuit and short circuit tests are carried out on an *actual* transformer to determine the parameters given above. State any assumptions. **[2.5+2.5 marks]**

b) If the transformer above is connected to a load whose power factor varies, determine;

   i. The worst-case voltage regulation for full load output. **[6 marks]**

   ii. Efficiency when the transformer delivers full load at rated voltage and 0.85 power factor lagging. . **[4 marks]**

   iii. The percentage loading of the transformer at which the efficiency is a maximum and calculate this efficiency if the *pf* is 0.85 lagging and load voltage is 230 V.

[3+3 marks]

c) Explain the shape of the waveform of the input current of a transformer on no load. **[4 marks]**

4.

(a) Derive an expression for the frequency *f* of the induced voltage in a general conductor of a rotating machine with *p* pole pairs when the machine is driven at constant speed *n*.

[5 marks]

(b) A two-pole machine has 300 conductors on its armature and 80% are directly under the pole faces. The armature which is on the rotor has length of 20 cm and radius of 15 cm, while the field is 0.8 T at the conductor locations. The current in the conductor is 40 A and the rotor is rotating at 1800 r/min. Ignoring losses, calculate

i. the frequency of the induced voltage in the armature conductor

[5 marks]

ii. the total force developed by the armature

[5 marks]

iii. the mechanical power developed by the machine

[5 marks]

iv. the total counter induced voltage as appearing at the machine terminals.

[5 marks]

END OF EEE3352 TEST!

SOLUTIONS

1. (a)

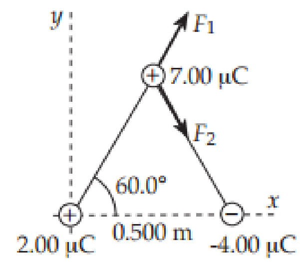
The forces on the 7.00 μC charge are shown in the sketch to the right. Applying Coulomb's Law to calculate each force, we get

$$F_1 = \left(8.99\times10^9\ \frac{\text{N}\cdot\text{m}^2}{\text{C}^2}\right)\frac{(7.00\times10^{-6}\ \text{C})(2.00\times10^{-6}\ \text{C})}{(0.500\ \text{m})^2}$$

$$= 0.503\ \text{N}$$

$$F_2 = \left(8.99\times10^9\ \frac{\text{N}\cdot\text{m}^2}{\text{C}^2}\right)\frac{(7.00\times10^{-6}\ \text{C})(4.00\times10^{-6}\ \text{C})}{(0.500\ \text{m})^2}$$

$$= 1.01\ \text{N}$$



From the superposition principle, we know

$$\Sigma F_x = (F_1 + F_2)\cos 60.0° = 0.755\ \text{N},$$

and $\Sigma F_y = (F_1 - F_2)\sin 60.0° = -0.436\ \text{N}$

So the resultant force on the 7.0 μC charge is

$$F_R = \sqrt{(\Sigma F_x)^2 + (\Sigma F_y)^2} = 0.872\ \text{N} \text{ at } \theta = \tan^{-1}\left(\frac{\Sigma F_y}{\Sigma F_x}\right) = -30.0°,$$

or $\mathbf{F}_R = \boxed{0.872\ \text{N at } 30.0° \text{ below the } +x \text{ axis}}$

Now we have two capacitors with capacitance $\frac{1}{2}C_0$ in parallel with a capacitor whose capacitance is C_0. Find their equivalent capacitance:

$$C'_{eq} = \tfrac{1}{2}C_0 + C_0 + \tfrac{1}{2}C_0 = \boxed{2C_0}$$

(*b*) If the central capacitance is $10C_0$, then:

$$C'_{eq} = \tfrac{1}{2}C_0 + 10C_0 + \tfrac{1}{2}C_0 = \boxed{11C_0}$$

(c)

$$u_E = \frac{1}{2}\varepsilon_0 E^2 = \frac{1}{2}\left(8.85\times10^{-12}\text{C}^2/\text{N}\cdot\text{m}^2\right)\left(3\times10^6\ \text{V/m}\right)^2 = 40\ \text{J/m}^3$$

(d) The highest value of the voltage gradient occurs at the surface of the conductor and is given by

$$E_m = \frac{V}{r\ln R/r}$$

If V and R are fixed and r is variable, the value of r which gives the minimum value of E_m is that which makes $\frac{dE_m}{dR}$ equal to zero.

$$\frac{dE_m}{dr} = \frac{-V\left(\ln\frac{R}{r} + r\frac{r}{R}\left(\frac{-R}{r^2}\right)\right)}{\left(r\ln\frac{R}{r}\right)^2}$$

For E_m to be a minimum; $-V\left(\ln\frac{R}{r}+r\frac{r}{R}\left(\frac{-R}{r^2}\right)\right)=0$

i.e., $\ln\frac{R}{r}-1=0,\qquad \ln\frac{R}{r}=1,\qquad \frac{R}{r}=e$ and $r=\frac{R}{e}$

If the value of r is substituted into the first equation above, the minimum value of E_m becomes

$$E_m=\frac{V}{r}$$

Thus, the optimum value of r is given by

$r=\frac{V}{E_m}=\frac{100\sqrt{2}}{55}=2.57\ \text{cm}$, assuming that the value given for V is rms and that for voltage gradient is peak.

2. (a) Hysteresis is the lagging of magnetic induction behind the magnetizing field. Applied in motors, generators and transformers.

(b)

Solution Consider each section in turn.

Air Gap

$$B_g = \Phi_g/A_g = (6 \times 10^{-3})/(2 \times 10^{-2}) = 0.3 \text{ T}$$
$$H_g = (7.96 \times 10^5)(0.3) = 2.388 \times 10^5 \text{ At/m}$$

Sections ab and cd

$$B_{ab} = B_{cd} = B_g = 0.3 \text{ T}$$
$$H_{ab} = H_{cd} = 250 \text{ At/m} \quad \text{(from Figure 12–19)}$$

Ampere's Law (Loop 2)

$\sum_{\bigcirc} NI = \sum_{\bigcirc} H\ell$. Since you are going opposite to flux in leg *da,* the corresponding term (i.e., $H_{da}\ell_{da}$) will be subtractive. Also, $NI = 0$ for loop 2. Thus,

$$0 = \sum_{\bigcirc \text{ loop2}} H\ell$$
$$0 = H_{ab}\ell_{ab} + H_g\ell_g + H_{cd}\ell_{cd} - H_{da}\ell_{da}$$
$$= (250)(0.25) + (2.388 \times 10^5)(0.25 \times 10^{-3}) + (250)(0.25) - 0.2H_{da}$$
$$= 62.5 + 59.7 + 62.5 - 0.2H_{da} = 184.7 - 0.2H_{da}$$

Thus, $0.2H_{da} = 184.7$ and $H_{da} = 925$ At/m. From Figure 12–19, $B_{da} = 1.12$ T.

$$\Phi_2 = B_{da}A = 1.12 \times 0.02 = 2.24 \times 10^{-2} \text{ Wb}$$
$$\Phi_1 = \Phi_2 + \Phi_3 = 2.84 \times 10^{-2} \text{ Wb.}$$
$$B_{dea} = \Phi_1/A = (2.84 \times 10^{-2})/0.02 = 1.42 \text{ T}$$
$$H_{dea} = 2125 \text{ At/m} \quad \text{(from Figure 12–19)}$$

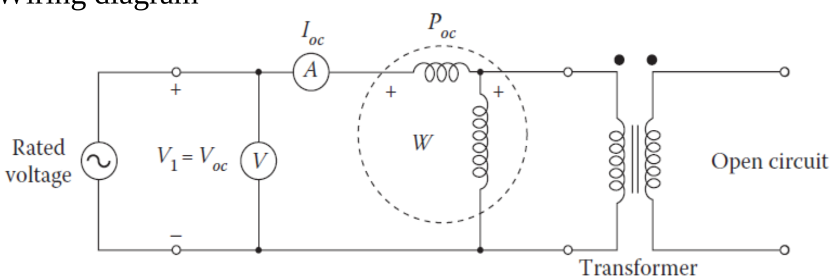
Ampere's Law (Loop 1)

$$NI = H_{dea}\ell_{dea} + H_{ad}\ell_{ad} = (2125)(0.35) + 184.7 = 929 \text{ At}$$
$$I = 929/200 = 4.65 \text{ A}$$

3. a)

i. Open circuit test

Wiring diagram



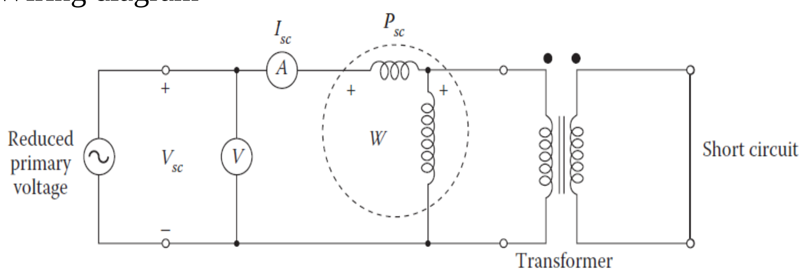
For safety and convenience, the instruments shown above are placed on the low-voltage side of the transformer. A rated voltage $V_1 = V_{oc}$ is then applied on the low-voltage winding with a high-voltage winding open-circuited. V_{oc}, I_{oc} and P_{oc} are then measured and the shunt parameters are thus determined as follows:

$$\cos\theta = PF = \frac{P_{oc}}{V_{oc}I_{oc}} \qquad Y_E = \frac{I_{oc}}{V_{oc}}\angle -\theta = \frac{I_{oc}}{V_{oc}}\angle -\cos^{-1} PF \qquad Y_E = G_C - jB_M = \frac{1}{R_C} - j\frac{1}{X_M}$$

$$R_C = \frac{1}{G_C} \qquad X_M = \frac{1}{B_M}$$

ii. Short circuit test

Wiring diagram



One winding (*usually the low-voltage winding*) is short-circuited and a *reduced* voltage is applied to the other winding until the current in the shorted winding is equal to its rated value. Assume current flowing through the excitation branch negligible; therefore, all the voltage drop in the transformer is due to the series elements in the circuit. V_{sc}, I_{sc} and P_{sc} are then measured and the series parameters determined as follows;

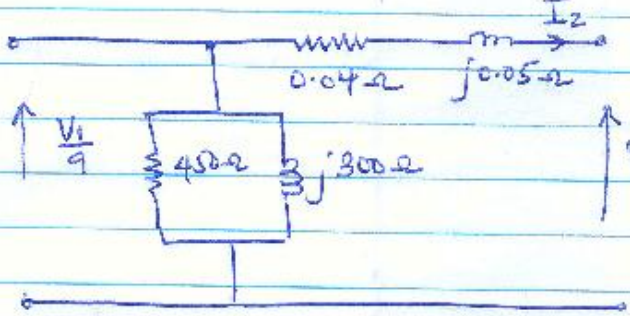
$$PF = \cos\theta = \frac{P_{SC}}{V_{SC}I_{SC}} \qquad Z_{SE} = \frac{V_{SC}\angle 0°}{I_{SC}\angle -\theta°} = \frac{V_{SC}}{I_{SC}}\angle \theta°$$

$$Z_{SE} = R_{eq} + jX_{eq}$$

$$Z_{SE} = \left(R_p + a^2R_S\right) + j\left(X_p + a^2X_S\right)$$

b)

Approximate equivalent cct referred to secondary;



$a = \frac{2300}{230} = 10$

$|Z_{eq}| = \sqrt{0.04^2 + 0.05^2} = 0.064\,\Omega$

$\theta_{eq} = \tan^{-1}\left(\frac{0.05}{0.04}\right) = 51.34^\circ$

i) $VR = \frac{I_2 Z_{eq}}{V_2} \cos(\theta_{eq} - \theta_L)$

For worst-case VR $\rightarrow \theta_{eq} = \theta_L = 51.34^\circ$ (lagging)

$\Rightarrow$ Worst-case $VR = \frac{I_2 Z_{eq}}{V_2}$; $I_2 = \frac{25000}{230} \cong 108.7\ A$

$= \frac{(108.7)(0.064)}{230} \times 100\%$

$= \boxed{3.03\%}$ 6 marks

ii) $P_{out} = S\cos\theta_L = 25000 \times 0.85 = 21.25\,kW$

$P_{cu} = I_2^2 R_{eq} = (108.7)^2 \times 0.04 = 472.63\,W$

$P_{core} = \frac{230^2}{450} = 117.56\,W$

$Eff = \frac{21,250}{21,250 + 472.63 + 117.56} \times 100\% = \boxed{97.3\%}$ 4 marks

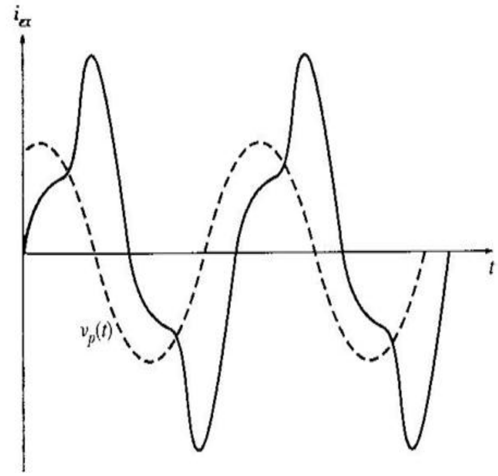
iii) $n = \frac{I_{actual}}{I_{full\ load}} = \sqrt{\frac{P_{core}}{P_{cu\,full\ load}}} = \sqrt{\frac{117.56}{472.63}} = 0.499 = \boxed{49.9\%}$

3 marks

At $Eff_{max.}$; $P_{cu} = P_{core} = 117.56\,W$ and $P_{out} = nS\cos\theta_L$

$\therefore P_{out} = 0.499 \times 21.25\,kW \cong 10.6\,kW$

$Eff = \frac{10603.75}{10603.75 + (2 \times 117.56)} \times 100\% = \boxed{98.9\%}$ 3 marks c)



1. It is not sinusoidal but a combination of high frequency oscillation on top of the fundamental frequency due to magnetic saturation.
2. The current lags the voltage at 90o
3. At saturation, the high frequency components will be extreme as such that harmonic problems will occur.