NANYANG TECHNOLOGICAL UNIVERSITY

SEMESTER 2 EXAMINATION 2013 - 2014

EE3010 ELECTRICAL DEVICES AND MACHINES

April/May 2014 Time Allowed: 2 hours

INSTRUCTIONS

1. This paper contains 4 questions and comprises 4 pages.
2. Answer all questions.
3. This is a closed-book examination.
4. All questions carry equal marks.

---

1. Tests conducted on a single-phase, 10-kVA, 2200/220-V, 50-Hz transformer gave the following test results:

   Open-circuit Test (with high-voltage side open)

   $V_{OC} = 220$ V, $I_{OC} = 2.5$ A, $P_{OC} = 100$ W

   Short-circuit Test (with low-voltage side shorted)

   $V_{SC} = 150$ V, $I_{SC} = 4.55$ A, $P_{SC} = 215$ W

   (a) Calculate the parameters of the transformer and draw the approximate equivalent circuit referred to the low-voltage side.

   (10 Marks)

   (b) Determine the voltage regulation and the maximum efficiency of the transformer when it delivers an output of 10 kVA at 220 V and 0.8 lagging power factor. The core loss of the transformer at rated voltage is 100 W.

   (8 Marks)

   (c) If three identical units of the single-phase transformer as above are connected to form a three-phase Δ/Y transformer bank, determine the input voltage of the three-phase transformer bank when it supplies full load at 0.8 lagging power factor at rated voltage. Ignore the no-load current.

   (7 Marks)

2. An electromagnet lift system shown in Figure 1 is excited by a coil of 2000 turns. The dimensions of the magnetic system are shown in the figure. The relative permeabilities of the magnetic core and the steel bar can be considered to be infinitely high. The permeability of free space is given as $\mu_o = 4\pi \times 10^{-7}$ H/m.

(a) Determine the inductance of the system.

(5 Marks)

(b) Find the dc current required in the coil to produce a flux density of 1.2 T in the air gap 'g_1' of the side core. What is the total energy stored in the system?

(8 Marks)

(c) Calculate the force required to lift the steel bar under the condition of part 2(b).

(7 Marks)

(d) If the coil is connected to a 50-Hz ac source, what would be the voltage induced in the coil when it carries a current of $1.5\sin(100\pi t)$ A?

(5 Marks)

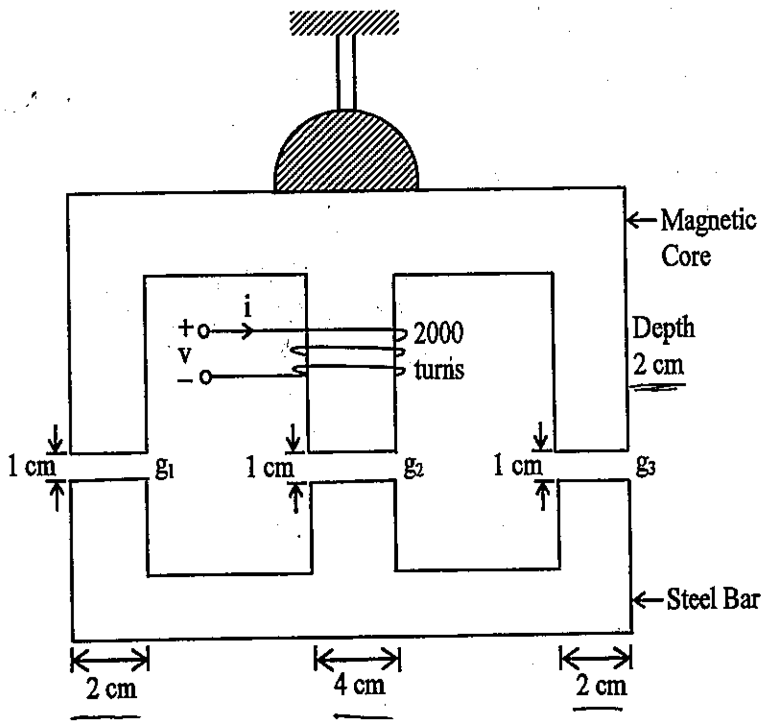


Figure 1

3. A DC machine with compensating windings operates as a separately-excited motor with an armature voltage supply of 120 V. The armature and field resistances of the machine are found to be 0.12 Ω and 100 Ω respectively. The field winding is connected to a separate voltage supply of 120 V. Under no-load condition, it is found that the motor draws an input current of 5 A. The magnetization curve for this machine at a speed of 1200 rpm is given in the following table:

E_a (V)	5	78	95	112	118	126
I_f (A)	0	0.8	1	1.28	1.44	1.88

(a) Calculate the rotational losses and no-load speed of the motor. (4 Marks)

(b) Determine the developed torque, speed and efficiency of the motor at its rated current of 60 A. (7 Marks)

(c) Determine the required armature voltage when the motor runs at 900 rpm and its developed torque reduces to 70% of that in part 3(b). (6 Marks)

(d) Determine the additional external resistance in the field circuit required to run the motor at 1500 rpm while developing a torque equal to 50% of that in part 3(b). The armature voltage is kept fixed at 120 V. (8 Marks)

4. The per-phase parameters of a three-phase, Y-connected, 415-V, 50-Hz, 1460-rpm, 4-pole induction motor, with all quantities referred to the stator, are:

$R_1 = 0.4\ \Omega$ $R_2 = 0.5\ \Omega$ R_c may be neglected

$X_1 = 1.2\ \Omega$ $X_2 = 1.5\ \Omega$ $X_m = 80\ \Omega$

R_2/s

The motor is connected to rated voltage supply.

(a) Compute the speed at which the maximum torque is developed. (3 Marks)

Note : Question No. 4 continues on page 4.

(b) Calculate the corresponding maximum torque, input current and power factor.

(7 Marks)

(c) Determine the starting current and the corresponding torque developed.

(7 Marks)

It is desired to limit the starting current within a safe limit via reduced voltage supply. This can be achieved by connecting a three-phase autotransformer starter in between the voltage supply and the motor terminals. During start-up, the autotransformer is connected to the motor terminals to supply a lower voltage. Once the motor is nearly up to speed, the autotransformer is disconnected and the motor terminals are connected directly to the voltage supply.

(d) Calculate the voltage ratio of the autotransformer required to limit the starting current to 3.5 times its rated value. What will be the starting torque under this condition? Assume that the autotransformer is ideal.

(8 Marks)

END OF PAPER

Date: No.

1) a) Open-circuited Test : Find R_{cL} & X_{ML}

$$P_{oc} = \frac{V_{oc}^2}{R_{cL}}$$
$$R_{cL} = \frac{220^2}{100}$$
$$R_{cL} = 484\,\Omega$$

$$I_c = \frac{V_{oc}}{R_{cL}} = \frac{220}{484} = 0.4545\,A$$
$$I_M = \sqrt{I_{oc}^2 - I_c^2} = \sqrt{2.5^2 - 0.4545^2} = 2.4583\,A$$

$$X_{ML} = \frac{V_{oc}}{I_M} = \frac{220}{2.4583}$$
$$X_{ML} = 89.49\,\Omega$$

Short-circuit Test : Find R_{eH} & X_{eH}

$$P_{sc} = I_{sc}^2 R_{eH}$$
$$R_{eH} = \frac{215}{4.55^2}$$
$$R_{eH} = 10.39\,\Omega$$

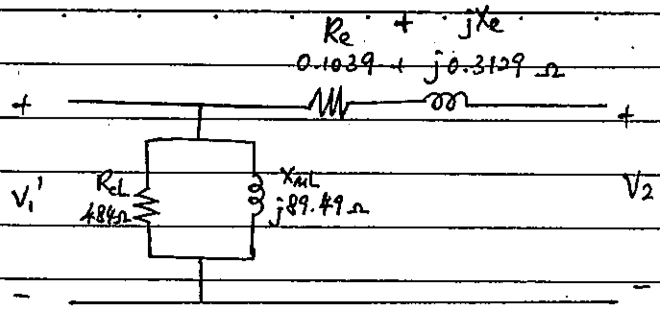
$$Z_e = \frac{V_{sc}}{I_{sc}} = \frac{150}{4.55} = 32.967\,\Omega$$
$$X_{eH} = \sqrt{Z_e^2 - R_{eH}^2}$$
$$X_{eH} = 31.29\,\Omega$$

$$a = \frac{e_1}{e_2} = \frac{2200}{220} = 10$$

$$R_{eH} = a^2 R_e \qquad \therefore R_e = \frac{R_{eH}}{a^2} = \frac{10.39}{10^2}$$
$$R_e = 0.1039\,\Omega$$

$$X_{eH} = a^2 X_e \qquad \therefore X_e = \frac{X_{eH}}{a^2} = \frac{31.29}{10^2}$$
$$X_e = 0.3129\,\Omega$$

Date: No.



The approximate equivalent circuit referred to the low-voltage side

b)

$$S = 10\,000 \angle 36.87^\circ \text{ VA}$$

$$V_2 = 220 \angle 0^\circ \text{ V}$$

$$I_2 = \left(\frac{S}{V_2}\right)^*$$

$$= \frac{10\,000 \angle -36.87^\circ}{220 \angle 0^\circ}$$

$$= 45.45 \angle -36.87^\circ \text{ A}$$

$$V_1' = I_2(R_e + jX_e) + V_2$$

$$= (45.45 \angle -36.87^\circ)(0.1039 + j0.3129) + 220 \angle 0^\circ$$

$$= 232.47 \angle 2.11^\circ \text{ V}$$

$$\text{Voltage Regulation} = \frac{V_1' - V_2}{V_2} \times 100\%$$

$$= \frac{232.47 - 220}{220} \times 100\%$$

$$= 5.67\%$$

At maximum efficiency, $P_{cu} = P_M = 100$ W

$$P_{cu\text{-}fl} = |I_2|^2 R_e$$

$$= 45.45^2 \times 0.1039$$

$$= 214.63 \text{ W}$$

$$x^2 P_{cu\text{-}fl} = P_M$$

$$x = \sqrt{\frac{100}{214.63}}$$

$$= 0.6826$$

$$P_o = 10000 \times 0.8 \times 0.6826$$

$$= 5460.8 \text{ W}$$

$$\text{maximum efficiency, } \eta = \frac{P_o}{P_o + P_{cu} + P_M} \times 100\%$$

$$= \frac{5460.8}{5460.8 + 100 + 100} \times 100\% = 96.47\%$$

Date: No.

1) c) Rating = 30 kVA, 2200 / 381.05 V, 50 Hz

$$V_{1Y} = \frac{2200}{\sqrt{3}} = 1270.17\ V$$

$$V_{2Y} = \frac{381.05}{\sqrt{3}} = 220\ V$$

$$a_{Y-Y} = \frac{V_{1Y}}{V_{2Y}} = \frac{1270.17}{220}$$

$$a_{Y-Y} = 5.774$$

$$S = 10000 \angle 36.87^\circ\ VA$$

$$V_2 = 220 \angle 0^\circ\ V$$

$$I_2 = \left(\frac{S}{V_2}\right)^*$$

$$= 45.45 \angle -36.87^\circ\ A$$

$$V_1' = I_2 Z_e + V_2$$

$$= (45.45 \angle -36.87^\circ)(0.1039 + j0.3129) + 220\angle 0^\circ$$

$$= 232.47 \angle 2.11^\circ\ V$$

$$|V_1| = a|V_1'|$$

$$= 5.774 \times 232.47$$

$$= 1342.28\ V$$

$$|V_{1,line}| = |V_1| = 1342.28\ V$$

2) a)

$$R_{g_1} = \frac{1 \times 10^{-2}}{4\pi \times 10^{-7} \times 4 \times 10^{-4}}$$

$$= 19.894\ MH^{-1}$$

$$R_{g_3} = R_{g_1} = 19.894\ MH^{-1}$$

$$R_{g_2} = \frac{1 \times 10^{-2}}{4\pi \times 10^{-7} \times 8 \times 10^{-4}}$$

$$= 9.947\ MH^{-1}$$

$$R_T = (R_{g_1} \parallel R_{g_3}) + R_{g_2}$$

$$= \frac{19.894}{2} + 9.947$$

$$= 19.894\ MH^{-1}$$

$$L = \frac{N^2}{R_T}$$

$$= \frac{2000^2}{19.894 \times 10^6}$$

$$= 0.201\ H$$

Date: No.

b) $\varphi_1 = BA_1$

$= 1.2 \times (2\times10^{-2} \times 2\times10^{-2})$

$= 4.8 \times 10^{-4}$ Wb

$\varphi_2 = 2\varphi_1$

$= 2 \times 4.8 \times 10^{-4}$

$= 9.6 \times 10^{-4}$ Wb

$Ni = \varphi_2 R_T$

$i = \dfrac{9.6\times10^{-4} \times 19.894\times10^{6}}{2000}$

$= 9.549$ A

$W_f = \frac{1}{2}\varphi_2^2 R_T$

$= \frac{1}{2}(9.6\times10^{-4})^2(19.894\times10^{6})$

$= 9.167$ J

c) $F = \dfrac{dW_f}{dg}$

$R_T = \frac{1}{2}R_{g_1} + R_{g_2}$

$F = \frac{1}{2}\varphi^2 \times \left(\frac{1}{2}\times\frac{1}{\mu_0\times4\times10^{-4}} \times \frac{1}{\mu_0\times8\times10^{-4}}\right)$

$= \frac{1}{2}(9.6\times10^{-4})^2\left[\left(\frac{1}{2}\right)\left(\frac{1}{4\pi\times10^{-7}\times4\times10^{-4}}\right) + \frac{1}{4\pi\times10^{-7}\times8\times10^{-4}}\right]$

$= 572.96$ N

d) $I = 1.5\sin(100\pi t)$ A

$I_{rms} = \dfrac{1.5}{\sqrt{2}}$

$= 1.06$ A

$V_{rms} = I_{rms}(R + j\omega L)$ $\boxed{\omega = 2\pi f}$

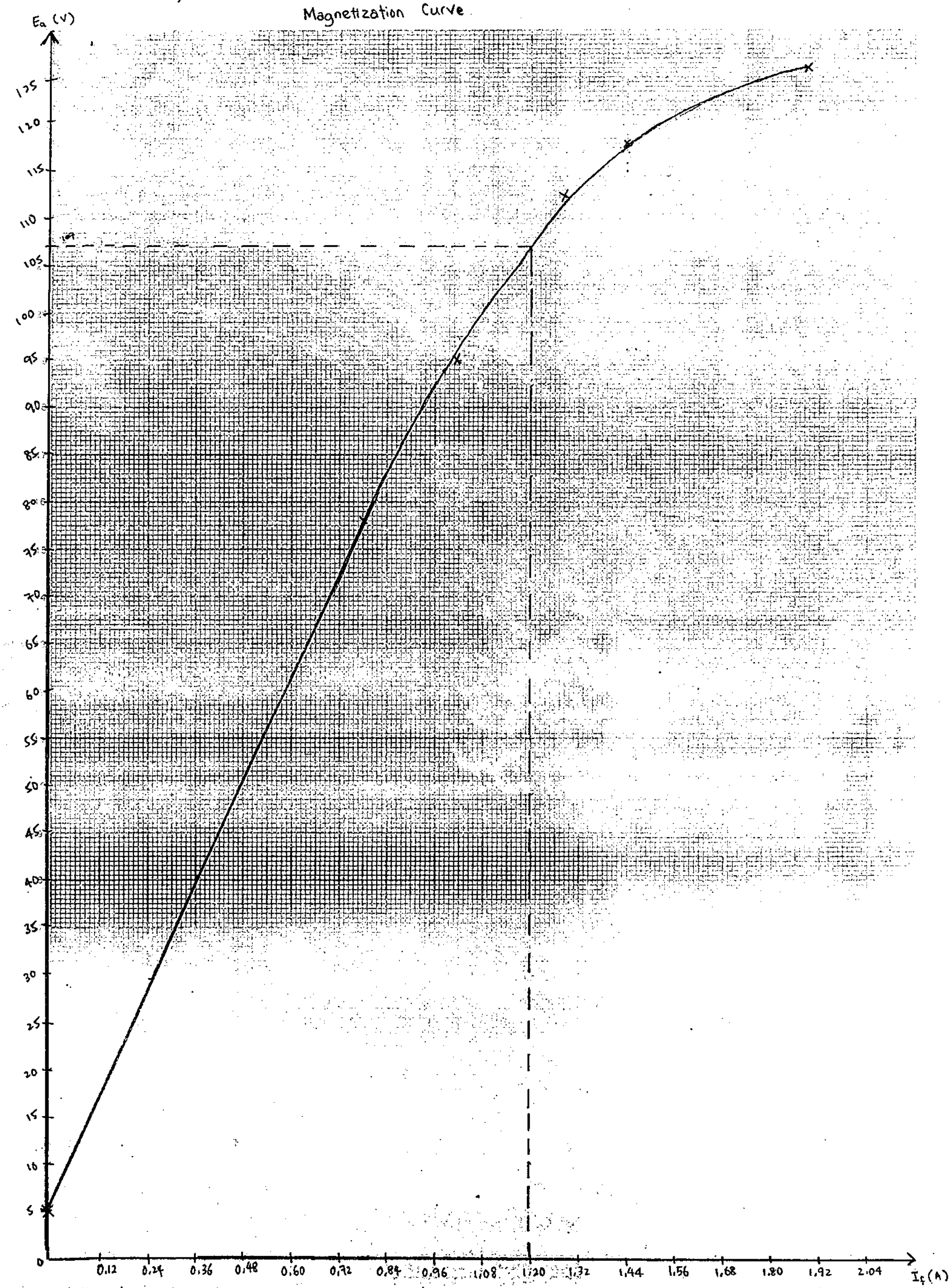
$= 1.06\,(j \times 2\pi \times 50 \times 0.201)$

$= 66.93 \angle 90^\circ$ V

$|V_{rms}| = 66.93$ V

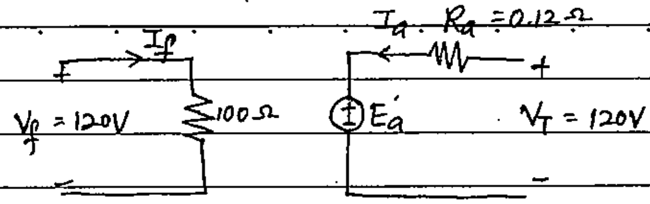
3) EE3010 Sem 2 2013 - 2014

Magnetization Curve



Date: No.

3) a)



$$I_f = \frac{120}{100} = 1.2A$$

From magnetization curve, $E_a = 107V$ @ 1200 rpm

At no-load condition, $E_a = V_T - I_aR_a$

$$= 120 - 5(0.12)$$
$$= 119.4V$$

$$\omega_m = \frac{119.4}{107} \times 1200$$
$$= 1339 \text{ rpm} = 140.22 \text{ rads}^{-1}$$

Under no-load condition, $P_{out} = 0W$

$$P_{dev} = P_{rot} = E_aI_a = 119.4 \times 5$$
$$P_{rot} = 597W$$

b) $I_a = 60A$, $E_a = V_T - I_aR_a$

$$= 120 - 60(0.12) = 112.8V$$

$$I_f = 1.28A$$
$$P_{dev} = E_aI_a$$
$$T_e\omega_m = E_aI_a$$
$$\omega_m = \frac{112.8}{107} \times 1200$$
$$= 1265.05 \text{ rpm} = 132.48 \text{ rads}^{-1}$$
$$T_e = \frac{112.8 \times 60}{132.48} = 51.09 \text{ Nm}$$

$$P_{dev} = E_aI_a$$
$$= 112.8 \times 60$$
$$= 6768W$$

$$P_{out} = P_{dev} - P_{rot}$$
$$= 6768 - 597$$
$$= 6171W$$

$$P_{in} = V_TI_{in} + V_fI_f$$
$$= 120(60) + 120(1.28)$$
$$= 7353.6W$$

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$
$$= \frac{6171}{7353.6} \times 100\%$$
$$= 83.92\%$$

Date: No.

c) $E_a \propto \omega_M$

$\omega_M = 900 \text{ rpm}$

$E_a = \frac{900}{1200} \times 107 = 80.25 \text{ V}$

$T_e' = 0.70\, T_e$

$T_e \propto I_a$

$I_a' = 0.7\, I_a = 0.7(60) = 42 \text{A}$

$V_T = E_a + I_a R_a$

$= 80.25 + 42(0.12)$

$= 85.29 \text{ V}$

d) $\frac{T_e'}{T_e} = \frac{\phi'}{\phi} \cdot \frac{I_a'}{I_a} = 0.5$

$I_a' = 0.5 \frac{\phi}{\phi'}$

$I_a' = 30 \frac{\phi}{\phi'}$

$\frac{E_a'}{E_a} = \frac{\phi'}{\phi} \times \frac{\omega_M'}{\omega_M}$

$\frac{E_a'}{112.8} = \frac{1500}{1265.05} \times \frac{\phi'}{\phi}$

$E_a' = 133.755 \frac{\phi'}{\phi}$

$V_T = 120\text{V} = E_a' + I_a' R_a$

$120 = 133.75 \frac{\phi'}{\phi} + (30 \frac{\phi}{\phi'})(0.12)$

$\times \frac{\phi'}{\phi}$, $133.75 (\frac{\phi'}{\phi})^2 - 120 \frac{\phi'}{\phi} + 3.6 = 0$

$\frac{\phi'}{\phi} = 0.8661$ or $\frac{\phi'}{\phi} = 0.0311$ (ignored)

$I_f \propto \phi$

$\frac{I_f'}{I_f} = 0.8661$

$I_f' = 0.8661 \times 1.28$

$= 1.1086$

$\frac{V_f}{I_f'} = R_{ext} + R_f$

$R_{ext} = \frac{120}{1.1086} - 100$

$= 8.245\ \Omega$

Date: No.

4) a) $Z_{th} = j80 \parallel (0.4 + j1.2)$

$= 1.2462 \angle 71.85^\circ \ \Omega$

$= 0.388 + j1.184 \ \Omega$

$S_{MAX} = \dfrac{R_2}{\sqrt{R_{th}^2 + (X_{th}+X_2)^2}}$

$= \dfrac{0.5}{\sqrt{0.388^2 + (1.184+1.5)^2}}$

$= 0.1844$

$\omega_s = \dfrac{120(50)}{4} = 1500 \text{ rpm} = 157.08 \text{ rads}^{-1}$

$\omega_M = (1-s)\omega_s$

$= (1-0.1844)(1500)$

$= 1223.4 \text{ rpm} = 128.11 \text{ rads}^{-1}$

b) $Z_{eq} = \left(\dfrac{R_2}{s} + jX_2\right) \parallel jX_M$

$= \left(\dfrac{0.5}{0.1844} + j1.5\right) \parallel j80$

$= 2.61 + j1.56 \ \Omega$

$Z_T = Z_{eq} + Z_1$

$= 2.61 + j1.56 + 0.4 + j1.2$

$= 3.01 + j2.76 \ \Omega$

$V_1 = \dfrac{415}{\sqrt{3}} = 239.6 \text{ V}$

$I_1 = \dfrac{V_1}{Z_T}$

$= \dfrac{239.6 \angle 0^\circ}{3.01 + j2.76}$

$= 58.67 \angle -42.52^\circ \text{ A}$

$pf = \cos 42.52^\circ = 0.7370 \text{ lag}$

$P_{in} = 3|V_1||I_1|\cos\theta$

$= 3 \times 239.6 \times 58.67 \times 0.7370$

$= 31.081 \text{ kW}$

$P_{cu,s} = 3|I_1|^2 R_1$

$= 3 \times (58.67)^2 \times 0.4$

$= 4.131 \text{ kW}$

$P_{ag} = P_{in} - P_{cu,s}$

$= 31.08 - 4.131 = 26.95 \text{ kW}$

$T_{MAX} = \dfrac{P_{ag}}{\omega_s}$

$= \dfrac{26.95 \times 10^3}{157.08} = 171.57 \text{ Nm}$

Date: No.

4) c) $s = 1$, $Z_{eq} = \left(\frac{0.5}{1} + j1.5\right) \parallel j80$

$= 0.482 + j1.475\ \Omega$

$Z_T = Z_{eq} + Z_1$

$= 0.482 + j1.475 + 0.4 + j1.2$

$= 2.817 \angle 71.76^\circ\ \Omega$

$V_1 = 239.6 \angle 0^\circ\ V$

$I_1 = \frac{V_1}{Z_T}$

$= \frac{239.6 \angle 0^\circ}{2.817 \angle 71.76^\circ}$

$= 85.06 \angle -71.76^\circ\ A$

$P_{in} = 3|V_1||I_1| \cos\theta$

$= 3 \times 239.6 \times 85.06 \times \cos 71.76^\circ$

$= 19.14\ kW$

$P_{cu,s} = 3|I_1|^2 R_1$

$= 3 \times (85.06)^2 \times 0.4$

$= 8.682\ kW$

$P_{ag} = P_{in} - P_{cu,s}$

$= 19.14 - 8.682$

$= 10.46\ kW$

$T_e = \frac{P_{ag}}{\omega_s}$

$= \frac{10.46 \times 10^3}{157.08}$

$= 66.59\ Nm$

d) $I_{start} = 3.5 I_{rated}$

$I_1 = 3.5 I_2$

$\frac{I_2}{I_1} = \frac{1}{3.5}$

$= \frac{2}{7}$

$\frac{V_1}{V_2} = \frac{I_2}{I_1} = \frac{2}{7}$

$V_1 : V_2 = 2 : 7$

$T_e \propto V^2$

$T_{start} = \left(\frac{2}{7}\right)^2 \times 66.59$

$= 5.44\ Nm$