NANYANG TECHNOLOGICAL UNIVERSITY

SEMESTER 1 EXAMINATION 2016-2017

EE3010 – ELECTRICAL DEVICES AND MACHINES

November / December 2016 Time Allowed: 2 hours

INSTRUCTIONS

1. This paper contains 4 questions and comprises 6 pages.
2. Answer ALL questions.
3. All questions carry equal marks.
4. This is a closed-book examination.
5. Unless specifically stated, all symbols have their usual meanings.

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1. (a) A magnetic circuit with the specified dimensions is as shown in Figure 1 on page 2. The center limb has a winding of 500 turns and there are air gaps in the left and right limbs as shown. The mean lengths of the various magnetic sections are $l_1 = 100$ cm, $l_2 = 79.85$ cm, $l_3 = 120$ cm and $l_g = 1.5$ mm. The center limb has a cross-sectional area of 32 cm^2 and each of the side limbs has a cross-sectional area of 16 cm^2. The magnetization curve for the material is given by the following:

H (At/m)	100	220	260	300	320
B (T)	0.1	0.2	0.25	0.3	0.35

(i) Let ϕ_c be the flux in the center limb and ϕ_g be the flux in the air gaps. Using the magnetic equivalent circuit of Figure 1, determine the exciting current I required to produce a flux of 0.4 mWb in each air gap. You may neglect leakage and fringing in your calculations. The permeability of free space μ_o is $4\pi \times 10^{-7}$ H/m.

(12 Marks)

Note: Question No. 1 continues on page 2.

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(ii) Determine the energy stored in the air gaps and in the core, respectively.

(5 Marks)

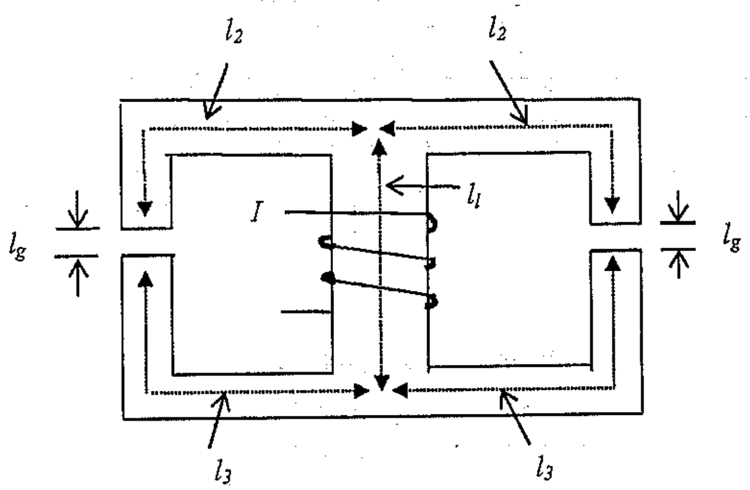

Figure 1

(b) A magnetic circuit is as shown in Figure 2, where f_s is the force exerted on the movable part. Each of the fixed and movable parts has a cross-sectional area of 12 cm^2. The fixed part has a winding of 200 turns. Determine the supply voltage V_s required to keep the movable part at a distance of $x = 1.5$ mm from the fixed part if $R_s = 25$ Ω and the magnetic force acting on the movable part is $f_s = 167$ N. Also, determine the energy stored in the magnetic field for $x = 1.5$ mm. The permeability of free space μ_o is 4π x 10^{-7} H/m. You may neglect the reluctances of the fixed and moveable parts in your calculations.

(8 Marks)

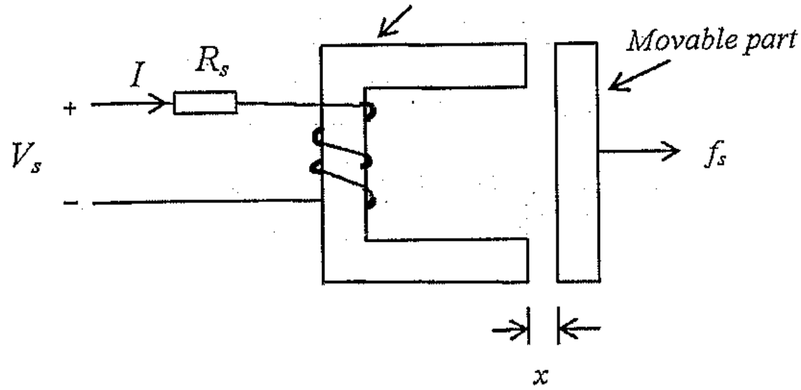

Figure 2

2. (a) Consider a 10-kVA, 440/220-V, 50-Hz single-phase transformer. The open-circuit test measurement was performed on the low-voltage side of the transformer and the short-circuit test measurement was performed on the high-voltage side of the transformer. The tests gave the following results:

Open-circuit test:

$V_{oc} = 220$ V, $I_{oc} = 1.5$ A, $P_{oc} = 80$ W.

Short-circuit test:

$V_{sc} = 15$ V, $I_{sc} = 22.727$ A, $P_{sc} = 80$ W.

Find the parameters of the approximate equivalent circuit referred to the low-voltage side. Using the approximate equivalent circuit obtained, determine the (a) voltage regulation and (b) efficiency of the transformer at full-load and 0.85 power factor lagging with rated voltage across the load.

(17 Marks)

(b) A 440/220-V, 20-kVA, 50-Hz transformer is connected as an autotransformer to give 440/660 V. Calculate its kVA rating and the currents in its windings as well as the efficiency at full-load, 0.8 power factor lagging if the two-winding transformer has an efficiency of 98% at full-load, 0.8 power factor lagging.

(8 Marks)

3. (a) A 3-phase, 460-V, 60-Hz, 4-pole wye-connected induction motor draws a line current of 90 A at a lagging power factor of 0.8 from the supply when running at a slip of 2.5%. The stator resistance per phase is 0.07 Ω and the rotational losses are 2800 W. Determine

(i) the speed at which the motor is running.

(ii) the torque developed by the motor.

(iii) the efficiency of the motor.

(6 Marks)

Note: Question No. 3 continues on page 4.

(b) A 3-phase, 2300-V, 60-Hz, 4-pole, wye-connected induction motor is tested with the following results:

No-load test	:	$V_{line} = 2300\,\text{V},\ I_{line} = 7.7\,\text{A},\ P_{in} = 2870\,\text{W}$
Locked-rotor test	:	$V_{line} = 768\,\text{V},\ I_{line} = 50.3\,\text{A},\ P_{in} = 18.2\,\text{kW}$
DC test	:	$V_{DC} = 23.2\,\text{V},\ I_{DC} = 10.3\,\text{A}$

(i) Calculate the rotational losses of the motor.

(3 Marks)

(ii) Obtain the parameters of the induction motor and draw its single-phase equivalent circuit referred to the stator. Assume that the stator leakage reactance and the rotor leakage reactance referred to the stator are equal in magnitude.

(9 Marks)

(c) A 3-phase, 230-V, 60-Hz, 6-pole, wye-connected induction motor develops its maximum torque at a slip of 15% when operated at rated voltage and frequency. Assume that the stator resistance R_1 is negligible. Determine the speed at which maximum torque is developed if the motor is operated at rated voltage and 50-Hz frequency. (Hint: You may use the Thevenin's equivalent circuit.)

(7 Marks)

4. (a) The armature and field resistances of a dc machine are $0.15\,\Omega$ and $150\,\Omega$, respectively. The effects of armature reaction can be neglected. The magnetization curve of the machine obtained at a speed of 1700 rpm is shown in Figure 3 on page 6. Consider the following cases:

(i) The machine is driven at 1700 rpm and is operated as a separately-excited dc generator. If the generator is supplying a load with an armature current of 100 A, determine its output power for a constant field current of 0.5 A.

(4 Marks)

(ii) The machine is driven at 1500 rpm and is operated as a separately-excited dc generator. If the generator is supplying a load with an armature current of 100 A, determine its output power for a constant field current of 1 A.

(4 Marks)

Note: Question No. 4 continues on page 5.

(iii) The machine is reconnected as a shunt dc generator and is driven at 1700 rpm. An external resistor $R_{ext} = 20\ \Omega$ is connected in series with the field winding. If the generator is delivering an armature current of 200 A, determine its terminal voltage.

(5 Marks)

(b) A 240-V dc shunt motor has an armature resistance of $0.75\ \Omega$. At full load, the motor rotates at 1200 rpm, draws a line current of 7 A from the supply and the field current is 1 A. The rotational losses and armature reaction in the motor are negligible. Assume that the motor is operating in the linear part of the magnetization curve. Consider the following cases:

(i) If the field current is reduced to 0.7 A due to the addition of a series resistance in the field circuit, determine the speed of the motor when it is running with 60% full load torque.

(6 Marks)

(ii) Determine the speed of the motor when driving a load whose torque varies directly as the speed (i.e., $T_L \propto n_m$) and the field current is reduced to 0.5 A due to the addition of a series resistance in the field circuit.

(6 Marks)

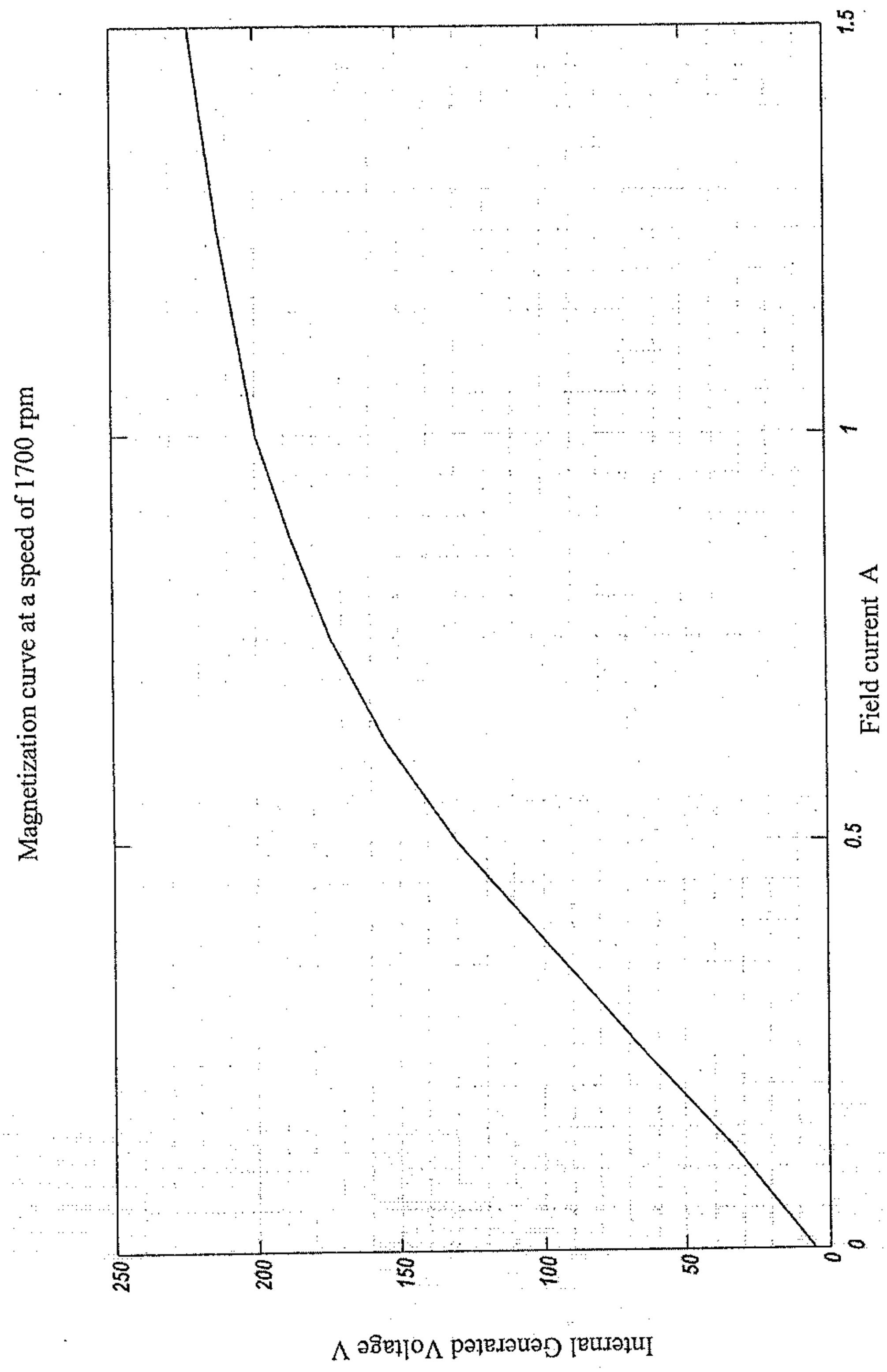

Figure 3

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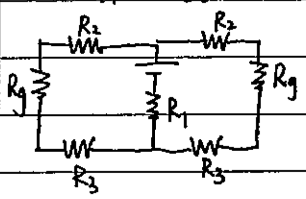
1(a) $l_1 = 1\text{m}$, $l_2 = 0.7985\text{ m}$, $l_3 = 1.2\text{m}$, $l_g = 1.5\times10^{-3}\text{m}$.

$A_c = 32\times10^{-4}\text{m}^2$, $A_s = 16\times10^{-4}\text{m}^2$

i) $\Phi_g = 0.4\times10^{-3}\text{Wb}$, $B_g = \frac{0.4\times10^{-3}}{16\times10^{-4}} = 0.25$

$\Phi_c = 0.4\times10^{-3}\times2 = 0.8\times10^{-3}\text{Wb}$, $B_c = \frac{0.8\times10^{-3}}{32\times10^{-4}} = 0.25$

$\mu = \frac{B}{H} = \frac{0.25}{260}$



$R_1 = \frac{l_1}{\mu A_c} = \frac{1}{\frac{0.25}{260}\times32\times10^{-4}} = 325000\ \text{At/wb}$

$R_2 = \frac{l_2}{\mu A_s} = \frac{0.7985}{0.25/260\times16\times10^{-4}} = 519025\ \text{At/wb}$

$R_3 = \frac{l_3}{\mu A_s} = \frac{1.2}{0.25/260\times16\times10^{-4}} = 780000\ \text{At/wb}$

$R_g = \frac{l_g}{\mu_0 A_s} = \frac{1.5\times10^{-3}}{4\pi\times10^{-7}\times16\times10^{-4}} = 746039\ \text{At/wb}$

$\text{mmf}_{total} = R_1\cdot\Phi_c + (R_2+R_3+R_g)\,\Phi_g$

$= 325000\times0.8\times10^{-3} + (519025+780000+746039)\times0.4\times10^{-3}$

$= 1078.0256\ \text{At}$

$I = \frac{\text{mmf}}{N} = \frac{1078.0256}{500} = 2.156\text{A}$

ii) $E_g = \frac{1}{2}\times R_g\cdot\Phi_g^2\times2 = 746039\times(0.4\times10^{-3})^2$

$= 0.1194\text{J}$

$E_c = \frac{1}{2}(R_2+R_3)\cdot\Phi_g^2\times2 + \frac{1}{2}R_1\cdot\Phi_c^2$

$= (519025+780000)\times(0.4\times10^{-3})^2 + \frac{1}{2}\times325000\times(0.8\times10^{-3})^2$

$= 0.3118\text{J}$

b) $R = \frac{2x}{\mu_0\cdot A} = \frac{2x}{4\pi\times10^{-7}\times12\times10^{-4}}$

$= 1326291192x$

$\cancel{x = 1.5\times10^{-3}\text{m}}$

$\cancel{R = 1989437\ \text{At/wb}}$

$|f| = \left|\frac{dW}{dx}\right|$

$167 = \frac{1}{2}I^2\cdot\left|\frac{d}{dx}\frac{200^2}{1326291192x}\right|$

$167\times2 = I^2\cdot\frac{40000}{1326291192}\left|\frac{d}{dx}\frac{1}{x}\right|_{x=1.5\times10^{-3}}$

$I = 4.992\text{A}$

$R = 1989437\ \text{At/wb}$ when $x = 1.5\times10^{-3}\text{ m}$.

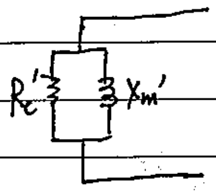
$W = \frac{1}{2}LI^2$

$= \frac{1}{2}\frac{N^2}{R}\cdot I^2$

$= \frac{1}{2}\times\frac{200^2}{1989437}\times4.992^2$

$= 0.2505\text{J}$

7(a)



$pf = \frac{P_{oc}}{V_{oc} \cdot I_{oc}} = \frac{80}{220 \times 1.5} = 0.2424$

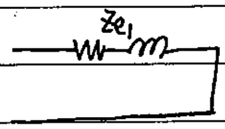
$\theta = \cos^{-1} 0.2424 = 75.97°$

$I_c' = 1.5 \times \cos 75.97° = 0.3636$

$I_m' = 1.5 \times \sin 75.97° = 1.4553$

$R_c' = \frac{220}{0.3636} = 605.06\,\Omega$

$X_m' = \frac{220}{1.4553} = 151.17\,\Omega$.



$Ze_1 = \frac{V_{sc}}{I_{sc}} = \frac{15}{22.727} = 0.66\,\Omega$

$I_{sc}^2 \cdot Re_1 = P_{sc}$

$Re_1 = \frac{80}{22.727^2} = 0.155\,\Omega$.

$Xe_1 = \sqrt{Ze_1^2 - Re_1^2} = \sqrt{0.66^2 - 0.155^2}$

$a = 440/220 = 2$ $\quad = 0.642\,\Omega$.

$Re_2 = \frac{Re_1}{a^2} = \frac{0.155}{4} = 0.03875\,\Omega$.

$Xe_2 = \frac{Xe_1}{a^2} = \frac{0.642}{4} = 0.1605\,\Omega$

$\theta = \cos^{-1} 0.85 = 31.788°$

$S = 10000 \angle 31.788°$ kVA

$I_2 = \left(\frac{S}{V_2}\right)^* = \left(\frac{10000 \angle 31.788}{220}\right)^* = 45.455 \angle -31.788°$ A

$V_1' = V_2 + I_2 \cdot Ze_2$

$= 220 + 45.455 \angle -31.788 \times (0.03875 + j0.1605)$

$= 225.402 \angle 1.341°$ V

Voltage regulation $= \frac{225.402 - 220}{220} = 2.455\,\%$

$P_{out} = 10\,000 \times 0.85 = 8500$ W

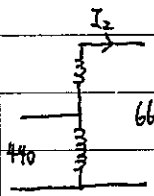
$P_{loss} = I_2^2 \cdot Re_2 + \frac{V_1^2}{R_c}$

$= 45.455^2 \times 0.155 + \frac{225.402^2}{605.06}$

$= 404.223$ W

$\eta = \frac{8500}{8500 + 404.223} = 95.46\,\%$

b)



$I_2 = \frac{20000}{220} = 90.909$ A

kVA Rating $= I_2 \cdot V_2' = 90.909 \times 660$

$= 60$ kVA

$P_{loss} = 10k \times 0.8 \times (1 - 98\%) = 160$ W

$\eta = \frac{60000 \times 0.8}{60000 \times 0.8 + 160} = 99.67\,\%$

3/a i)

$$n_{sync} = \frac{120f}{P} = \frac{120 \times 60}{4}$$
$$= 1800 \text{ rpm}$$

$$n_m = n_{sync}(1-s)$$
$$= 1800 \times (1 - 2.5\%)$$
$$= 1755 \text{ rpm}$$

ii)

$$P_{in} = V_L I_L pf \cdot \sqrt{3}$$
$$= 460 \times 90 \times 0.8 \times \sqrt{3}$$
$$= 57366 \text{ W}$$

$$P_{SCL} = 3 \times I_L^2 \cdot R_1$$
$$= 3 \times 90^2 \times 0.07$$
$$= 1701 \text{ W}$$

$$P_{AG} = P_{in} - P_{SCL} = 57366 - 1701$$
$$= 55665 \text{ W}$$

$$T_{dev} = \frac{P_{AG}}{W_m}$$
$$= \frac{55665}{1755 \times \frac{2\pi}{60}}$$
$$= 302.884 \text{ N-m}$$

iii)

$$P_{dev} = P_{AG}(1-s)$$
$$= 55665 \times (1 - 2.5\%)$$
$$= 54273.375 \text{ W}$$

$$P_{out} = P_{dev} - P_{rot}$$
$$= 54273.375 - 2800$$
$$= 51473.375 \text{ W}$$

$$\eta = \frac{P_{out}}{P_{in}} = \frac{51473.375}{57366} = 89.73\%$$

b) DC Test

$$2R_1 = \frac{V_{DC}}{I_{DC}} = \frac{23.2}{10.3}$$
$$R_1 = 1.1262 \, \Omega$$

Lock-rotor Test($S=1$)

$3 \cdot I_{line}^2 \cdot (R_1+R_2) = P_{in}$

$3 \times 50.3^2 \; (R_1+R_2) = 18.2 \times 10^3$

$R_1+R_2 = 2.3978\Omega$

$R_2 = 1.2716\Omega$

$Z = \frac{V_{line}/\sqrt{3}}{I_{line}} = \frac{768/\sqrt{3}}{50.3}$

$= 8.8152\Omega$

$X_1+X_2 = \sqrt{Z^2-(R_1+R_2)^2}$

$= \sqrt{8.8152^2 - 2.3978^2}$

$= 8.4828\Omega$

$X_1 = X_2 = 4.2414\Omega$

No-load Test ($S=0$)

$Z' = \frac{V_{line}/\sqrt{3}}{I_{line}} = 172.4553\Omega$

$X_1 + X_m = \sqrt{Z'^2 - R_1^2}$

$= \sqrt{172.4553^2 - 1.1262^2}$

$= 172.4516\Omega$

$X_m = 172.4516 - 4.2414$

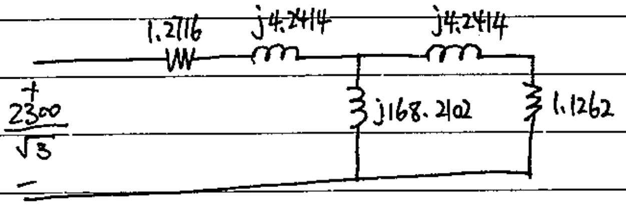
$= 168.2102\Omega$

i) $P_{rot} = P_{in} - 3 \cdot I_{Line}^2 \cdot R_1$ @ no-load

$= 2870 - 3 \times 7.7^2 \times 1.1262$

$= 2670\,W$

ii)

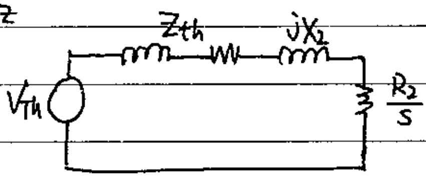


c) $n_{sync} = \frac{60 \times 120}{6} = 1000$ rpm @ 50Hz

$n_m = n_{sync}(1 - S_{max})$

$= 1000 \times (1 - 15\%)$

$= 850$ rpm.

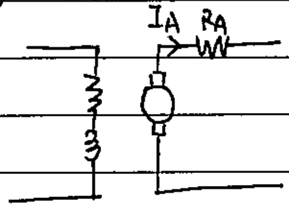


$S_{max} = \frac{R_2}{|jX_2 + Z_{th}|}$

~~Zth no change~~

so S_{max} no change.

4/a i) generator



$I_F = 0.5\,A,\ E_A = 130V$

$V_T = E_A - I_A R_A$

$= 130 - 100 \times 0.15$

$= 115\,V$

$P_{out} = V_T I_A$

$= 115 \times 100$

$= 11.5\,kW$

ii) $I_F = 1A,\ E_A = 200\,V$ @1700 rpm

$\frac{E_A}{E_A'} = \frac{n_m}{n_m'}$ $\quad \frac{200}{E_A'} = \frac{1700}{1500}$

$E_A' = 176.4706V$

$V_T' = E_A' - I_A R_A$

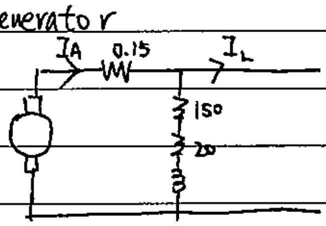
$= 176.4706 - 100 \times 0.15$

$= 161.4706\,V$

$P_{out} = V_T' \cdot I_A$

$= 16147.06\,W$

iii) generator



$E_A = I_A R_A + I_F\,(R_F + R_{ext})$

$= 0.15 \times 200 + I_F(150+20)$

$\cancel{= 30 + I_F 170}$

$= 30 + 170 I_F$

$\therefore\ I_F = 1A,\ E_A = 200A$

$V_T = I_F\ (R_F + R_{ext})$

$= 1 \times 170$

$= 170\,V$

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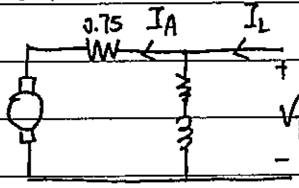
bi) motor



$T_{dev} \propto \Phi \cdot I_A \qquad \Phi \propto I_F$

$\frac{T_{dev}}{T_{dev}'} = \frac{I_F \cdot I_A}{I_F' \cdot I_A'}$

$\frac{1}{0.6} = \frac{1}{0.7} \times \frac{(7-1)}{I_A'}$

$I_A' = 5.1429\,A$

$E_A' = V_T - I_A' \cdot R_A$

$= 236.1428\,V \qquad E_A \propto \Phi W_m \quad \Phi \propto I_F \quad W_m \propto n_m$

$\frac{E_A}{E_A'} = \frac{I_F}{I_F'} \cdot \frac{n_m}{n_m'}$

$\frac{240 - 6 \times 0.75}{236.1428} = \frac{1}{0.7} \times \frac{1200}{n_m'}$

$n_m' = 1719$ rpm.

ii) $E_A'' = V_T - I_A'' \cdot R_A$

$= 240 - (7-0.5) \times 0.75$

$= 235.125\,V$

$T_L = T_{dev}$ (no P_{rot}) $\quad T_{dev} = \frac{E_A I_A}{W_m} \propto n_m$

$\therefore E_A \propto n_m^2$

$\frac{E_A}{E_A''} = \frac{I_F}{I_F''} \cdot \frac{n_m^2}{n_m''^2}$

$\frac{240 - 6 \times 0.75}{235.125} = \frac{1}{0.5} \times \frac{1200^2}{n_m''^2}$

$n_m'' = 1696$ rpm