MIDDLE EAST TECHNICAL UNIVERSITY

ELECTRICAL AND ELECTRONICS ENGINEERING DEPARTMENT

EE 462 Utilization of Electrical Energy

Second Midterm Examination

**Duration: 100 minutes**

**Attempt all questions**

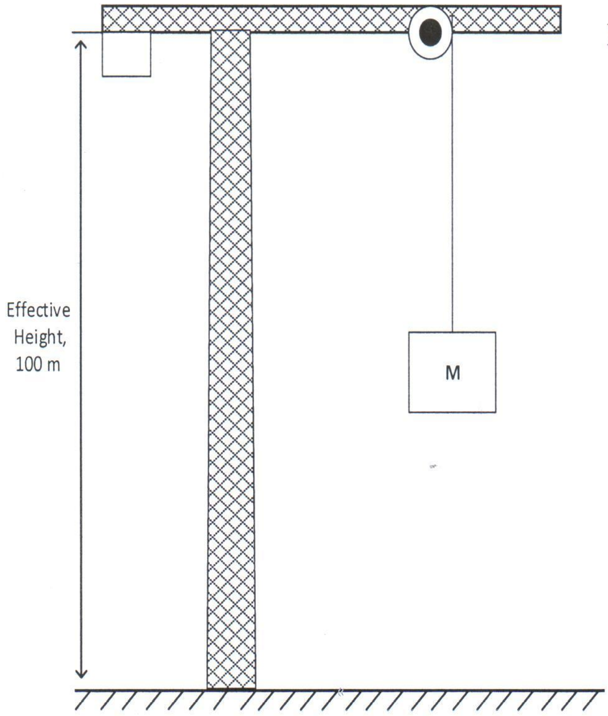
**Show all your calculations.**

26 May 2016

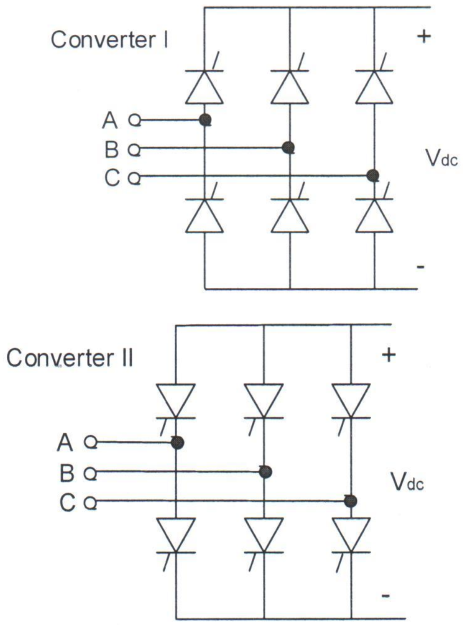
NAME and SURNAME _________________________

| | |
|---|---|
| **Q1** | |
| **Q2** | |
| **Total** | |

**Q1(50+10 pts bonus)**




Recommended blocks:




Consider the crane hoist shown in the figure.

- Loaded hook, 1000 kg max
- Unloaded hook, 50 kg
- Drum diameter, D = 50 cm
- The loaded hook is initially stationary on the ground and accelerated to the constant hoisting speed by the dc motor at limit value of electromechanical torque.
- Constant hoisting speed for loaded hook, v = 10 m/s. This condition defines the motor rating (rated speed and rated torque).
- Overhauling speed for unloaded hook, v = 25 m/s.
- The separately excited dc motor is coupled to the shaft via a speed down gear-box having $1/(5\pi/6)$ gear ratio.
- Induced armature emf $E_a$ = 250 V at rated speed and rated $I_f$ . Magnetization characteristic can be assumed to be linear. $R_a = 0.2\ \Omega$
- In overhauling mode, field weakening technique ($I_f$ is temporarily reduced) is applied in order to keep $E_a$ constant at 250 V.
- $T_{e(limit)} = 1.25 \times T_{e(rated)}$ during acceleration and braking.
- The load is suspended electrically at the top of the tower for a period of 15 s.
- The loaded hook while ascending at constant speed and approaching the top of the tower, is brought to a stop by the drag of gravity.
- The unloaded hook is accelerated downwards under the influence only of gravitational force. The dc machine is energized after reaching overhauling speed.

- The unloaded hook is brought to a stop by regenerative braking while approaching the ground level.
- Neglect rotational losses and viscous friction. Take g ≈ 10 $m^2/s$. Comprehension force cannot be applied to the steel rope.

a) Calculate rated values of electromechanical force and torque, and rotational speed on the drum side.

b) Calculate rated values of electromechanical torque and speed at the motor shaft.

c) Write down the force balance in bringing the speed of the initially stationary loaded hook to the hoisting speed. Calculate the accelerating force, linear acceleration, vertical displacement, and the corresponding acceleration time.

d) Calculate armature current and applied armature voltage during hoisting operation. Find the time spent in hoisting the loaded hook at constant speed by assuming that the corresponding displacement is 75 meters.

e) The ascending load is then brought to a stop at the top of the tower under the drag of the gravitational force after deenergizing the motor. Calculate the required time and corresponding displacement.

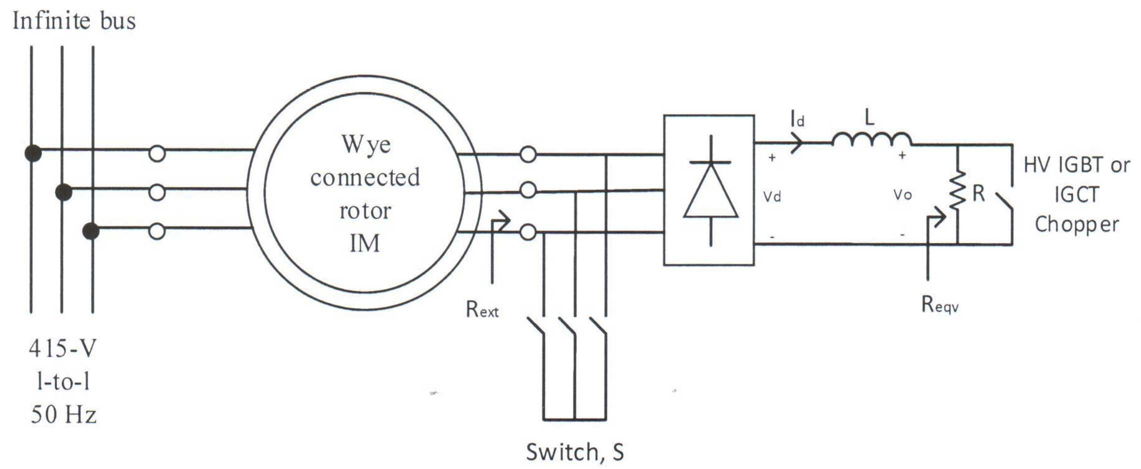
f) Write down the force balance equation in bringing the linear speed of the initially stationary unloaded hook to overhauling speed under the influence of the gravitational force. Calculate the corresponding displacement and the required time.

g) Calculate armature current and applied armature voltage in overhauling mode. Do not forget about field weakening action!

h) (5 pts bonus) The overhauling speed should be reduced by regenerative braking while the unloaded hook is approaching to the ground surface. Is the application of the regenerative braking enough to put the hook gently on the surface? Explain why.

i) (5 pts bonus) One complete operation cycle of the crane hoist is as described above. Which converter or converters should be used for this purpose? Mark it/them on four-quadrant speed/torque plane.

**Q2(50+5 pts bonus).** A 415-V, 3-phase, 4-pole, 50-Hz, Y-connected induction motor of wound-rotor type is used to drive a constant-torque load, $T_L = 2000$ Nm. Starting and speed control will be achieved by external rotor resistance control as shown in the figure below.




The induction motor has the following parameters on per-phase-wye basis:

$r_1 = 0.01\overline{3}\ \Omega$, $r_2' = 0.01\overline{6}\ \Omega$, $x_1 = x_2' = 0.05\ \Omega$, $x_m = 5\ \Omega$

stator / rotor turns-ratio of this machine is 1.5. $J = 1.0$ Kg-m2

Use the simplified equivalent circuit in which the magnetizing branch has been moved to the stator terminals and neglect friction and windage loss.

**a.** Show that $R_{ext} \approx R_{eqv}/2$

**b.** Calculate $R_{eqv}$ in order to produce maximum starting torque when the motor-load combination is stationary. What is the maximum value of electromechanical torque?

**c.** Suppose now that the above system is equipped with a digital controller in order to adjust $R_{eqv}$ steplessly. Recommend the minimum value of R to keep the electromechanical torque constant at its maximum value during starting while the motor-load combination is accelerating from standstill to 1250 rpm (starting at maximum torque). Calculate the duty-cycle, D of the chopper for the recommended value of R at shaft speeds i) 0, and ii) 1250 rpm.

**d.** Calculate the acceleration time at maximum torque as in (c) from standstill to 1250 rpm.

**e.** Does your design in (c) allow the wound-rotor induction motor to drive the given constant-torque load at 1000 rpm? Prove your proposition.

**f.** (5 pts bonus) What may be the practical usefulness of the switch, S in the circuit diagram? Explain.

Q1. a) During constant hoisting speed period:

$$\omega_d = V/r = 10/0.25 = 40 \text{ rad/s} \;//$$

$$f_e = f_g = m \cdot g = 1000 \times 10 = 10\,000 \text{ N} \;//$$

During hoisting at constant speed $T_d = T_e = f_g \cdot r$

$$T_d = 10\,000 \times 0.25 = 2500 \text{ Nm} \;//$$

b) $N_m/N_d = (5\pi/6)$ given.

$$\omega_{r(rated)} = \left(\frac{N_m}{N_d}\right)\omega_d = \left(\frac{5\pi}{6}\right) \cdot 40 = 33.\bar{3}\pi = 104.72 \text{ rad/s} \;//$$

$$\equiv 1000 \text{ rpm} \;//$$

$$T_{e(rated)} = T_d / (N_m/N_d) = 2500/(5\pi/6) = 955 \text{ Nm} \;//$$

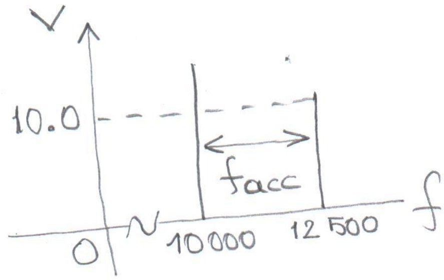
$$P_{m(rated)} = T_{e(rated)} \times \omega_{r(rated)} \equiv 100 \text{ kW}$$

c) $f_{e(lim)} - f_g = Ma \;//$

$$f_{e(lim)} = 1.25 \times f_{e(rated)} = 1.25 \times 10000 = 12\,500 \text{ N} \;//$$

$$12\,500 - 10\,000 = 1000 \times a \Rightarrow a = 2.5 \text{ m/s}^2 \;//$$

$$f_{acc} = 12\,500 - 10\,000$$
$$= 2\,500 \text{ N} \;//$$

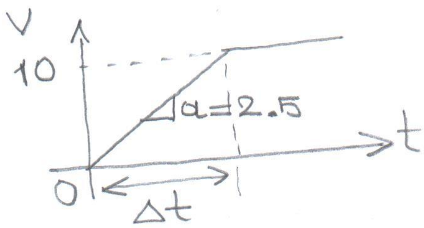



$$\frac{\Delta V}{\Delta t} = a$$

$$\frac{10}{\Delta t} = 2.5 \Rightarrow \Delta t = 4 \text{ s} \;//$$

Alternatively,

$$V = V_0 + at \Rightarrow \Delta t = \frac{10}{2.5} = 4 \text{ s}$$

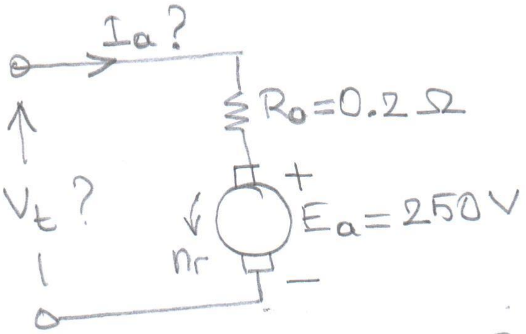


2/10

$x - x_0 = V_0 t + \frac{1}{2} a \Delta t^2$ where, $x_0 = V_0 = 0$

$\Delta x = \frac{1}{2} \times 2.5 \times 4^2 = 20 \text{ m}$ //

d) $E_a = 250$ V at $n_r = 1000$ rpm




$E_a = K \omega_r$

$250 = K * 33.\overline{3}\pi$

$\Rightarrow K = 2.387$

$T_e = K I_a \Rightarrow$

$I_a = T_e/K = 955/2.387 = 400$ A //

$V_t = E_a + R_a I_a$

$= 250 + 0.2 \times 400$

$V_t = 330$ V //

$\Delta x = V \times \Delta t \Rightarrow \Delta t = \Delta x / V = 75/10$

$\Delta t = 7.5$ s //

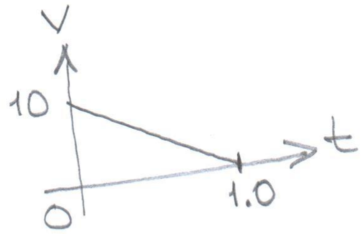
e) $a = -g = -10 \text{ m/s}^2$

$\frac{\Delta V}{\Delta t} = a \Rightarrow \frac{(0-10)}{\Delta t} = -10$

$\Delta t = 1$ s //

$\Delta x = \frac{1}{2} a (\Delta t)^2 = \frac{1}{2} 10 \times 1^2$

$\Delta x = 5$ m //

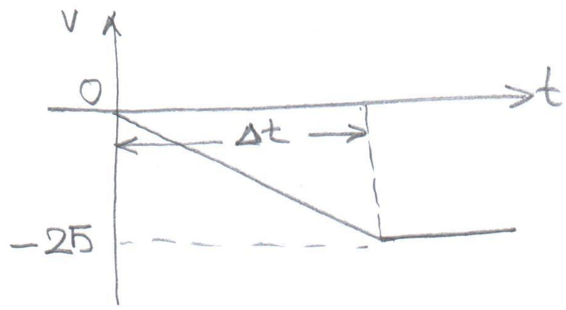



Check that

$20 + 75 + 5 = 100$ m

which is the tower height!

f) $a = g = 10\ \mathrm{m/s^2}$




$$\frac{\Delta V}{\Delta t} = g \Rightarrow \Delta t = \frac{\Delta V}{g}$$

$\Delta t = 2.5\ \mathrm{s}$ //

$$\Delta X = \frac{1}{2} g (\Delta t)^2 = \frac{1}{2} 10 \times (2.5)^2$$

$\Delta X = 31.25\ \mathrm{m}$ //

Note: $\Delta X$ and $\Delta t$ are independent of M!

$$f_g - f_e = Ma$$
$$Mg - 0 = Ma$$
$$\Rightarrow a = g$$ //

g) $T_e = \left(\frac{50}{1000}\right) \times T_{e(rated)}$

$$= \left(\frac{50}{1000}\right) \times 955\ \mathrm{Nm}$$

New $T_e = 47.75\ \mathrm{Nm}$ //

$E_a = 250 = K' \times \omega_r' = K'\left(\frac{25}{10}\right) 104.72$ ← $E_a$ is kept cnst by controlling $I_f$, in field weakening mode.

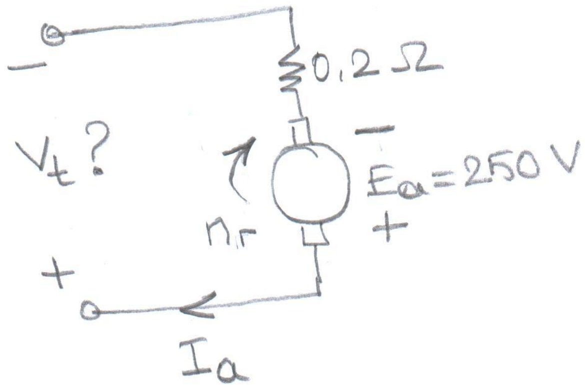
New K, $K' = \frac{250 \times 10}{25 \times 104.72} = 0.955$ //

New $I_a = T_e / K' = 47.75 / 0.955 = 50\ \mathrm{A}$ //

$V_t = E_a - I_a R_a$

$= 250 - 50 \times 0.2$

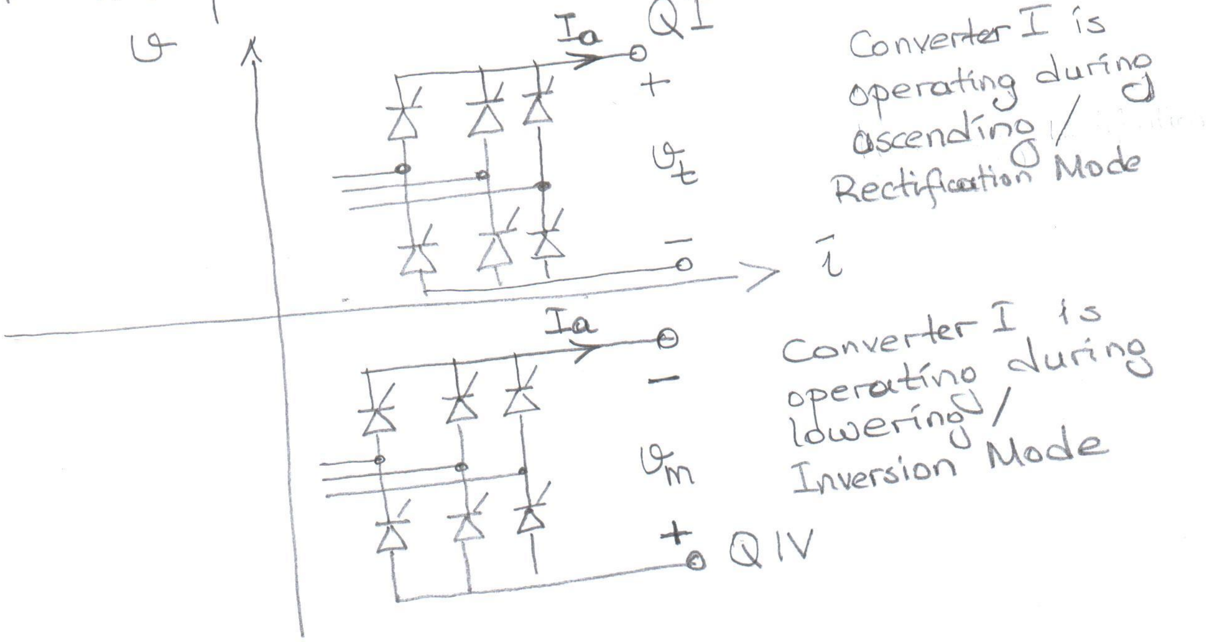
$V_t = 240\ \mathrm{V}$ //

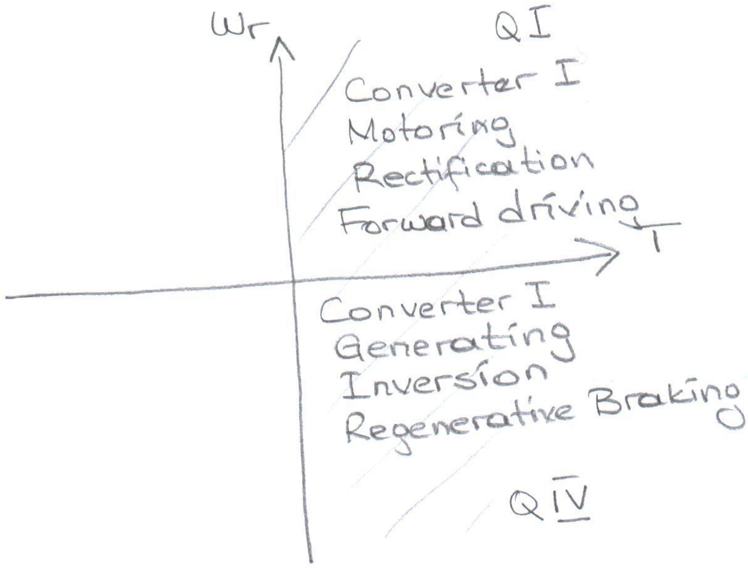



Observe:
with respect to hoisting operation, direction of armature current remains the same while the polarities of $V_t$ and $E_a$, and direction of rotation are all reversed!

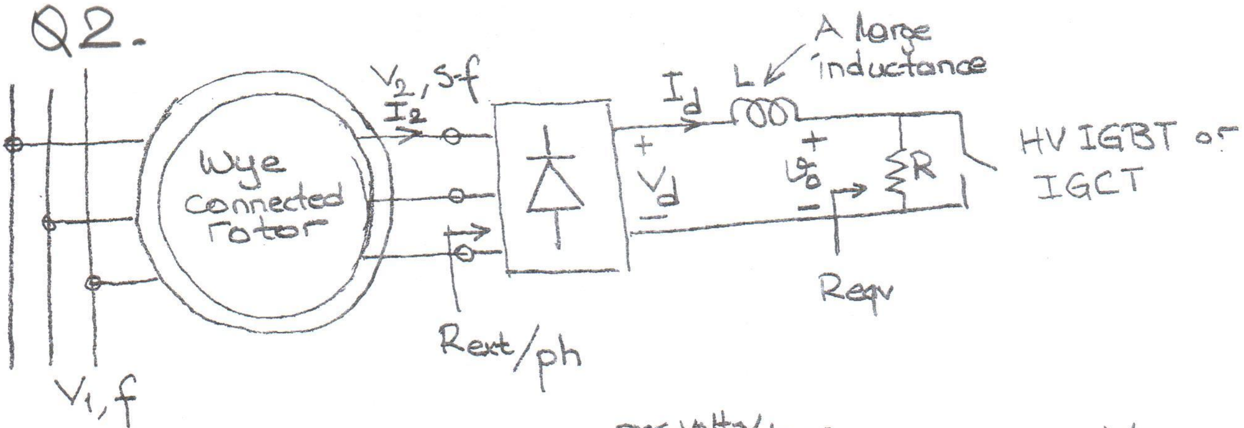
h) Just after regenerative braking (regenerative braking is not effective at very low speeds) fail-safe brake is to be operated.

i) On $v/i$ plane



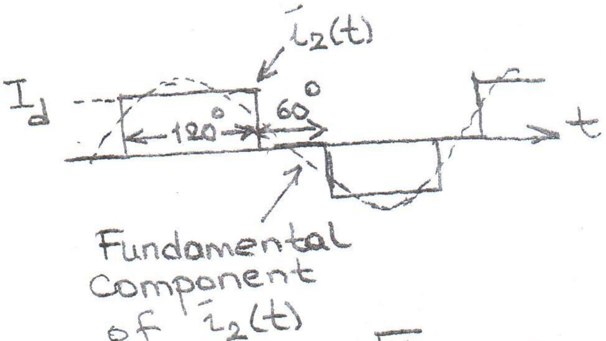



Q2. 




rms volts/phase

$$V_d = \frac{3\sqrt{3}}{\pi}\hat{V}_2 = \frac{3\sqrt{3}}{\pi}\sqrt{2}\cdot V_2 \implies V_2 = \frac{\pi V_d}{3\sqrt{3}\sqrt{2}} \quad //$$



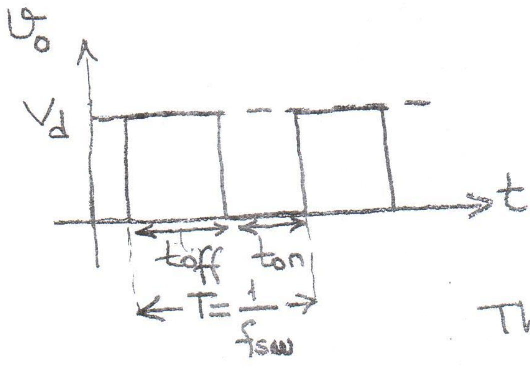

Since L is very large, $i_d(t)$ can be assumed to be a pure dc, $I_d$.

Therefore,

$$I_2 \simeq I_{2f} \quad //$$

True rms; rms value of fundamental component

$$I_2 = \sqrt{\frac{2}{3}}\cdot I_d \quad //$$




Duty ratio, $D = \dfrac{t_{on}}{t_{on}+t_{off}} = \dfrac{t_{on}}{T}$

$$R_{eqv} = \frac{t_{off}}{T}\cdot R = \frac{V_d}{I_d} \quad //$$

Therefore, $R_{eqv} = (1-D)\cdot R$ //

$$R_{ext} = \frac{V_2}{I_{2f}} \simeq \frac{V_2}{I_2} = \frac{(\pi V_d / 3\sqrt{3}\sqrt{2})}{\sqrt{\frac{2}{3}}\, I_d} = \left(\frac{\pi}{3}\right)\frac{1}{2}\left(\frac{V_d}{I_d}\right)$$

per phase

Since $\left(\frac{\pi}{3}\right) \simeq 1$ then $R_{ext} \simeq \frac{1}{2}\left(\frac{V_d}{I_d}\right)$ //

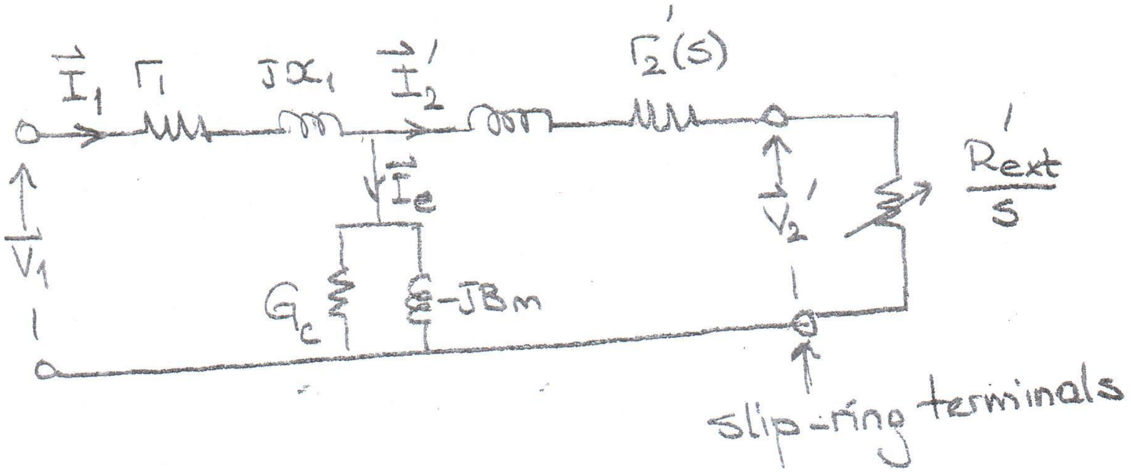
Therefore, $R_{ext} = \dfrac{R_{eqv}}{2}$ //

$$R_{ext} = [(1-D)R]/2 \quad //$$

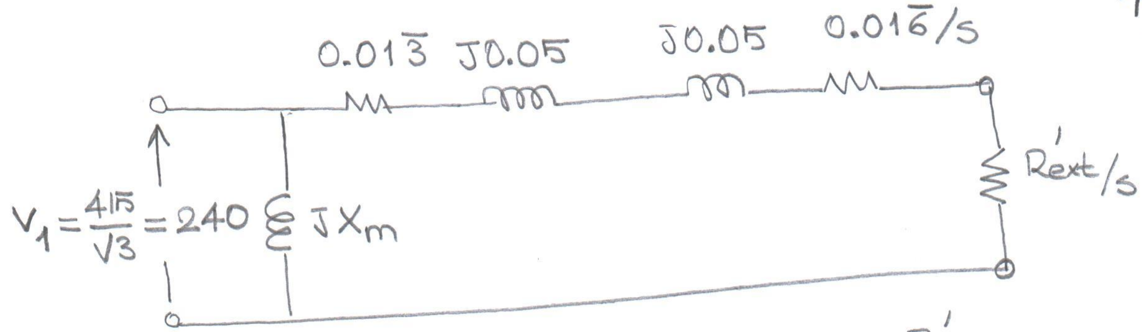
pto →

Frequency transformation : $R_{ext} \longrightarrow R_{ext}/s$

Turns-ratio transformation : $R_{ext} \longrightarrow R'_{ext}/s = \left(\frac{N_1}{N_2}\right)^2 R_{ext}/s$



b)




$$S_{maxT} = 1.0 = \frac{r_2' + R'_{ext}}{\sqrt{[r_1^2 + (x_1 + x_2')^2]}} = \frac{R'_T}{\sqrt{[0.01\bar{3}^2 + 0.1^2]}}$$

$$R'_T = 0.1\ \Omega$$

$$R'_{ext} = R'_T - r_2' = 0.084\ \Omega$$

$$R_{ext} = 0.084/(1.5)^2 = 0.037\ \Omega$$

$$R_{eqv} = 2 \cdot R_{ext} = 0.075\ \Omega \ //$$

$$T_{e(max)} = T_{st} = \frac{1}{50\pi} \frac{415^2}{(0.01\bar{3} + 0.1)^2 + (0.1)^2} \times 0.1$$

$$= 4800\ \text{Nm} \ //$$

c)

$$S_{maxT} = \frac{r_2'}{\sqrt{r_1^2 + (x_1 + x_2')^2}} = \frac{0.01\bar{6}}{\sqrt{(0.01\bar{3})^2 + (0.1)^2}} = 0.1652$$

$$0.1652 = \frac{1500 - n_r}{1500} \Rightarrow n_r = 1250\ \text{rpm}$$

Therefore, this m/c can not produce $T_{e(max)}$ at 1350 rpm! Correct 1350 rpm by 1250 rpm.

$T_{e(max)}$ production

$n_r$: 0 ⟶ 1250 rpm

| $n_r = 0$ | $n_r = 1250$ rpm |
|---|---|
| ↓ | ↓ |
| $R_{ext} = 0.037\ \Omega$ | $R_{ext} = 0$ |
| ↓ | ↓ |
| $R_{eqv} = 0.075\ \Omega$ | $R_{eqv} = 0$ |
| ↓ | ↓ |
| $D = 0\%$ | $D = 100\%$ |

If one assumes that all parts of the rotor resistance control circuit are ideal,

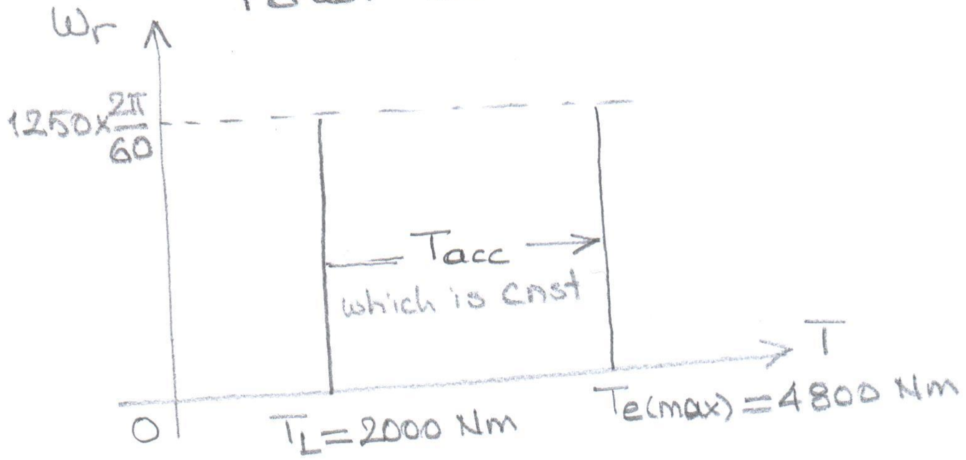
$R_{equ} = (1-D)R \Rightarrow R = \frac{0.075}{(1-0)}$, $R = 0.075\ \Omega$ can be chosen //

However in practice, $D = 5\%$ at $n_r = 0$ rpm can be chosen by considering finite turn-on and turn-off times of HV IGBT or IGCT, and more important than this because of resistance tolerance. This yields

$0.075 = (1.0 - 0.05)R \Rightarrow R \cong 0.08\ \Omega$ //

In summary, the design should be carried out according to the starting condition at which maximum rotor resistance is required.

d)




$$J \frac{\Delta\omega_r}{\Delta t} = T_{e(max)} - T_L = 4800 - 2000 = 2800$$

$$\Rightarrow \Delta t = \frac{1250 \times \frac{2\pi}{60}}{2800} \cong 0.05\ s\ //$$

Too small J!

e) $T_e = T_L = 2000\ \text{Nm}$ , $s = \frac{1500-1000}{1500} = 0.\bar{3}$

$$2000 = \frac{1}{\omega_s} \frac{3V_1^2}{(r_1 + \frac{R_T'}{0.\bar{3}})^2 + (x_1 + x_2')^2} \frac{R_T'}{0.\bar{3}}$$

$$= \frac{1}{50\pi} \frac{415^2}{(0.01\bar{3} + 3R_T')^2 + (0.1)^2} 3R_T'$$

$$\frac{2000 \times 50\pi\left[(0.01\bar{3} + 3R_T')^2 + 0.01\right]}{3 \times 172225} = R_T'$$

$$0.608\left[\underbrace{0.0001\bar{7} + 0.08R_T' + 9R_T'^2 + 0.01}_{0.0101\bar{7}}\right] = R_T'$$

$$5.472\,R_T'^2 - 0.95136\,R_T' + 0.0062 = 0$$

$$R_{T1,2}' = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$R_{T1,2}' = \frac{0.95136 \pm \sqrt{0.905 - 0.136}}{10.944} = \frac{0.951 \pm 0.877}{10.944}$$

$R_{T_1}' = 0.007 < r_2'$ it can not be the soln

$R_{T2}' = 0.167 \leftarrow$ the soln.

If $R = 0.075\ \Omega$ were chosen, corresponding $R_T'$ would be $0.1\ \Omega$ (maximum obtainable value) and hence the load can <u>not</u> driven at 1000 rpm since $0.1\ \Omega < R_{T2}' = 0.167$.

A similar conclusion can also be drawn for $R = 0.08\ \Omega$.

f) If it is intended to delete R, the chopper circuit should be operated with D = 100%. However still the diodes, dc link reactor (consider its internal resistance) and the hv IGBT of the chopper are carrying the rotor current. This results in a voltage drop across the slip-ring terminals. To approximate this voltage drop to zero, switch, S should be used and it should be closed whenever R is to be effectively set to zero.