MIDDLE EAST TECHNICAL UNIVERSITY

ELECTRICAL AND ELECTRONICS ENGINEERING DEPARTMENT

EE 462 Utilization of Electrical Energy

Final Examination

Duration: 120 minutes

Attempt all questions

Show all your calculations. 7 June 2016

NAME and SURNAME __SOLUTIONS_____

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Q1	
Q2	
Total	

Q1(55 pts). Take-up roll

Figure 1. shows a take-up roll operating in a paper industry to wrap the paper strips emerging from the mill rolls at a constant speed of v = 25 m/s, around a mandrel. In order not to tear the paper strip or in order to avoid its accumulation in front of the take-up roll, strip tension should be kept constant at f = 200 N during the formation of the paper roll. The radius of the empty mandrel is r_{min} = 25 cm and it reaches r_{max} = 50 cm when the paper roll is satisfactory formed.

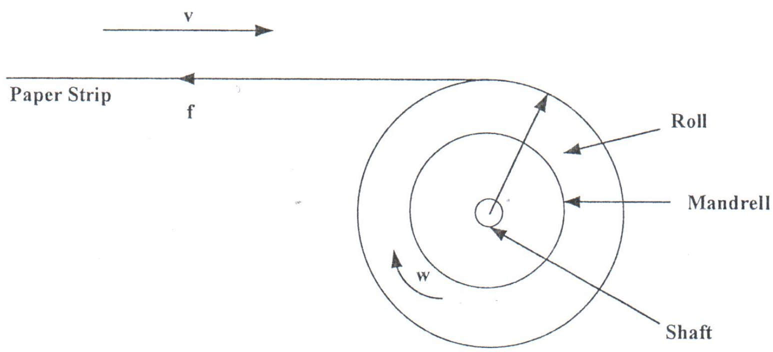

Figure 1. Take-up roll

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a) Calculate

- Torque, T in Nm,
- Angular speed, w in rad/s, and n in rpm,
- Mechanical power, P at the shaft of the mandrel,

for the roll diameters r = r_{min}, (r_{min} + r_{max}) / 2, and r_{max}.

Plot these quantities as a function of r, on a common graph paper.

What are the rated values of torque and shaft speed? Mark them on the previously developed graphs.

10

b) The mandrel is driven by a 3-phase squirrel-cage induction motor to form a satisfactory roll. Speed control is achieved by line frequency control. Determine the power rating of the electric motor drive. Give your reasoning.

10

c) The electric motor drive defined in (b) will be supplied from a 400 –V l-to-l, 50-Hz infinite bus. Draw the block diagram of the overall system. Among the standard 400-V, 50-Hz induction motors, the one having 2, 4, 6, or 8 magnetic poles can be chosen. Choose the number of poles, p of the induction motor to couple the motor shaft directly to the shaft of the mandrel (instead of a gear box).

15

d) Suppose now that (V_1 / f) ratio is kept constant in order to maintain proper magnetic conditions roughly in the magnetic circuit of the motor. Calculate frequency, f and rms voltage V_1 of the applied stator voltages for r = r_{min}, (r_{min} + r_{max}) / 2, and r_{max}. Plot these quantities as a function of r, on a common graph paper. One may assume that the normal working range of the induction motor torque / slip characteristic can be roughly approximated by

$$T_e = 1.\overline{1} \times 10^3 \times s$$

where, T_e is the electromechanical torque in Nm, and s is the slip. Friction and windage torque is neglected.

Hint: $n_r = (1 - s)n_s$

a) $T = f \cdot r = 200 \times 0.25 = 50 \text{ Nm}$ for $r_{min} = 25$

$= 200 \times 0.375 = 75 \text{ Nm}$ for $r = 37.5$

$= 200 \times 0.5 = 100 \text{ Nm}$ for $r = 50 \text{ cm}$

$P = f \cdot V = 200 \times 25 = 5000 \text{ W} \equiv 5 \text{ kW}$

$\omega = \frac{V}{r} = 25/0.25 = 100 \text{ rad/s}$ for $r = 25$

$= 25/0.375 = 66.\overline{6}$ for $r = 37.5$

$= 25/0.5 = 50$ for $r = 50$

$T_{rated} = 100 \text{ Nm}$ maximum value of T

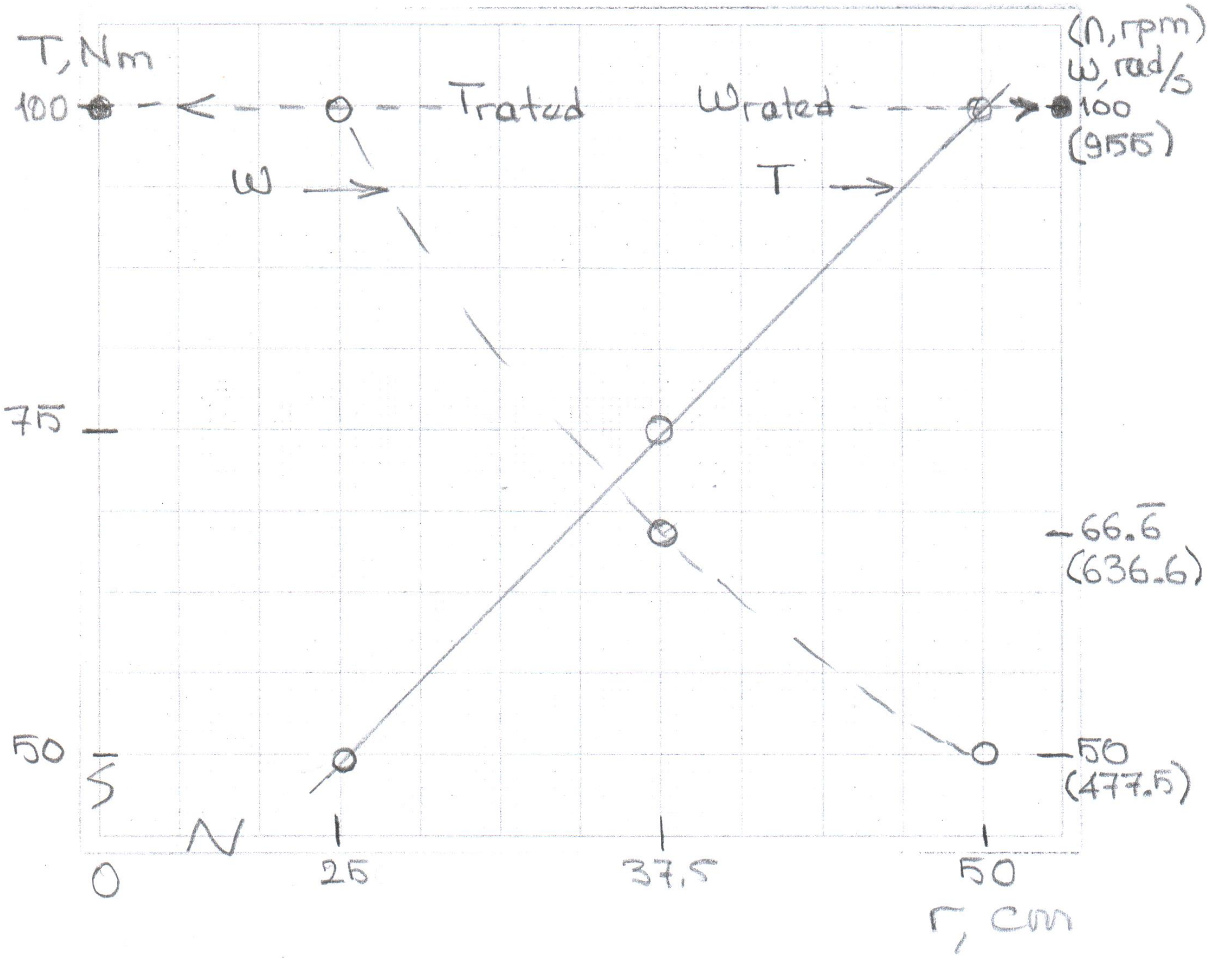
$\omega_{rated} = 100 \text{ rad/s}$ maximum value of ω

b) The electric motor drive should have a capability of producing 100 Nm, and should be able to operate at 100 rad/s

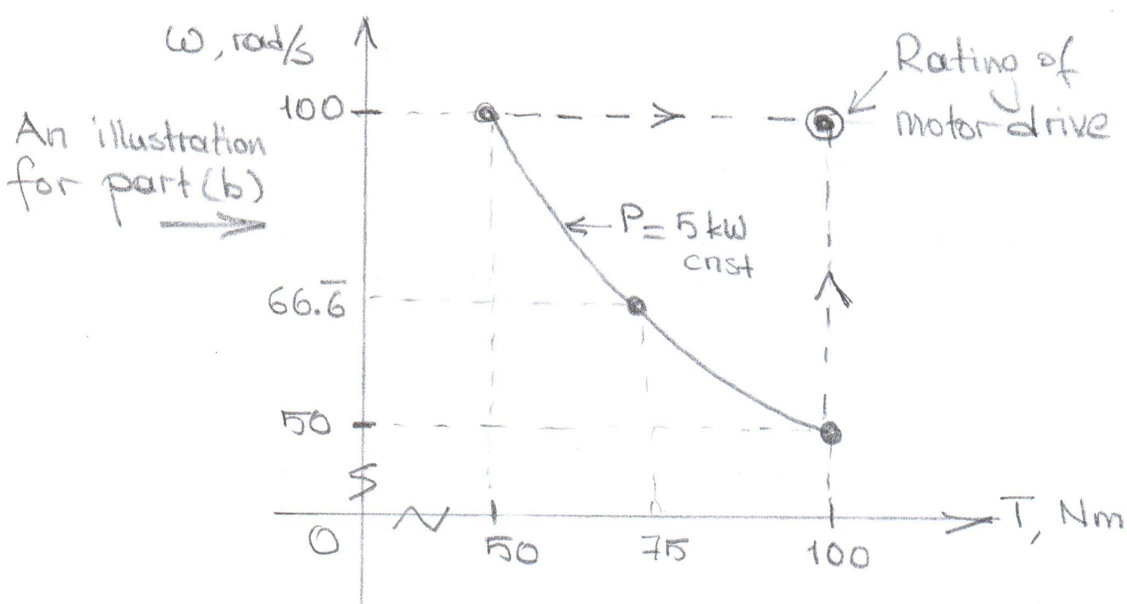
Therefore,

$P_{rated} = T_{rated} \times \omega_{rated} = 100 \times 100 \equiv 10 \text{ kW}$

That is $P_{rated} = 5 \text{ kW} \times \text{Speed Ratio} = 5 \times 2 = 10 \text{ kW}$

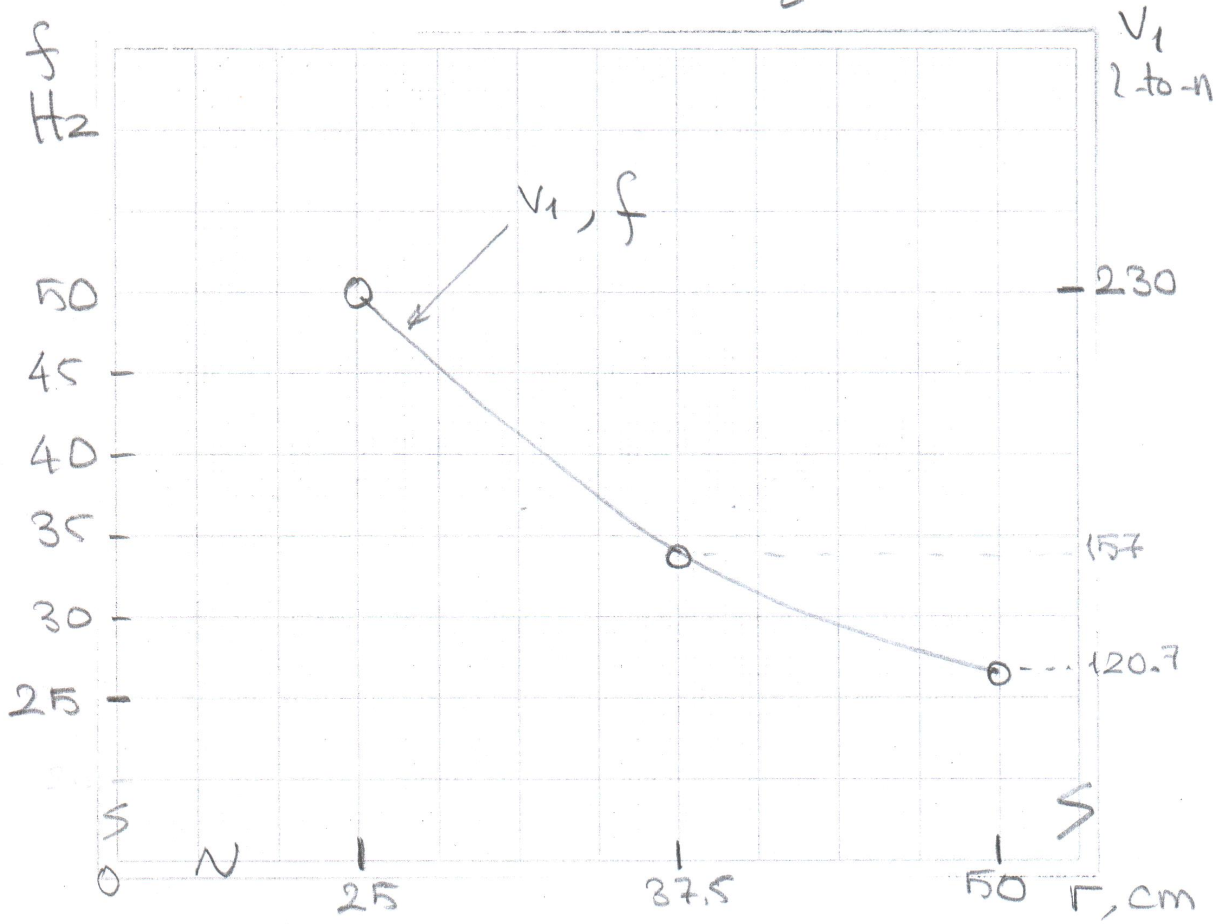


T, Nm
(n, rpm)
ω, rad/s
100
Trated
ωrated
100
(955)
ω
T
75
66.6
(636.6)
50
50
(477.5)
0
25
37.5
50
r, cm

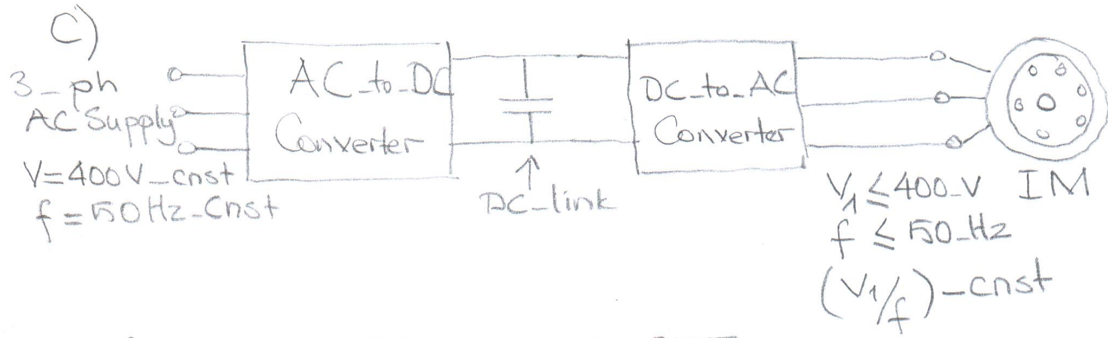


ω, rad/s
Rating of motor drive
100
An illustration for part (b)
P = 5 kW cnst
66.6
50
0
50
75
100
T, Nm

for part (C)



c)



from part (a), n_{max} is 955 rpm
It is the speed rating of the IM.
$V_1 = 400$ V l-to-l, 50-Hz voltages can be applied
to the stator at this speed.
Corresponding, $n_s = 1000 = \frac{120 \times 50}{p} \Rightarrow$
$p = 6$ is the optimum choice
Therefore, 400-V, 50-Hz, 10 kW induction
motor with $p=6$ can be ordered
for this application.

d) $r = 25\ cm$, $T = T_e = 50\ Nm$ $\quad T_e = 1.\bar{1} \times 10^3 s$

$50 = 1.\bar{1} \times 10^3 s \Rightarrow s = 0.045$ //

$n_r = (1-s) n_s \Rightarrow 955 = (1-0.045) n_s$

$\Rightarrow n_s = 1000\ rpm$ //

$n_s = \frac{120 f}{p} \Rightarrow f = \frac{6 \times 1000}{120} = 50\ Hz$ //

$V_1 = 400\ V$ l-to-l ; $230\ V$ l-to-n //

$r = 37.5\ cm$, $T_e = 75\ Nm = 1.\bar{1} \times 10^{+3} s \Rightarrow$

$s = 0.0675$ //

$636.6 = (1-0.0675) n_s \Rightarrow$

$n_s = 682.7\ rpm$ //

$f = \frac{6 \times 682.7}{120} = 34.1\ Hz$ //

$\frac{230}{50} = \frac{V_1'}{34.1} \Rightarrow V_1 = 157\ V$ l-to-n //

$\equiv 272\ V$ l-to-l

$r = 50\ cm$, $T_e = 100 = 1.\bar{1} \times 10^3 s \Rightarrow$

$s = 0.09$ //

$477.5 = (1-0.09) n_s \Rightarrow$

$n_s = 524.7\ rpm$ //

$f = \frac{6 \times 524.7}{120} = 26.2\ Hz$ //

$\frac{230}{50} = \frac{V_1'}{26.2} \Rightarrow V_1 = 120.7\ V$ l-to-n //

$\equiv 209\ V$ l-to-l //

Further comments on part (c)

Let it be a 4-pole m/c.

$P_{rated} = 10\ MW$, let $S_{rated} = 0.03$

$\omega_s = \frac{2\pi 50}{2} \simeq 157$ rad/s

$\omega_r = (1-s)\omega_s = 152.3$ rad/s

$\Rightarrow T_{e(rated)} = \frac{P_{rated}}{\omega_{r(rated)}} = \frac{10\,000}{152.3} \simeq 66$ Nm

Since 66 Nm < 100 Nm it can not be used.

A higher power rating ($\sim$ 15 kW) for 4-pole motor should be chosen to meet the requirements. It is not an economic soln.

Similar conclusions can be drawn for a 10 kW, 2-pole motor.

If one chooses a 10 kW motor with p=8:

$n_s = \frac{120 \times 50}{8} = 750$ rpm $\equiv 78.5$ rad/s

$\omega_{r(rated)} = (1-0.03)\,\omega_s = 76.2$ rad/s

Therefore, $T_{e(rated)} = \frac{10\,000}{76.2} = 131$ Nm > 100 Nm

This motor meets the torque requirement of the load but nearly 50% of time operates at frequencies higher than f_{rated} = 50 Hz

Q2(55 pts). Transportation Drive

A freight train is hauled by an electric locomotive. The locomotive is equipped with four identical squirrel-cage induction motor type traction motors.

Nameplate data of each traction motor are:

3-phase, 60-Hz, 1MW, 4-pole

Speed control is achieved by line frequency control.

The locomotive receives power from a 25-kV, 1-phase, AC Catenary Line by use of a pantograph mechanism. 25-kV AC is firstly reduced to 1.0-kV AC by a built-in step-down transformer and then rectified to give 1800 V DC-link voltage.

Suppose now that the train is running on a level track at a linear speed of 120 km/h. Aerodynamic drag force acting on the train is 60 kN at this speed. The shaft of each motor is coupled to the axle via a 5:1 speed reduction type gear-box.

The diameter of wheels is D=1 m.

Calculate,

3 **a.** Mechanical power; P required to run the train on a level track at 120 km/h.
3 **b.** Wheel speed in rpm.
6 **c.** Shaft speed, n_r, electromechanical torque, T_e, and gross mechanical output power, P_m of each traction motor by assuming a lossless gear-box and neglecting friction and windage torque at the motor shaft.
6 **d.** Frequency of applied stator voltages by assuming that slip, s=0.02 at the prespecified operating condition.

The train is now approaching to the next station while running at 120 km/h. the train should be brought to a controlled stop by regenerative braking technique. Total braking effort applied to the wheels is T_b = 60 kNm and kept constant during deceleration. Total mass of the train is M = 400 tons.

Calculate, by ignoring aerodynamic drag force,

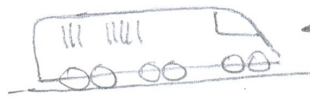
3 **e)** Total braking force, f_b acting on the train.
3 **f)** Deceleration of the train in m/s^2.
6 **g)** Deceleration time (from 120 km/h to standstill).
6 **h)** What should be the distance between the train and the station in meters at which the regenerative braking action starts, in order to bring the train to a stop just at the station.

10 Draw circuit diagrams of all possible AC to DC converter topologies which convert 1.0 kV AC to 1.8 kV DC and permit regenerative braking. Compare technical features of these device commutated HV IGBT based circuits with line commutated thyristor converters in view of harmonic generation and reactive power consumption.

In which quadrants of the speed/torque plane does the above locomotive operate?

10 Mark operation modes of all converters, traction motor drive and traction motors on the associated quadrants. In order to run the train in the reverse direction, what does the operator do?

a)



$\leftarrow f_d = 60\text{ kN}$

$\rightarrow V = 120\text{ km/h} = \dfrac{120000}{60\times 60} = 33.\overline{3}\text{ m/s}$

$P = f_d \cdot V = 60\times10^3 \times 33.3 \cong 2\text{ MW}$ // 3

It is less than P_{rated} because the train is moving on a level track.

b) $\omega = \dfrac{V}{r} = \dfrac{33.\overline{3}}{0.5} = 66.\overline{6}\text{ rad/s}$

$n = \omega \times \dfrac{60}{2\pi} = 636.6\text{ rpm}$ // 3

6 c) Gear ratio $= 1:5$ (speed reduction ratio $= 5:1$)

$n_r = 5\times n = 5\times 636.6 = 3183\text{ rpm}$ //

$n_{s(rated)} = \dfrac{120\cdot f}{p} = \dfrac{120\times60}{4} = 1800\text{ rpm}$

n_r is much higher than n_s, because frequency applied to the stator is much higher than 60 Hz in field weakening region.

$\text{Total } T = f_d \cdot r = 60\times10^3\times0.5 \cong 30\text{ kNm}$

$\text{Total } T_e = 30/5 = 6\text{ kNm}$ on the motor side

T_e per motor $= 6/4 = 1.5\text{ kNm} \cong 1500\text{ Nm}$ //

$P_m = T_e \cdot \omega_r = 1500 \times 3183 \times \dfrac{2\pi}{60} = 500\,000\text{ W} \cong 500\text{ kW}$ // for each motor

d) $n_r = (1-s)\,n_s$

$3183 = (1-0.02)\,n_s \Rightarrow$

$n_s = 3248$ rpm

Since $n_s = \frac{120f}{4}$ then $f = \frac{4 N_s}{120}$

Therefore, $f = 108.3$ Hz // 6

e) $M\frac{dv}{dt} = f_b$

$f_b = T_b/r = -60\ kNm/0.5 = -120\ kN$ // 3

f) $M \cdot a = f_b$

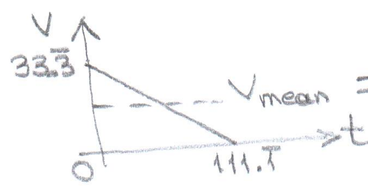
$a = f_b/M = -120/400 = -0.3\ m/s^2$ // 3

g) Since $a = \frac{dV}{dt}$ is constant

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

$\Delta t = \Delta V/a = 33.\bar{3}/0.3 = 111.\bar{1}$ s // 6

h)



$V_{mean} = \frac{33.\bar{3}}{2}$

$\Delta X = V_{mean} \times \Delta t = \frac{33.\bar{3}}{2} \times 111.\bar{1}$

$\Delta X = 1852$ m // 6

A huge mass moving at 120 km/h can not be brought to a quick stop!

1 kV single-phase AC can be converted to 1800 V DC by using a boost rectifier. The one shown below is a popular PWM rectifier circuit which is popular in electric locomotive applications and permits bidirectional power flow. It can operate at nearly unity pf and with minimum harmonic content in AC supply lines especially for interleaved operation of more than one PWM rectifier

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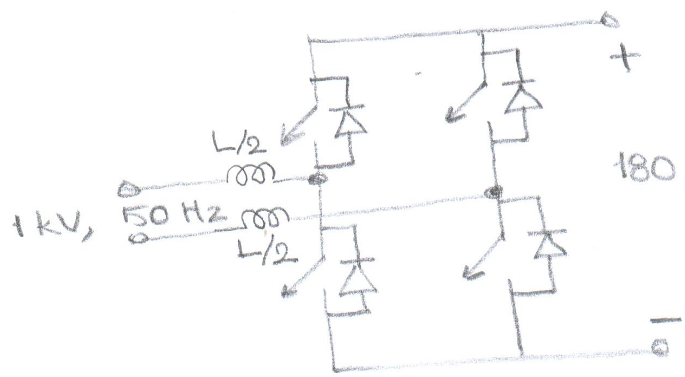

A voltage source, line commutated thyristor rectifier can not produce 1800 volts dc from 1-ph, 1000 V AC source. It should be a current source thyristor rectifier with boosting inductors on the supply side.

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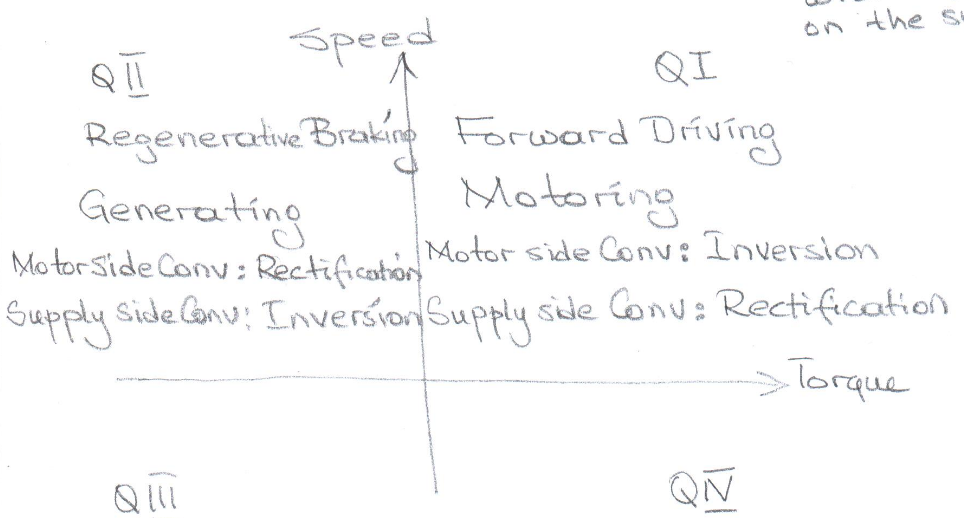

It is a two quadrant drive (A pause is required before starting to run in the reverse direction)

Operation in the reverse direction (Q III and Q IV) requires a change of phase sequence of applied stator voltages by changing the phase sequence of triggering signals within the Inverter.

10/10

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