[Q.1]

1) - Electric propulsion
- Pump, fans + Compressors
- Spindles + servos
- Cement kilns
- Steel mills
- Paper + pulp mills
- Automotive applications
- Underwater excavators
- Conveyors, elevators, escalators + lifts
- Textile mills

(3)

2) - Electric Machines
- Power Converters
- Controllers
- Load

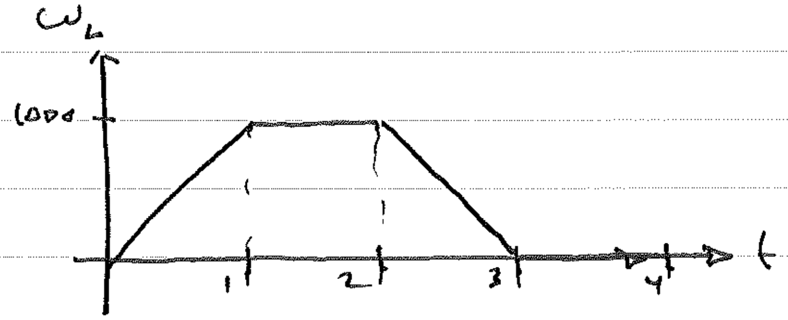
(4)

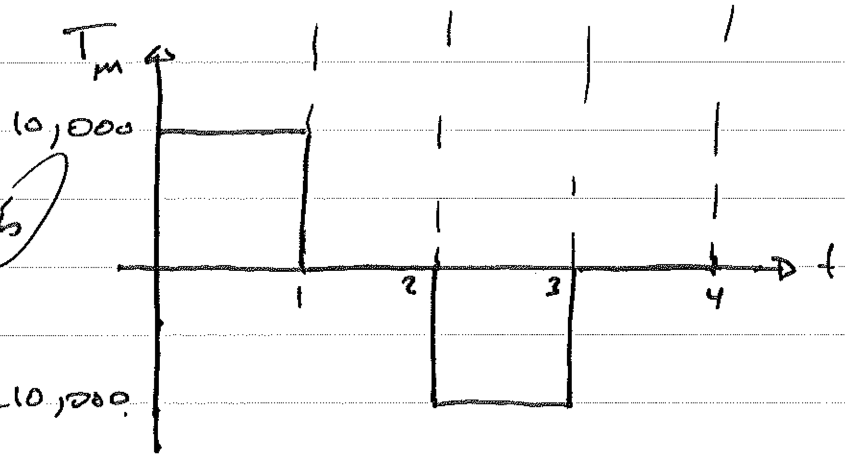
3) - Cost
- Thermal capacity
- Efficiency
- Torque - speed profile
- Acceleration.
- power density, volume of the motor.
- peak torque capability.

(4)

4) $T_m = J_{tot}\dfrac{d\omega_m}{dt} = \left(J_m + \dfrac{J_L}{\tau^2}\right)\dfrac{d\omega_m}{dt} = \left(J_m + \dfrac{J_L}{\tau^2}\right)\tau\dfrac{d\omega_L}{dt}$

$T_m = \left(10 + \dfrac{2.5}{(0.5)^2}\right)0.5\,\dfrac{d\omega_L}{dt} = 10\,\dfrac{d\omega_L}{dt}$





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$$T_{eff} = \sqrt{\frac{(10000)^2(1) + (0)^2(1) + (-10000)^2(1) + (0)^2(1)}{4}}$$

4

$$T_{eff} = \frac{10000}{\sqrt{2}} = 7071 \text{ N.m.}$$

5) $T_m = J_{tot}\dfrac{d\omega_m}{dt} = \left(J_m + \dfrac{J_L}{\tau^2}\right)\dfrac{d\omega_m}{dt} = \left(J_m + \dfrac{J_L}{\tau^2}\right)\tau\dfrac{d\omega_L}{dt}$

$T_m = \left(\tau J_m + \dfrac{J_L}{\tau}\right)\alpha_L \;;\; \alpha_L = \dfrac{d\omega_L}{dt}$ 6

$F(\tau) = \dfrac{T_m}{\alpha_L} = \tau J_m + \dfrac{1}{\tau}J_L$

$\dfrac{\partial F(\tau)}{\partial \tau} = J_m - \dfrac{J_L}{\tau^2} = 0 \implies \tau = \sqrt{J_L / J_m}$

[Q2] 1)(i) Constant torque region ($\omega_{m,n} < 1.0\,pu$)

$T_{el,n} = 1\ pu$

$\phi_{f,n} = 1\ pu$

$V_{a,n} = \omega_{m,n}$ 2.5

$e_{a,n} = \omega_{m,n}$

$P_{a,n} = \omega_{m,n}$

Constant power region ($\omega_{m,n} > 1.0\,pu$)

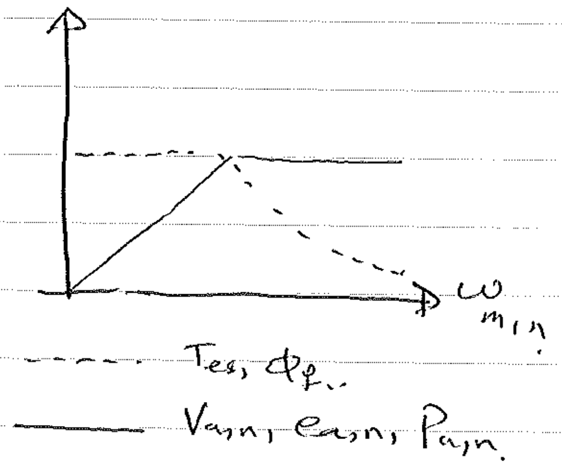
$T_{el,n} = \dfrac{1}{\omega_{m,n}}$

$\phi_{f,n} = \dfrac{1}{\omega_{m,n}}$ 2.5

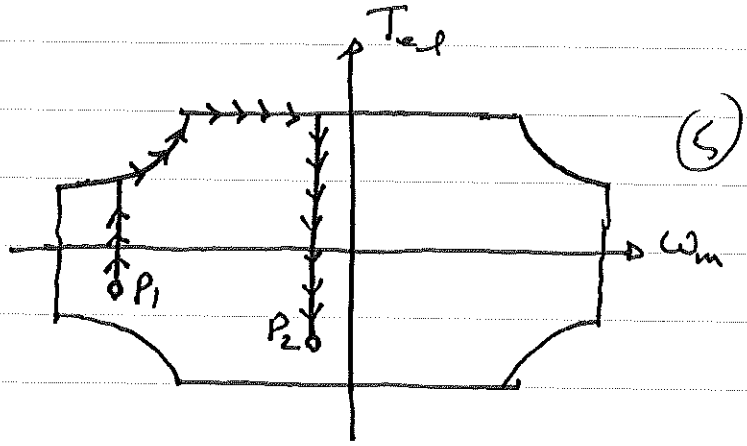
$V_{a,n} = 1\ pu$

$e_{a,n} = 1\ pu$

$P_{a,n} = 1\ pu$



(ii)



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2)

$$E_a = k' \omega_m$$

$$410 = k' \left(1000 \times \frac{\pi}{30}\right) \Rightarrow k' = 3.915 \text{ V.sec/rad.}$$

(2)

$$V_{a,r} = R_a I_{a,r} + E_{a,r}$$

$$T_{e,r} = \frac{P_{a,r}}{\omega_{m,r}} = \frac{100{,}000}{1000 \times \frac{\pi}{30}} = 954.93 \text{ N.m}$$

$$T_{e,r} = k' I_{a,r} \Rightarrow I_{a,r} = \frac{954.93}{3.915} = 243.92 \text{ A}$$

(3)

$$R_a = \frac{V_{a,r} - E_{a,r}}{I_{a,r}} = \frac{440 - 410}{243.92} = 0.123 \ \Omega$$

$$V_a = R_a I_a + k' \omega_m = (0.123)(0.75 \times 243.92) + 3.915\left(800 \frac{\pi}{30}\right)$$

$$V_a = 350.48 \text{ V}$$

$$V_a = \frac{3\sqrt{3}\, V_m}{\pi} \cos\alpha$$

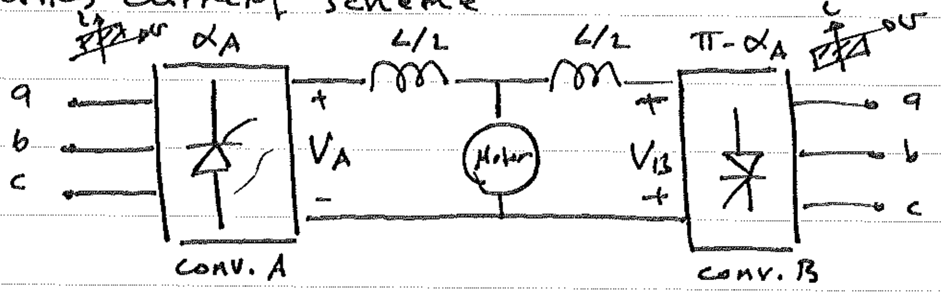
(3)

$$350.48 = \frac{3\sqrt{3}}{\pi}\left(\sqrt{\tfrac{2}{3}}\,(415)\right)\cos\alpha$$

$$\boxed{\alpha = 51.29^\circ}$$

3) To obtain 4-quadrant operation, it is necessary to have two converters operating back-to-back or in anti-parallel. The converters can be controlled in two ways: circulating + non-circulating scheme.

Circulating current scheme



In this scheme, convertor A is operated at α_A
convertor B " " " $\pi-\alpha_A$

Since $v_A \neq v_B \Rightarrow i_{cir,ac} \neq 0 \Rightarrow L$ is added to limit $i_{cir,ac}$

(6)

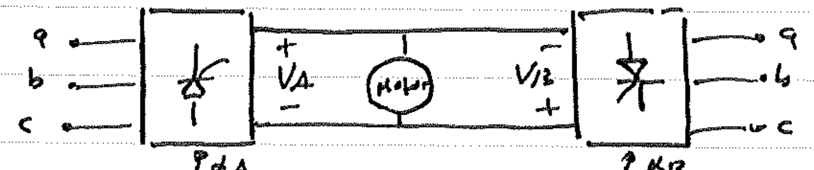
→ This scheme provide very fast current reversal time because ~~because~~ both converters keep running regardless of the direction of motor current

→ The main disadvantage of this scheme is using inductors which are larger and more expensive.

Non-circulating scheme.

In this scheme, we don't need L because we don't have i_{cir} flowing in the circuit. There are two methods deadband + change over-logic. → slow current reversal time.

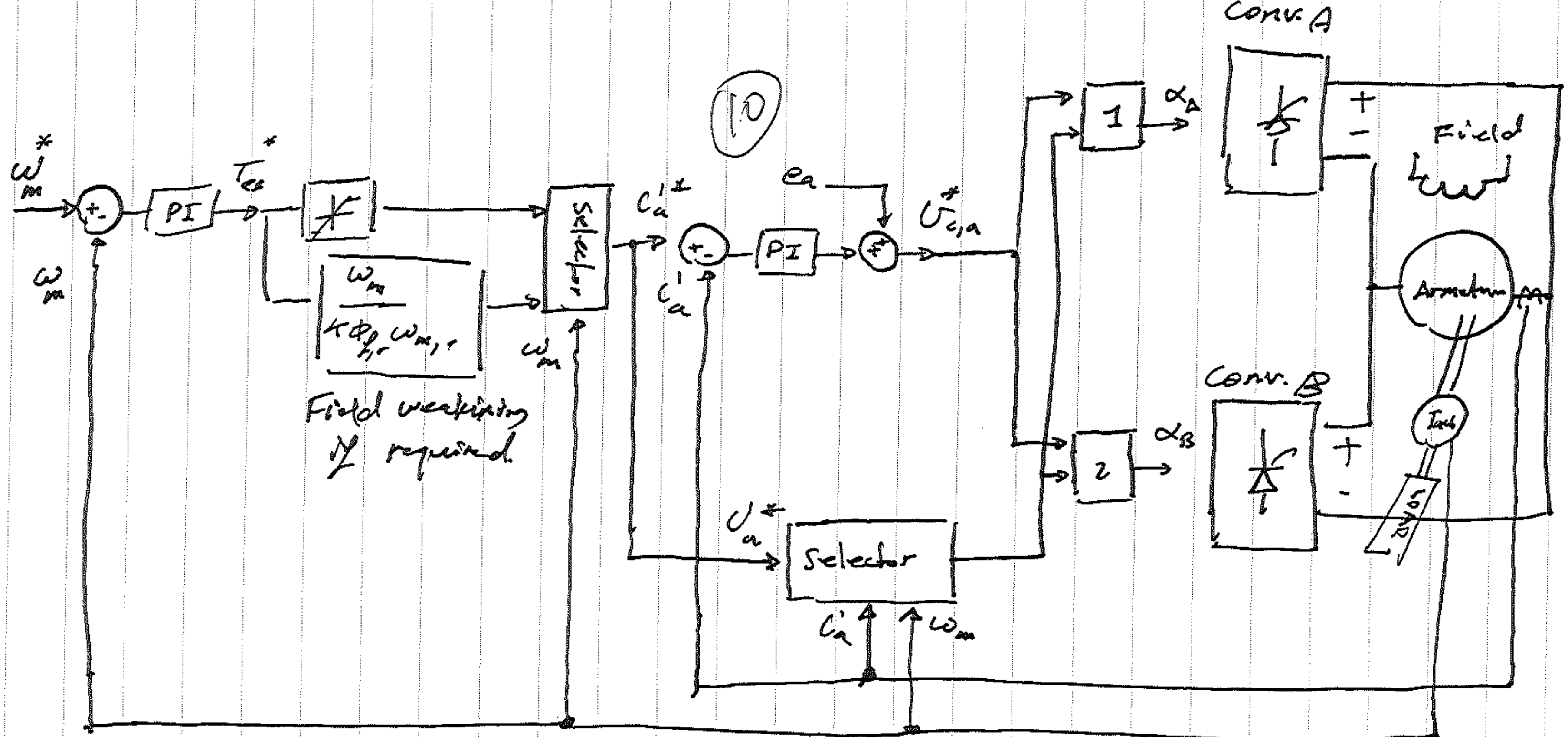
(6)



Dead band → both converter continue to recieve pulses but $\alpha_A + \alpha_B$ is adjusted so that $v_A + v_B = 0$ or $V_A + V_B < 0$

change over logic → only one converter recieve firing pulses at a time.

4)



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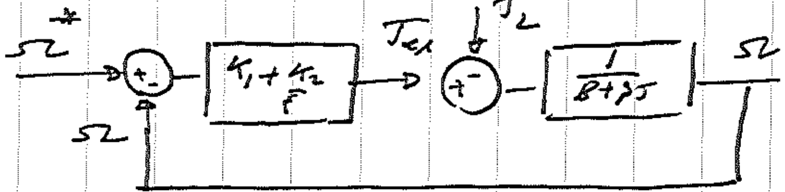


$$\frac{\Omega}{\Omega^*}\Big|_{T_L=0} = \frac{G}{1+G} \quad ; \quad G = \frac{K_1 s + K_2}{s[B+Js]}$$

$$\frac{\Omega}{\Omega^*} = \frac{K_1 s + K_2}{K_1 s + K_2 + Bs + Js^2} = \frac{K_1}{J}\left[\frac{s + K_2/K_1}{s^2 + (K_1+B)s + K_2}\right]$$

[Q3]

1) $V_{a_r} = R_a I_{a,r} + K'\omega_{m_r}$

$$230 = 0.115(90) + K'\left(500\,\frac{\pi}{30}\right)$$

$$K' = 4.195 \ \frac{V.s}{rad}$$

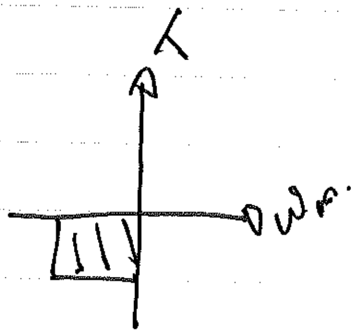
i) $V_a = R_a I_{a,r} + K'\omega_m$

$$V_a = 0.115(-90) + 4.195\left(300\,\frac{\pi}{30}\right)$$

$$V_a = 121.44 \ \underline{V}$$

4

$$\delta = \frac{121.44}{230} = 0.528$$



(ii) $V_a = R_a I_a + K'\omega_m$

$$V_a = -0.115(45) - 4.195\left(400\,\frac{\pi}{30}\right)$$

$$V_a = -180.89 \ \underline{V}$$

4

$$\delta = \frac{180.89}{230} = 0.786 .$$

2) $V_a = R_a I_a + k' \omega_m$

$$0.9(220) = 2 I_a + k'\left(1260 \frac{\pi}{30}\right)$$

$$I_a = \frac{1260}{1500}(11.6) = 9.744\,A$$ 2

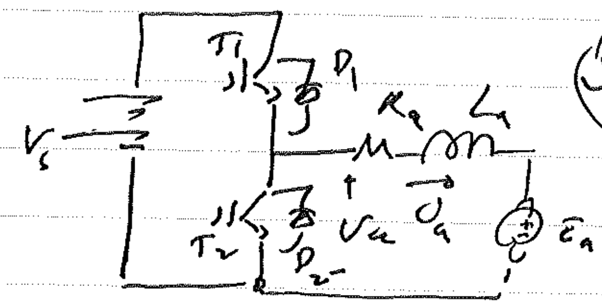
$$\Rightarrow k' = \frac{0.9(220) - 2(9.744)}{1260 \frac{\pi}{30}} = 1.353 \ \frac{V \cdot sec}{rad}$$ 2

$$V_a = 2\left(\frac{800}{1500}\right)(11.6) + 1.353\left(800 \frac{\pi}{30}\right)$$

$$V_a = 125.714\ V$$ 2

$$\delta = \frac{125.714}{220} = 0.571$$

3) (i)



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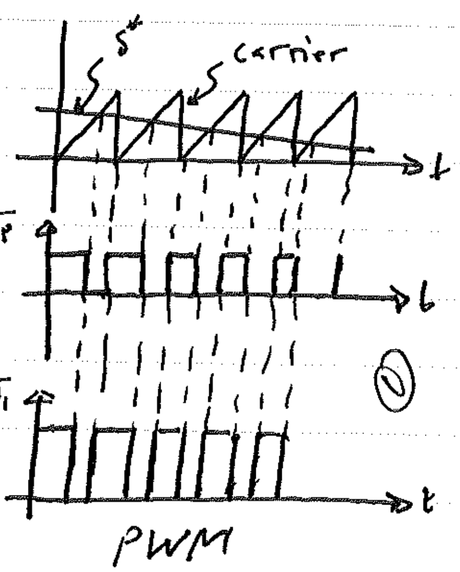
(ii)

operation



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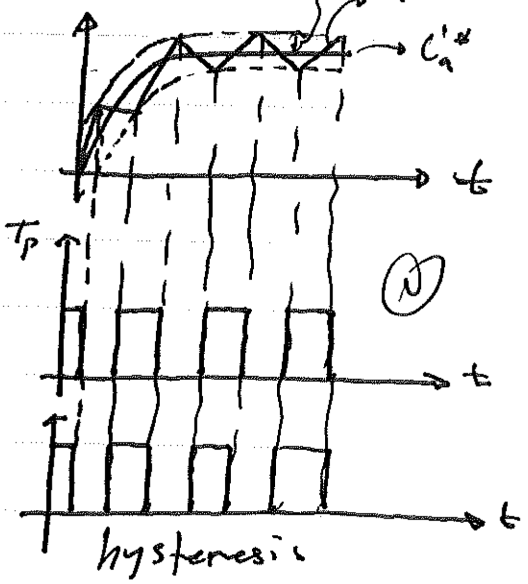

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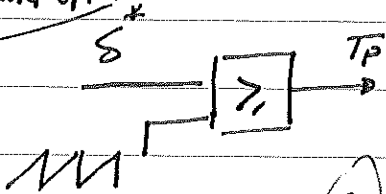
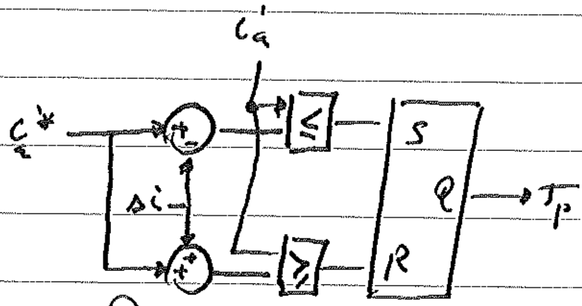
implementation



PWM



hysteresis

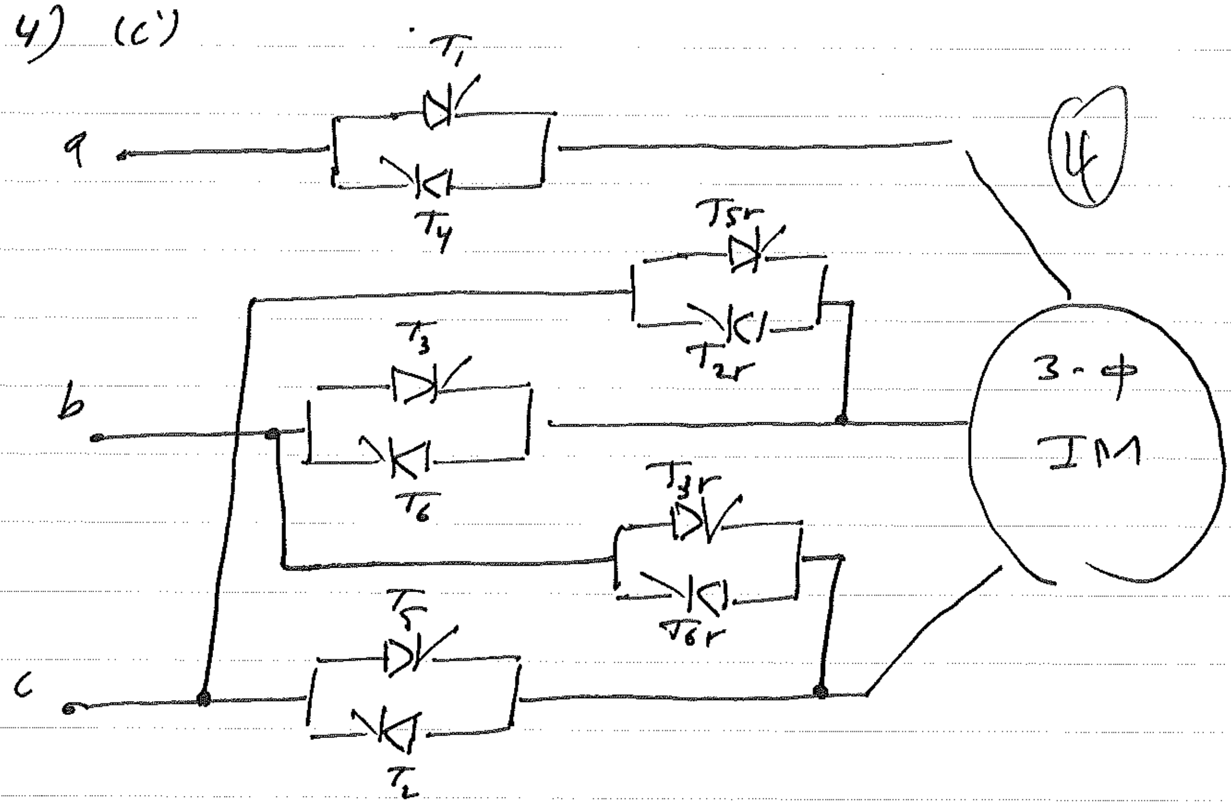
(iii)

feature	hysteresis	PWM
switching frequency	Varying	Fixed
switching Losses	usually high	Low
Filter size	Depending on Δi	small
speed of response	Fastest	Fast

(iv)

$\omega_m > 0$	$i_a^* > 0$	T_p	Q	T_1	T_2
1	1	1	1	1	0
1	0	0	4	0	1
1	0	1	4	0	0
1	1	0	1	0	0

4) (i)



(ii) $T_1\ T_2\ T_3\ T_4\ T_5\ T_6$

$T_1\ T_{2r}\ T_{3r}\ T_4\ T_{5r}\ T_{6r}$

(iii) $\omega_f = \frac{2}{P}\omega_e = \frac{2}{4}(2\pi \times 50) = 157 \text{ rad/sec}$

$\omega_{m_1} = 1250 \times \frac{\pi}{30} = 131 \text{ r/sec}$

$\omega_{m_2} = 750 \times \frac{\pi}{30} = 78.54 \text{ r/sec}$

$\sigma_1 = \frac{157 - 131}{157} = 0.1667$ $\quad I_{r_1} = \sqrt{\frac{\sigma_1 \omega_f T_1}{3R_r'}} = 533.985 A$

$\sigma_2 = \frac{157 - 78.54}{\cancel{78.54}\ 157} = 0.5$ $\quad I_{r_2} = \sqrt{\frac{\sigma_2 \omega_f T_2}{3R_r'}} = 554.933 A$

$T_1 = 1.2395 \omega_{m_1}^2 = 21.238 \text{ kN.m}$ $\quad I_{s_1} \approx I_{r_1}$

$T_2 = 1.2395 \omega_{m_2}^2 = 7.646 \text{ kN.m}$ $\quad I_{s_2} \approx I_{r_2}$

$V_{as_1} = \left[\left(R_s + \frac{R_r'}{\sigma}\right) + j(X_s + X_r')\right] I_{s_1} = 2.23\angle 9.9^\circ \text{ kV}$ $\quad V_{as_2} = \left[R_s + \frac{R_r'}{\sigma} + j(X_s + X_r')\right] I_{s_2} = 0.93\angle 15.4^\circ \text{ kV}$