USN

**Seventh Semester B.E. Degree Examination, Dec.2017/Jan.2018**

# Industrial Drives and Applications

Time: 3 hrs. Max. Marks:100

**Note:** ***Answer any FIVE full questions, selecting at least TWO questions from each part.***

2. Any revealing of identification, appeal to evaluator and /or equations written eg, 42+8 = 50, will be treated as malpractice.

## PART – A

1 a. Briefly explain the different power modulators that used in drive system. **(06 Marks)**

b. With the help of quadrantal diagram, explain four-quadrant operation of a motor driving a hoist load. **(10 Marks)**

c. Define active load torque and passive torque. Give an example. **(04 Marks)**

2 a. Explain the steady state stability in the drive system. **(05 Marks)**

b. Explain standard classes of motor duty with load diagram. **(08 Marks)**

c. A motor has heating-time constant of 70 min and a cooling time constant of 90 min. When run continuously on full load of 400 kW, final temperature rise is 50°C.

i) When used in short time periodic duty cycle consisting of loaded period of 10 min followed by no-load period long enough for the motor to cool down. What will be the maximum load that motor can carry?

ii) Determine the maximum load the motor can deliver when subjected to intermittent periodic load cycle consisting of a load period of 10 min followed by a no-load period of 15 min. **(07 Marks)**

3 a. Explain the dynamic braking of separately excited DC motor. **(06 Marks)**

b. A 220 V, 200 A, 800 rpm separately excited DC motor has an armature resistance of 0.06 Ω. The motor armature is fed from a variable voltage source with an internal resistance of 0.04 Ω. Calculate internal voltage of the variable voltage source when the motor is operating in regenerative braking at 80% of the rated motor torque and 600 rpm. **(06 Marks)**

c. Explain the operation of continuous conduction mode of a single-phase fully controlled rectifier control of separately excited DC motor. **(08 Marks)**

4 a. A 220 V, 1500 rpm, 10 A separately excited dc motor is fed from a single-phase fully controlled rectifier with an AC source voltage of 230 V, 50 Hz, $R_a = 2\ \Omega$. Conduction can be assumed to be continuous, calculate firing angle for:

i) Half the rated motor torque and 500 rpm

ii) Rated motor torque and −1000 rpm. **(08 Marks)**

b. Explain the multiquadrant operation of a separately excited DC motor using single-phase fully controlled rectifier with a reversing switch. **(06 Marks)**

c. Explain the regenerative braking of separately excited DC motor by chopper control. **(06 Marks)**

## PART – B

5 a. What is single phasing? Explain the operation of a 3-phase induction motor with unbalanced voltages. **(07 Marks)**

b. A 2200 V, 50 Hz, 3 phase, 6 pole, Y connected, squirrel cage induction motor has following parameters: $R_s = 0.075\ \Omega$, $R'_r = 0.12\ \Omega$, $X_S = X'_r = 0.5\ \Omega$. The combined inertia of motor and load is 100 kg-mt$^2$. Calculate time taken and energy dissipated in the motor during starting. **(08 Marks)**

c. Explain the reverse voltage braking (plugging) of an induction motor. **(05 Marks)**

6 a. Explain the available frequency control of an induction motor and mention any two features. **(07 Marks)**

b. Explain the operation of a voltage source inverter fed induction motor drive. **(07 Marks)**

c. Explain the static rotor resistance control. **(06 Marks)**

7 a. Explain pull-in process in synchronous motor operation from fixed frequency supply. **(05 Marks)**

b. Explain the modes of variable frequency control of synchronous motors. **(05 Marks)**

c. Explain the operation of self controlled synchronous motor drive employing load commutated thyristor inverter. **(10 Marks)**

8 a. With schematic diagram, explain the paper mill drive. **(10 Marks)**

b. With schematic diagram, explain the cement mill. **(10 Marks)**

* * * * *

higher (ratings), speed, torque and power ratings:

Synchronous Motor:- (high full-load η and PF).

↳ Wound field

↳ Perm Magnet . PM

* Compared to squirrel cage motor, wound field syn motors are high cost and needs more maintenance

* PM syn motors have all the adv of squ cage IM but available at lower power ratings:

-> Stepper motor is popular for position control

-> SRM " speed control.

POWER MODULATORS

1) Converters
2) Variable impedances
3) Switching ckts.

The need for converter arises when the available electric power is diff than that required by the motor.

1) Fixed voltag fixed fre AC } types of power source.
2) Fixed voltage dc.

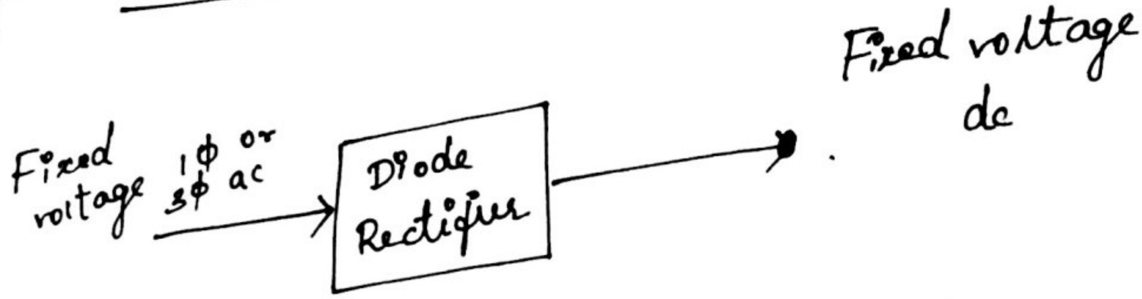
Types of converters:-

1) AC to DC converters
2) ac voltage controllers or ac regulators
3) Choppers or dc-dc converters
4) inverters (or) dc to ac conv
5) cyclo converters.

① CMR

# Ac to DC Converters

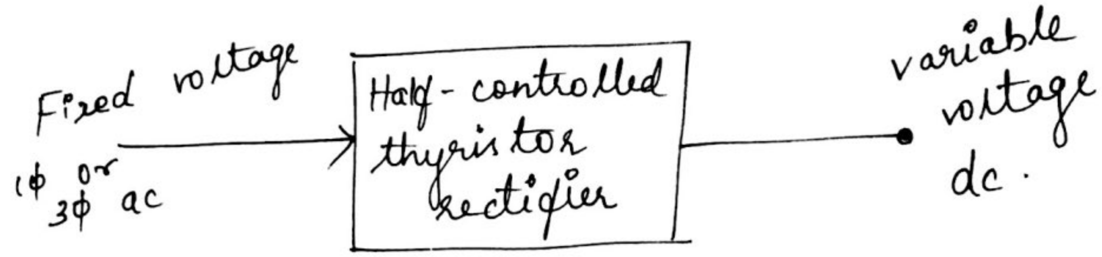
1)




2)


→ This is a two - quadrant converter. i.e capable of providing variable dc voltage of either polarity with +ve current.

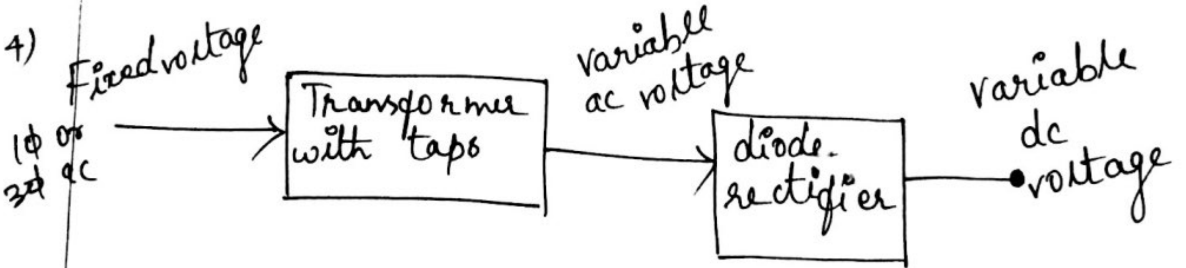
3)



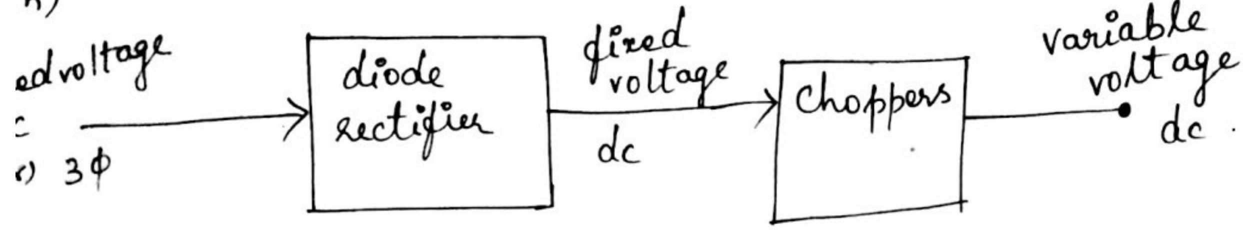

→ single quadrant converter.

(2) and (3) produces harmonics on both ac and dc side ∴ low PF at low dc voltages.

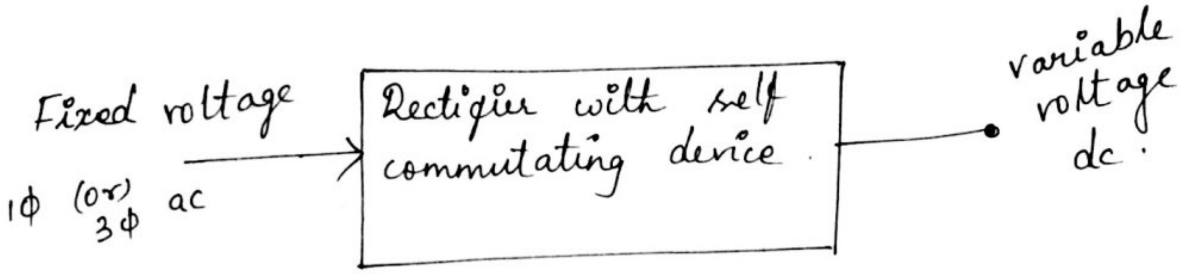
4)



5)

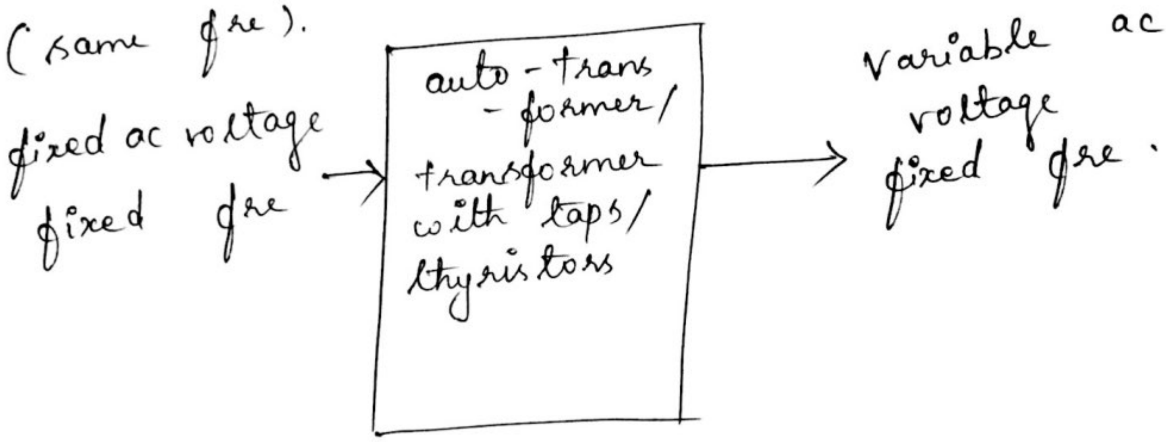



6)

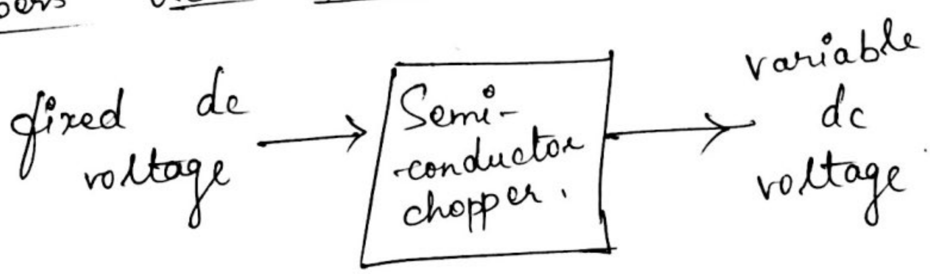



<u>Ac Voltage converters/ ac regulators</u> :-

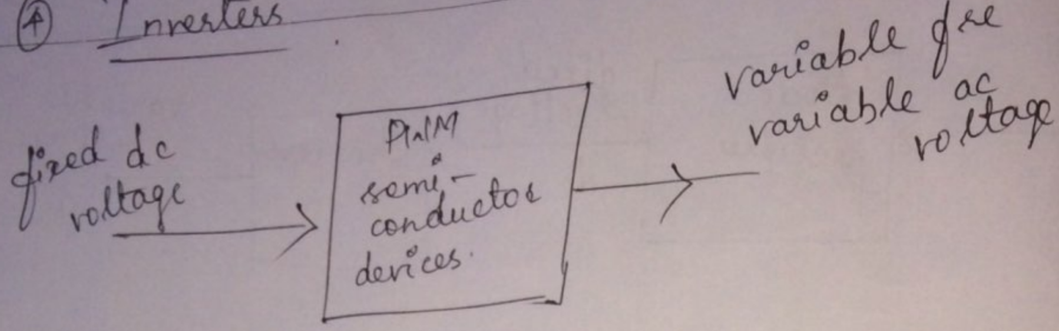
→ fixed ac voltage to variable ac voltage.
(same fre).



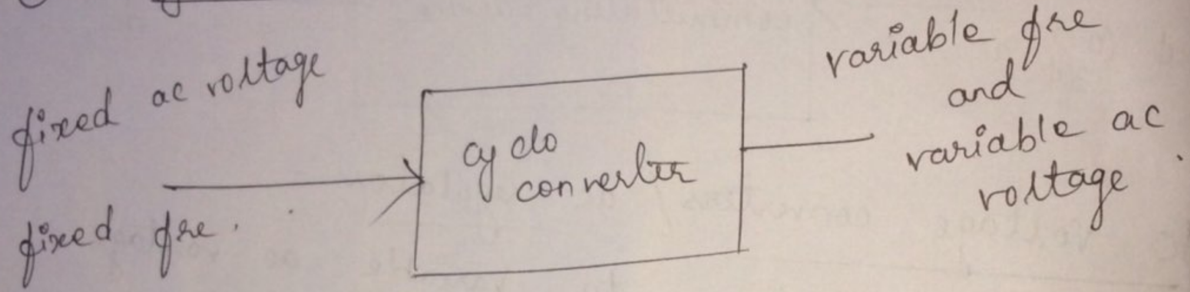

<u>Choppers or dc-dc converters</u> :-



④ Inverters




⑤ cyclo-converter




Variable Impedances :-

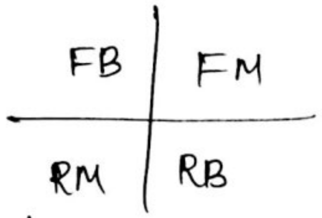
variable resistors – dynamic braking of drives
– control of low cost ac and dc drives.

Resistors are employed along with semi-conductor switch.

Inductors are used for limiting starting current of ac motors.

Old drives – reactors are used for control of induction motors.

(i) for changing motor connections to change its quadrant of operation




(ii) for changing motor ckt parameters for automatic starting and braking control.

(iii) for operating motors and drives for predetermined sequence.

(iv) provide interlocking to prevent mal-operation

eg

(v) disconnect motor during abnormal working conds

~~Control Unit~~

Switches - electro-magnetic relays called contactors.
- thyristor switches.

For sequencing and interlocking operations, PLCs are employed.

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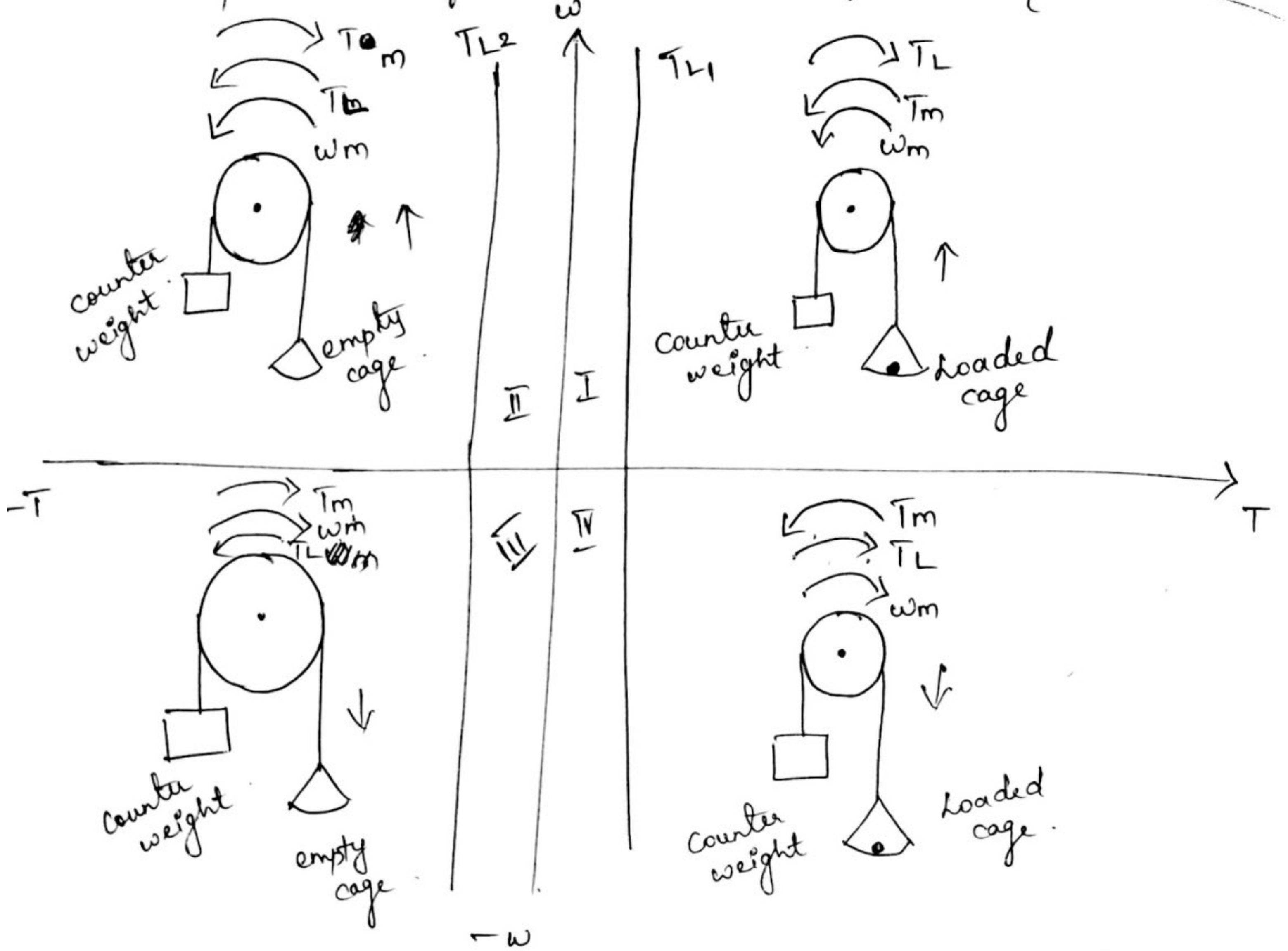


→ A hoist consists of a rope wound on a drum coupled to a motor shaft.

→ One end of the rope is connected to cage (used for transporting material) and other end has a counter weight.

→ Weight of the counter weight is choosen higher than the empty cage but lower than a fully loaded cage.

the load torque of the hoisting mechanism is of active type and assumed to be constant due to

Load torque $T_{L1}$ represents the N-T chac of hoist loaded hoist. $T_{L}$ is the diff of torque b/w loaded & counter weight.

Load torque $T_{L2}$ (II & III) represents the N-T chac of an empty hoist. This torque is due to diff in torque of counter weight and empty hoist. This is -ve bcoz the counter weight is always higher than the empty cage.

Quadrant I

Hoist requires the movement of the cage upward which corresponds to the +ve motor speed which is in CCW direction. It will be obtained if motor produce +ve torque in CCW direction (equal to $T_{L1}$). Since developed power is +ve, this is forward motoring operation.

Quadrant ~~III~~ IV

when the cage has to be lowered. Since counter weight is ~~greater than~~ < loaded cage, the hoist moves down due to gravity. To limit the speed within safe limit, the motor has to produce +ve torque in CCW direction (equal to $T_{L1}$).

When empty cage has to be moved up. Since counter weight is heavier than empty cage, it is able to pull it up. To limit the speed within safe limit, motor must produce a braking torque (equal to $T_{L2}$) in clockwise direction. $\omega \rightarrow +ve$, $T_m = -ve$, $P = -ve$

∴ forward braking.

## Quadrant III :-

when empty cage has to be lowered.
empty cage has lesser weight than counter weight, the $T_m$ will be in cw dir.
$\omega_m = -ve$, $T_m = -ve$, $P = +ve$.

∴ Reverse motoring.

## EQUIVALENT VALUES OF DRIVE PARAMETERS.

→ diff parts of load may be coupled thro diff mechanisms (eg:- gears, v-belts and crankshaft).

Finding the equivalent moment of inertia J of motor-load system and equivalent torque components.

Classification of load torque

- Active load torque
- Passive load torque.

**Active load torque :-**

Load torque which has the potential to drive the motor under equilibrium conditions - Such load torques retain the sign when the derive rotation is changed (reversed).

Eg :- Torque due to gravity, due to tension, due to compression and torsion.

**Passive load torque :-**

Load torques which always oppose the motion and change their sign on the rever of motion are called passive load torques.

Eg :- torque due to friction and cutting.

## Stability :-

The system is said to be stable if it retains its original position or in equilibrium position after the disturbance period and this equilibrium position may be a new position or original position

The system is unstable if it comes to rest or has continuous ↑ in speed following the disturbance i.e the system cannot achieve its new equilibrium position.

In practice, it is necessary to consider two types of disturbance :

1) Changes from the state of equilibrium take place slowly and the effect of either the inertia of the rotating mass or that of inductance is insignificant.

2) Sudden and fast changes from the equilibrium state, as a result of which the effect of neither the inertia nor the inductance can be ignored.

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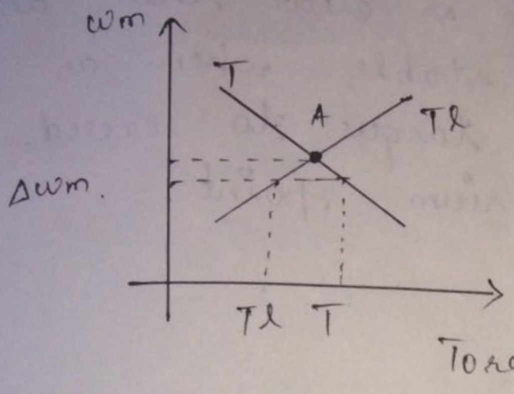
Case A)




A – equilibrium or steady state position.

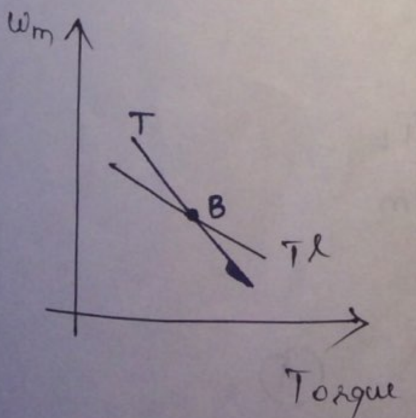
→ Let the disturbance causes a reduction of $\Delta\omega_m$ in speed.

→ At new speed, $T > T_l$ ∴ drive accelerates and speed ↑s. ∴ operation will be restored to A.

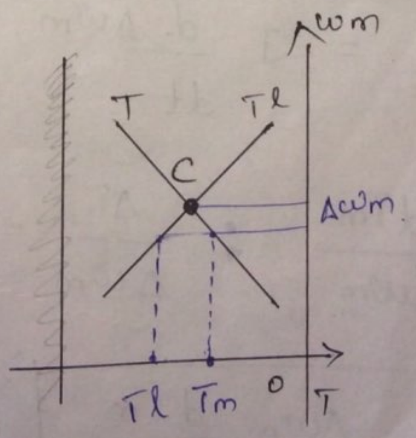
→ Similarly increase in $\Delta\omega_m$ will make $T_l > T$, ∴ drive decelerates and speed ↓s. Hence the operation is restored to A. Thus the drive is steady state at pt A.

We can do the similar analysis for the following cases.

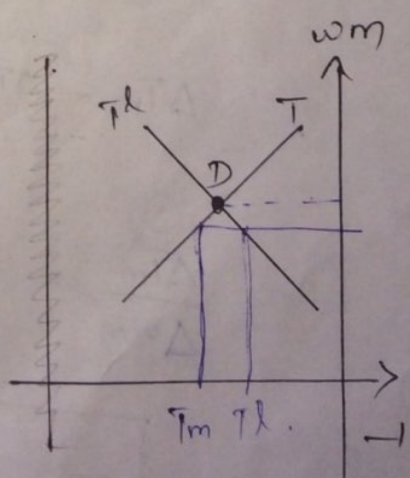
It is found that pts A and C are stable and B and D are unstable.




(B)




$T_m > T_l$



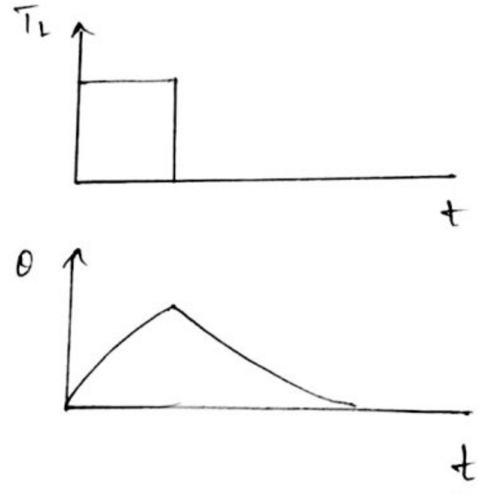

$T_l > T_m$

According to IS :- there are eight standard classes of duty.

(1) Continuous duty
(2) Short time duty
(3) Intermittent periodic duty
(4) Intermittent periodic duty with starting
(5) Intermittent periodic duty with starting and braking.
(6) Continuous duty with intermittent periodic loading
(7) Continuous duty with starting and braking.
(8) Continuous duty with periodic speed changes.

1) Short Time Duty :-

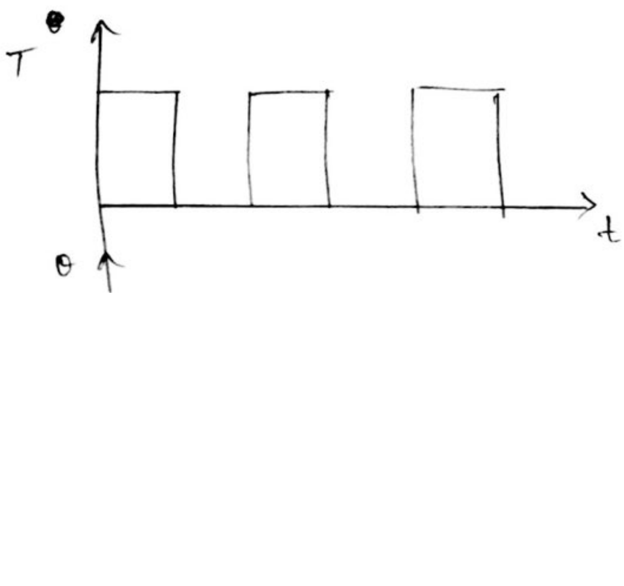
Eg:- Drives for household applications, crane drives, many m/c tool drives for position control.




→ time of drive operation less than heating time const and m/c is allowed to cool off to ambient temp (before the motor operates again).

t drives, centrifuga

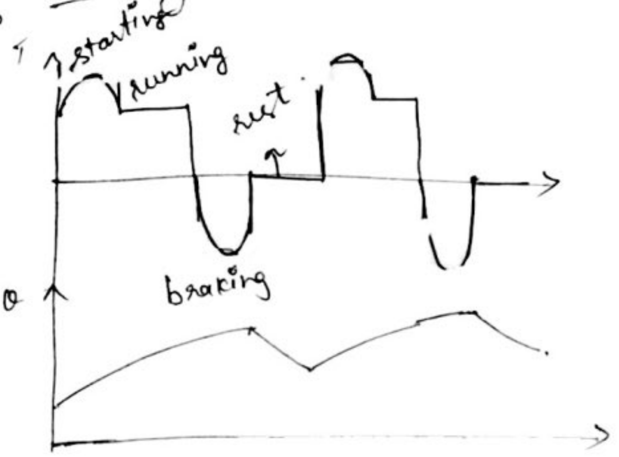
3) Intermittent periodic duty



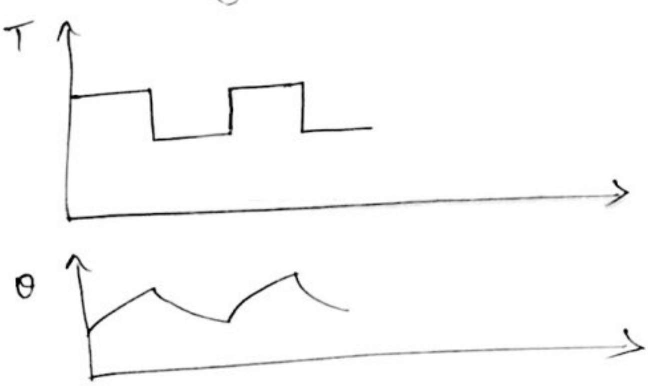

* consists of periodic duty cycle - period of running at const load and a rest period.
* the running period and being too

ntermittent periodic duty with starting and (6). braking

eg:- m/c tool drives

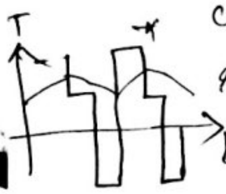



6) Continuous duty with intermittent perioding loading.




* consists of a period of starting running at const load and a period of no-load running.
* pressing, cutting, shearing and drilling m/cs

7) Continous duty with starting and braking.




* consists of a period of starting, a period of running at const load and a period of electrical braking (no rest) eg:- blooming mill.

8) Continous duty with periodic speed changes:-

* a period of running at one load and speed and another period of running at diff speed and load.

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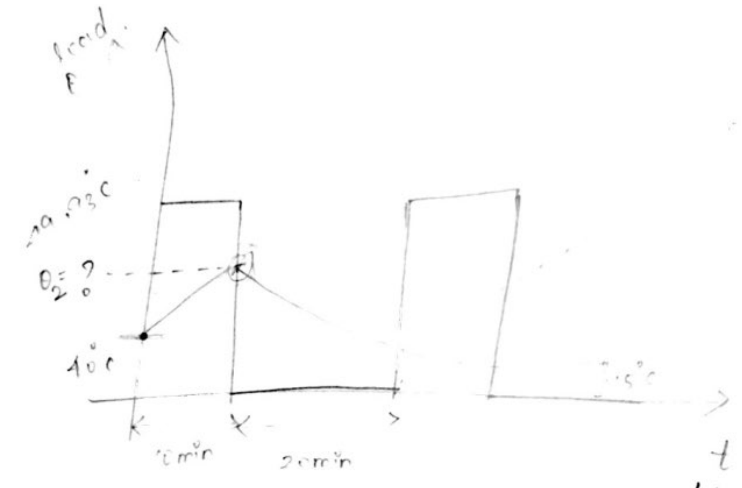
$\therefore \boxed{\theta = \theta_2 e^{\ldots}}$.

1) A motor operates on a periodic duty cycle which it is clutched to its load for 10min, declutched to run on no-load for 20min. M... temp rise is 40°c. Heating and cooling time cons... are equal and have a value of 60min. Then the load is declutched continuously the temp rise is 15°c. Find

(i) max temp during the duty cycle.

(ii) temp when the load is clutched continuou...



$? = \theta_{max}$

$\tau = \tau' = 6\ldots$

**heating**

$$\theta = \theta_{ss_1}(1 - e^{-t/\tau}) + \theta_1 e^{-t/\tau}$$

$\theta_1$ - initial temp rise.

$$\theta = \theta_{ss_1}(1 - e^{-10/60}) + 40\, e^{-10/60}.$$

$\theta_{ss_1} \rightarrow \theta_{max}$

$$\theta = \theta_{max}(0.1535) + 33.86.$$

$$\boxed{\theta = 0.15\,\theta_{max} + 33.86} \quad -(1).$$

$\theta = \theta_{ss}(1 - e^{\ldots}) + \theta_2 e^{\ldots}$

θ – mean temp rise at particular time

$\theta = 15\left(1 - e^{-20/60}\right) + \theta_2 e^{-20/60}$.

θ = 40° during cooling

$40 = 4.25 + \theta_2(0.716)$

$0.716\,\theta_2 = 35.75$

$\boxed{\theta_2 = 49.93°C}$

Take ①

$\theta = \theta_2$ b'coz mean temp during heating

$49.93 = \theta_{max}(0.1535) + 33.86$.

$0.1535\,\theta_{max} = 16.07$

$\boxed{\theta_{max} = 104.69}$

dubey (4.2)

② . A motor operates on a periodic duty cycle consisting of a loaded period of 20 min and a no-load period of 10 min. The max temp rise is 60°C. Heating and cooling time const are 50 and 70 min. When operating continuously on no-load the temp rise is 10°C. Find.

1) Min temp during the duty cycle.
2) temp when the motor is loaded continuously

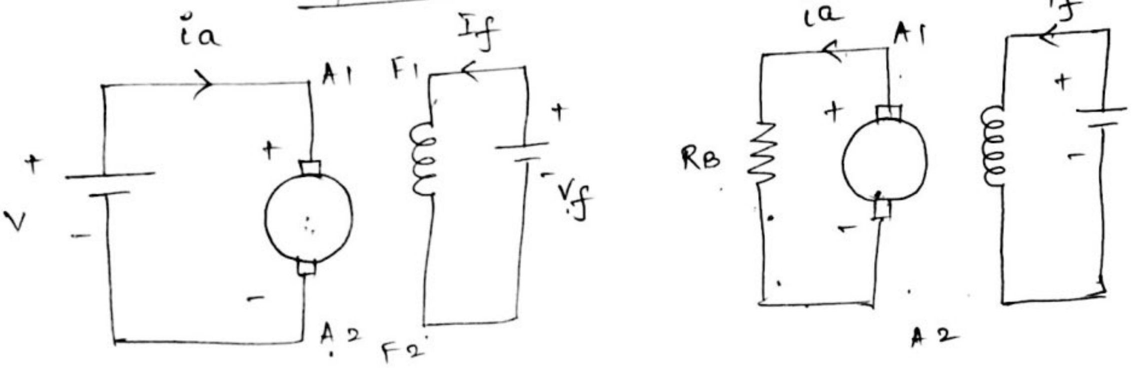
RB - not possible in series motor b'coz $E = K_e \phi \omega$
$\phi \to$ fxn of $I_a \downarrow$
$\omega_m = \frac{V}{K_e K_f I_a} - \frac{R_a}{K_e K_f}$

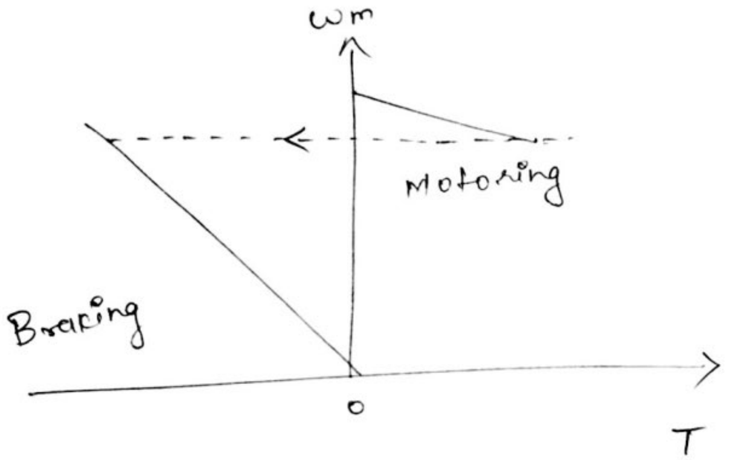
## Dynamic or Rheostatic Braking

→ Motor armature is disconnected from source and connected across a resistance RB.

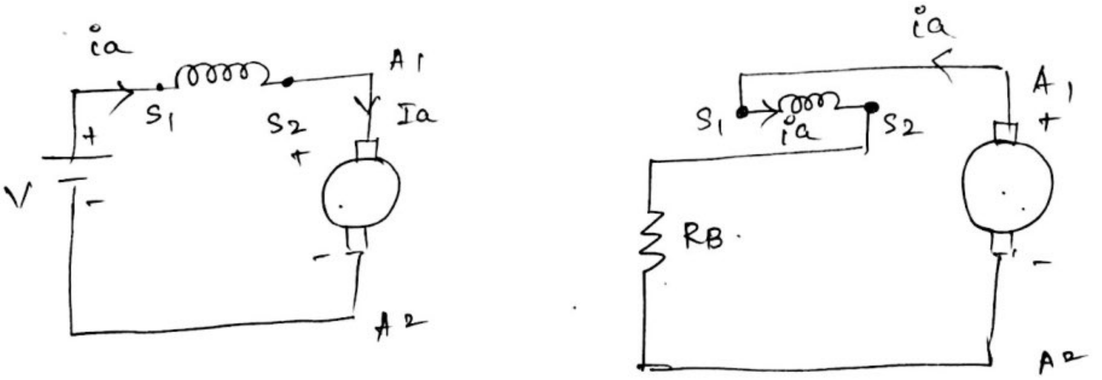
→ The generated energy will be dissipated in RB and Ra.

Separately Excited



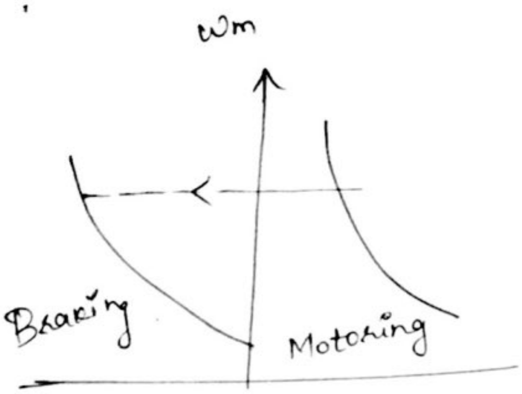

Series Motor



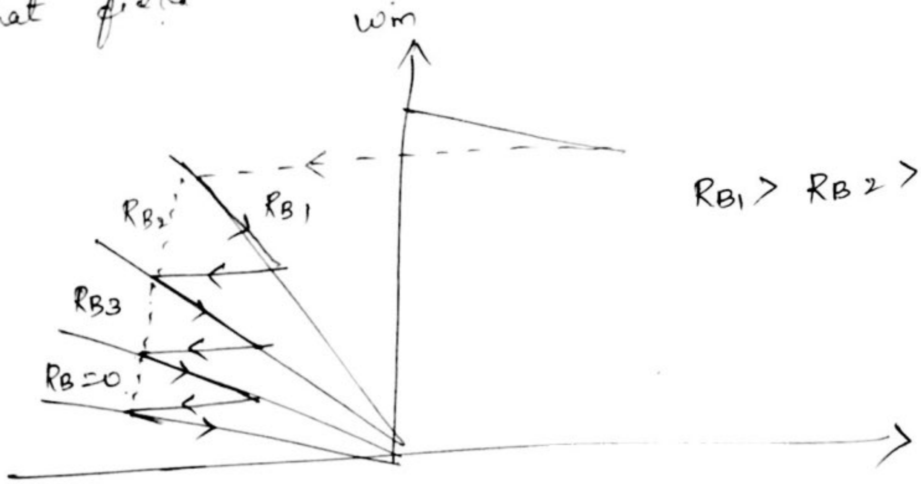
$V = E + i_a R_a$

$E > V$, $i_a$

$V = E - i_a R_a$




In series m/c, the field connection is reversed so that field assists the residual magnetism.




$R_{B1} > R_{B2} > R_{B3} > 0$.

When fast braking is needed - $R_B$ consists of few sections. As the speed ↓s, sections are cut-out to maintain a high avg torque.

## Plugging

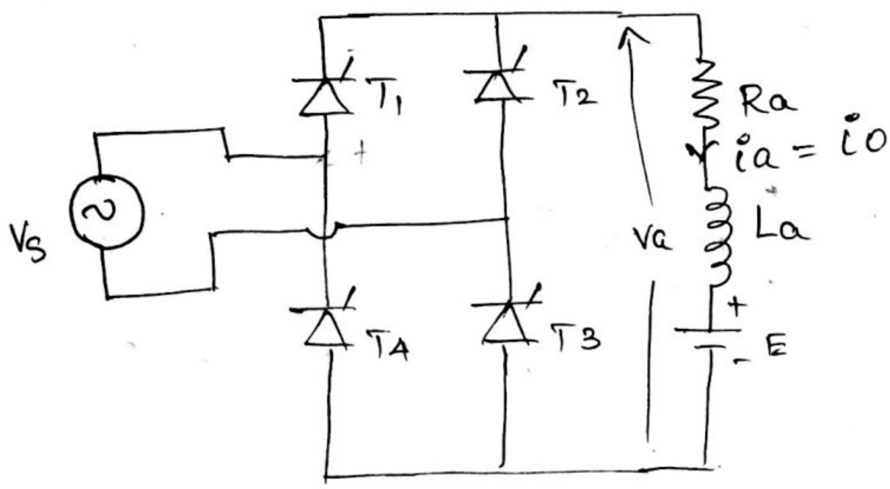
Separately excited:-

-> supply voltage is reversed so that it assist the back emf in forcing arm current in reverse direction.

-> $R_B$ is connected in series with arm to

1φ Fully controlled Rectifier control of dc separately excited motor

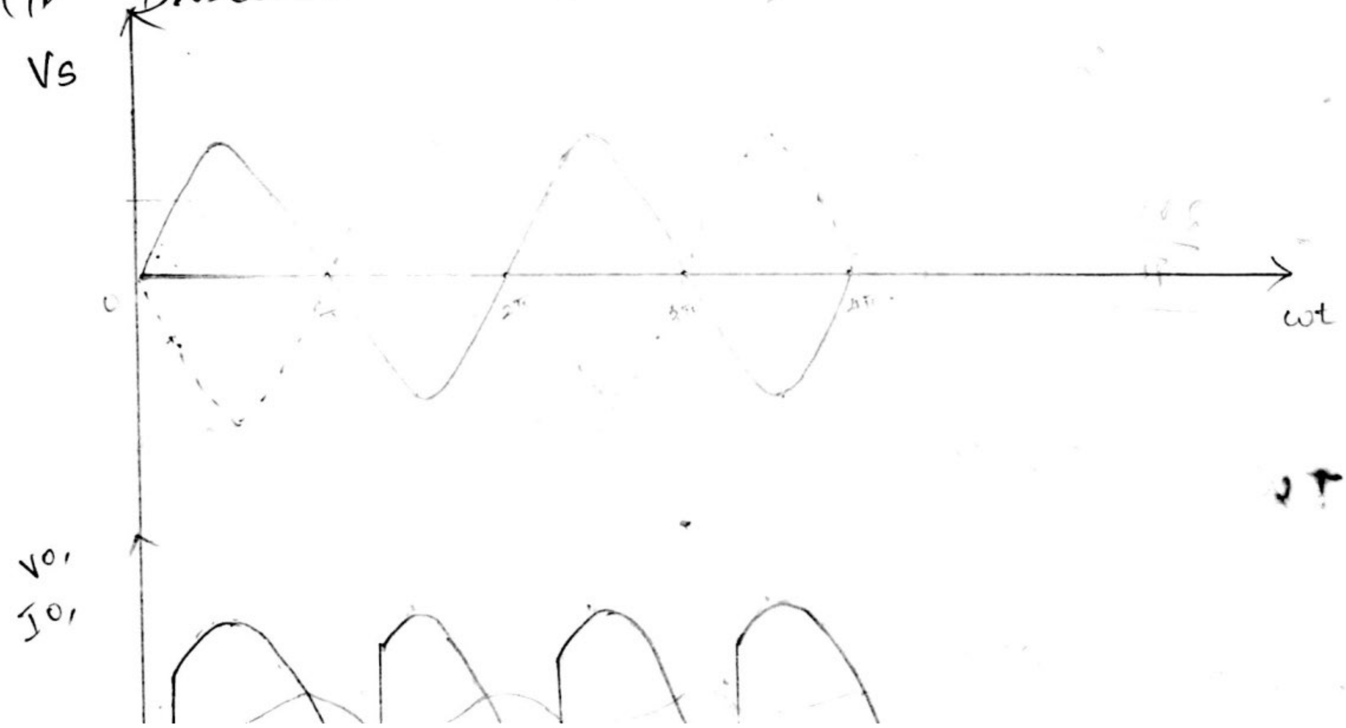
Øm



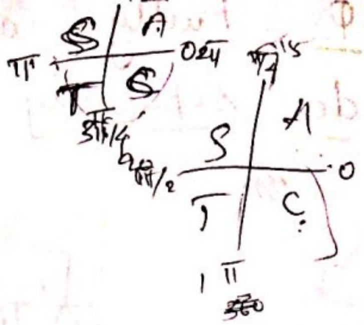

Controlled rectifier fed dc drives are known as Static Ward - Leonard drives.

(i) Continuous (current) mode

(ii) Discontinuous (current) mode



Continuous mode.




$$V_s = V_m \sin \omega t$$

$$V_a = \frac{1}{\pi} \int_{\alpha}^{\pi+\alpha} V_s \, d\omega t$$

$$= \frac{1}{\pi} \int_{\alpha}^{\pi+\alpha} V_m \sin \omega t \, d\omega t$$

$-\cos(\pi+\theta) = \cos\theta$.

$$= \frac{V_m}{\pi} \left(-\cos \omega t\right)_{\alpha}^{\pi+\alpha}$$

$$= \frac{V_m}{\pi} \left(-\cos(\pi+\alpha) + \cos\alpha\right)$$

$$= \frac{V_m}{\pi} (\cos\alpha + \cos\alpha)$$

$$\boxed{V_a = \frac{2V_m}{\pi} \cos\alpha} \quad — (1)$$

$i_a = \frac{T}{K^2}$

$E = K_e \phi \omega_m$

$= K\omega_m$. $\quad T = K i_a$,

sep ext $\quad T\omega_m = EI_a$.

$$V - i_a R_a = K\omega_m$$

$$\omega_m = \frac{V - i_a R_a}{K} = V -$$

$$\boxed{\omega_m = \frac{2V_m}{\pi K} \cos\alpha - \frac{R_a T}{K^2}} \quad — (2)$$

$$V_a = \frac{1}{\pi}\left[\int_{\alpha}^{\beta} v_a + \int_{\beta}^{\pi+\alpha} E\right] d\omega t$$

$$= \frac{1}{\pi}\left[\int_{\alpha}^{\beta} V_m \sin \omega t \, d\omega t + \int_{\beta}^{\pi+\alpha} E \, d\omega t\right]$$

$$= \frac{1}{\pi}\left[V_m (-\cos \omega t)_{\alpha}^{\beta} + E (\omega t)_{\beta}^{\pi+\alpha}\right]$$

$$= \frac{1}{\pi}\left[V_m (-\cos\beta + \cos\alpha) + E(\pi+\alpha-\beta)\right]$$

$$V_a = \frac{V_m(\cos\alpha - \cos\beta) + (\pi+\alpha-\beta)E}{\pi}$$

$i_a R_a$

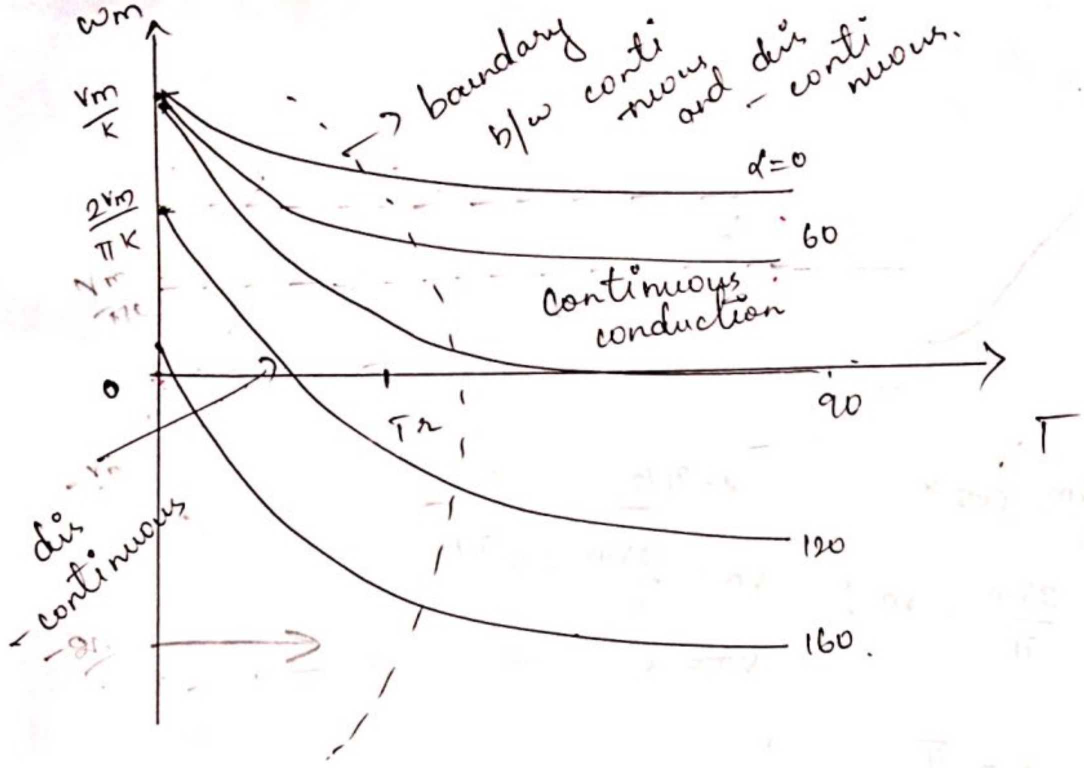
$i_T = K i_a$

$$\omega_m = \frac{V - i_a R_a}{K}$$

$$= \frac{V_m(\cos\alpha - \cos\beta) + (\pi+\alpha-\beta)E}{\pi K} - \frac{i_a R_a}{K}$$

$$\omega_m = \frac{V_m(\cos\alpha - \cos\beta) + (\pi+\alpha-\beta)K\omega_m}{\pi K} - \frac{R_a T}{K^2}$$

$$\omega_m - \frac{K\omega_m(\pi+\alpha-\beta)}{\pi K} = \frac{V_m(\cos\alpha - \cos\beta)}{\pi K} - \frac{R_a T}{K^2}$$




$$\omega m \left[ 1 - \frac{(\pi + \alpha - \beta)}{\pi} \right] = \frac{V_m(\cos\alpha - \cos\beta)}{\pi K} - \frac{R_a T}{K^2}.$$

$$\Rightarrow \frac{\pi - \pi - \alpha + \beta}{\pi}$$

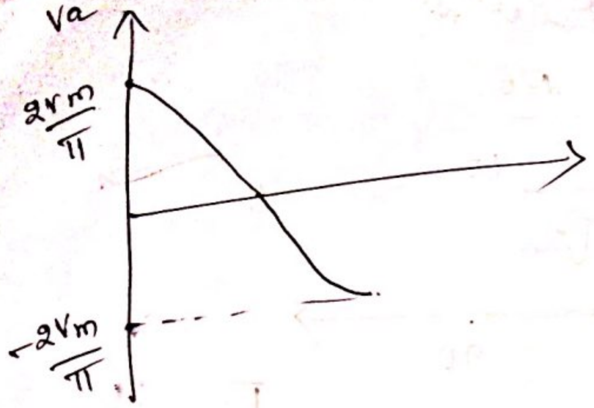
$$\omega m \frac{-(\alpha - \beta)}{\pi} = \frac{V_m(\cos\alpha - \cos\beta)}{\pi K} - \frac{R_a T}{K^2}$$

$$\times \frac{\pi}{(\alpha-\beta)} \quad \omega m = \frac{V_m(\cos\alpha - \cos\beta)}{K-(\alpha-\beta)} - \frac{R_a T}{K^2}$$

$$\omega m \frac{(\beta - \alpha)}{\pi} = \frac{V_m(\cos\alpha \cdot \cos\beta)}{\pi K} - \frac{R_a T}{K^2}$$

$$\boxed{\omega m = \frac{V_m(\cos\alpha - \cos\beta)}{K(\beta - \alpha)} - \frac{R_a T \pi}{K^2(\beta - \alpha)}}$$

$E = V_m.$




$\omega_m \propto T$ ✓

$T \propto i_a$ ↑

Va -.

$V_a = \frac{2V_m}{\pi} \cos\alpha$

if $\alpha = 0$, $\frac{2V_m}{\pi} = V_a$ ;

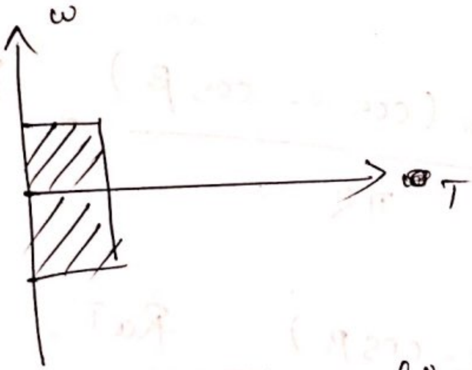
$\alpha = \pi/2$

$V_a = \frac{2V_m}{\pi} \cos \pi/2$

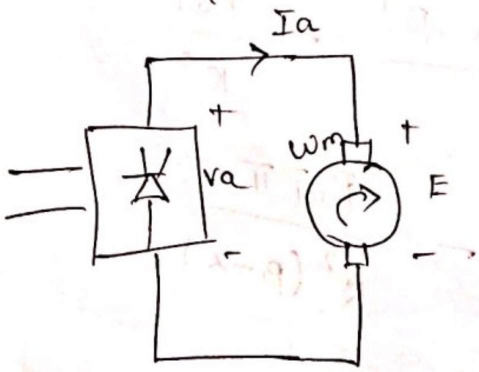
$V_a = 0$

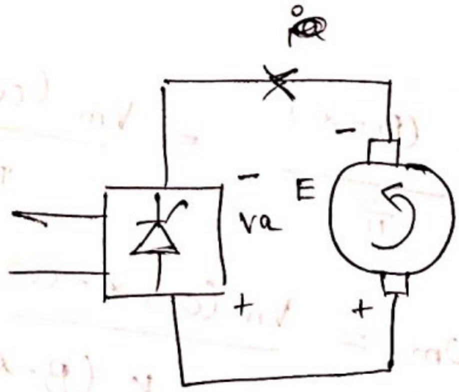
$\alpha > 90$ ; $\alpha = \pi$

$V_a = \frac{2V_m}{\pi} \cos \pi = -\frac{2V_m}{\pi}$




fully-controlled rectifier : operates in I and IV quadrant.




$\alpha > 90$, $\omega_m < 0$.

~~α>90~~

$\alpha < 90$, $\omega_m > 0$

+ve

① A 200V, 875 rpm, 150A separately excited dc motor has an arm resistance of 0.06 Ω. It is fed from a 1φ fully controlled rectifier with an ac source voltage of 220V, 50Hz. Assume continuous conduction, calculate

(150V, 100A, 0.05 Ω)

(i) α for rated motor torque and 750 rpm (600 rpm)

(ii) α for rated motor torque and −500 rpm. (450 rpm)

(iii) motor speed for α = 160° (150°) and rated torque.

(i) $E_1$ − rated $E_1 = V - i_a R_a = 200 - (150 \times 0.06) = 191V$.

$E_1 = 191V$, $N_1 = 875$ rpm. $\frac{E_1}{E_2} = \frac{N_1}{N_2}$

$E_2 = ?$ $N_2 = 750$ rpm

$$E_2 = E_1 \frac{N_2}{N_1} = 191 \times \frac{750}{875} = 163.71 V$$

$$\frac{2V_m}{\pi} \cos\alpha = V_a$$

$$V_a = E_2 + i_a R_a = 163.71 + (150 \times 0.06) = 172.71$$

$$V_m = V_L \sqrt{2} = 220\sqrt{2} = 311.13 V$$

$$\cos\alpha = \frac{V_a \pi}{2V_m} = \frac{172.71 \pi}{2 \times 311.13} = 0.8719$$

$$\boxed{\alpha = 29.31^\circ}$$

(ii) $E_2$ at −500 rpm, $= 191 \times \frac{-500}{875} = -109.14$.

$V_a = E_2 + i_a R_a \Rightarrow -109.14 + (150 \times 0.06) = -100.14$.

$$\cos\alpha = \frac{-100.14 (\pi)}{2 \times 311.13} = -0.5055$$

$$\boxed{\alpha = 120.369}$$

(iii) $\alpha = 160°$,

$$\frac{2V_m}{\pi}\cos\alpha = V_a$$

$$V_a = \frac{2(311.13)}{\pi}\cos 160 = -186.12\,V.$$

$E_2 = V_a - i_a R_a$ . $E_2 = -186.12 - (150 \times 0.06)$

$$E_2 = -195.126$$

$$E_2 = E_1 \frac{N_2}{N_1} ; \; N_2 = \frac{E_2}{E_1} N_1 = \frac{-195.126}{191} \times 875$$

$$\boxed{N_2 = -893.90} \text{ rpm.}$$

(exercise)
5.36
G.K. Dubey

② A 220V, 1500 rpm, 10A sep exc dc motor is fed from a 1Φ FCC with an ac source voltage of 230V, 50Hz. $R_a = 2\Omega$. Conduction can be assumed to be continuous.

Calculate firing angle for

(i) half the rated motor torque and 500 rpm.

(ii) rated motor torque and (-1000) rpm.

(i) half the rated motor torque,

$$T \propto I_a$$

$$\therefore I_a \Rightarrow I_a/2 \Rightarrow 5A.$$

$$E_1 = V - i_a R_a = 220 - (10 \times 2) = 200V.$$

$$E_2 = \frac{N_2}{N_1} \times E_1 = \frac{500}{1500} \times 200 = 66.67\,V.$$

$$V_a = E_2 + i_a R_a = 66.67 + (5 \times 2) = 76.67\,V$$

$$\frac{2V_m}{\pi}\cos\alpha = V_a$$

$$\cos\alpha = \frac{V_a \times \pi}{2V_m} = \frac{76.67 \times \pi}{2 \times 230 \times \sqrt{2}} = 0.3702$$

$$\boxed{\alpha = 68.26}$$

# Multi-quadrant operation of separately excited dc motor fed from fully controlled rectifier.

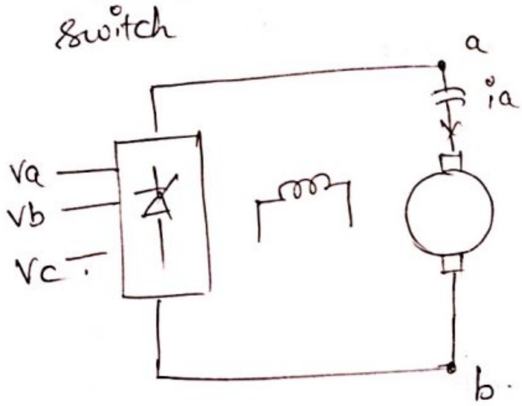
a) 1ϕ fully controlled rectifier with a reversing switch

b) Dual converter

c) 1ϕ fully controlled rectifier in the armature with field current reversal.

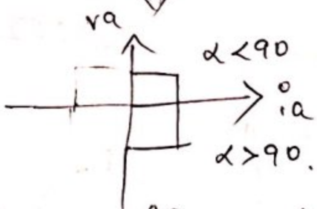
Fully controlled converter – quadrant I & IV

1ϕ fully controlled rectifier with a reversing switch

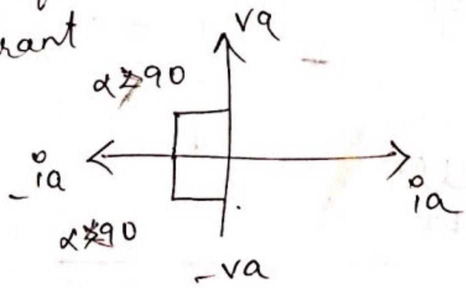



→ Reversing switch RS is used to reverse the arm connection w.r.t to rectifier

→ FCC → I and IV




→ The reversal of armature connection provides II and III quadrant



The switch can be relay-operated contactor with 2 normally NO and NC closed contactors. (fig a)

OR

using thyristors fig (b)

fig (a)

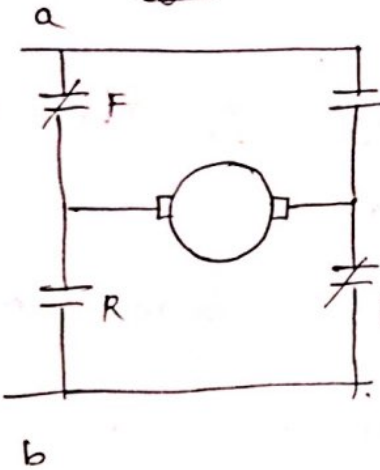
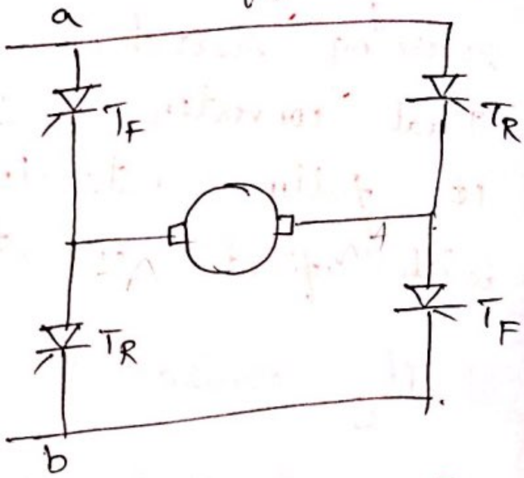



fig (b)



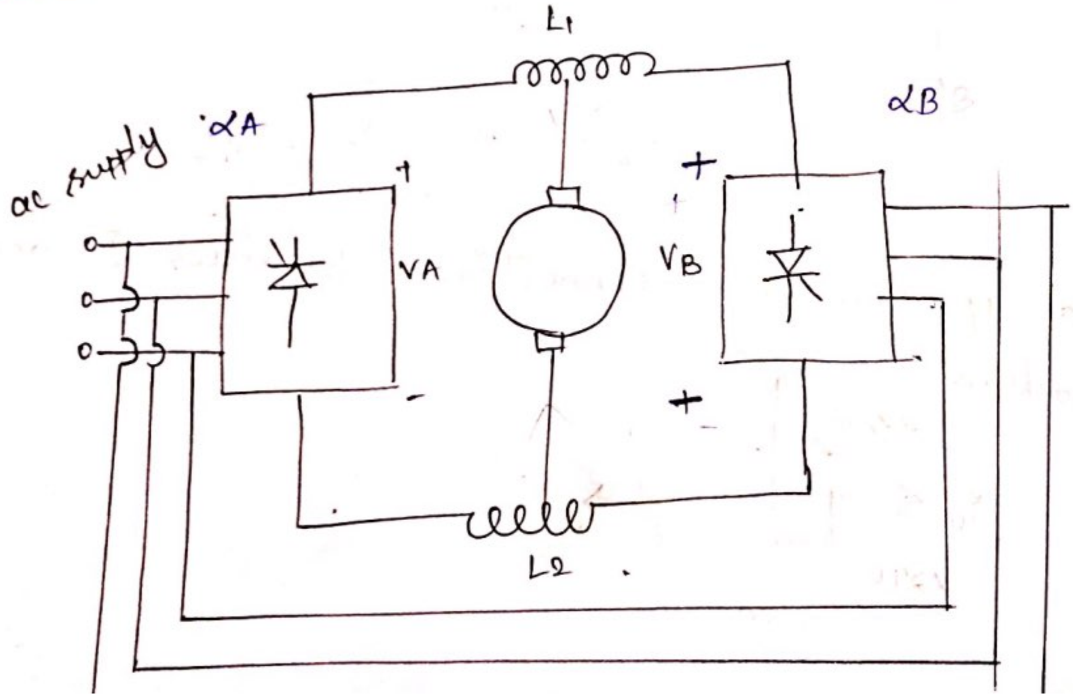

NO – a – F – M – F – b ⇒ I & IV

relay operates NC – a – R – M – R – b.

$T_F$-ON ($T_R$-OFF) – I & IV

$T_R$-ON ($T_F$-OFF) – III & II.

## Dual Converter:-



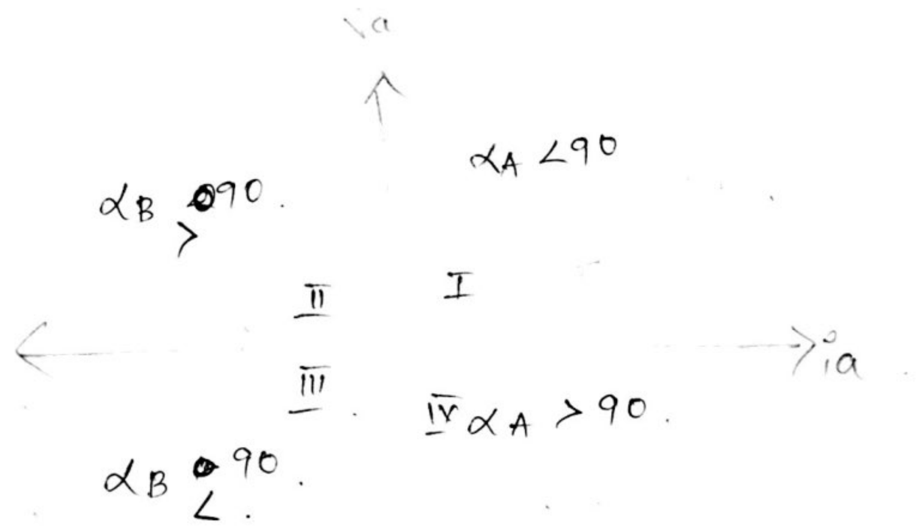
→ 2 fully controlled converters connected in anti-parallel across the armature.

→ Rectifier A – +ve current and +VA and –VA
∴ I and IV quadrant

→ Rectifier B – –ve current and +VB and –VB.
∴ III and II quadrant.

E =

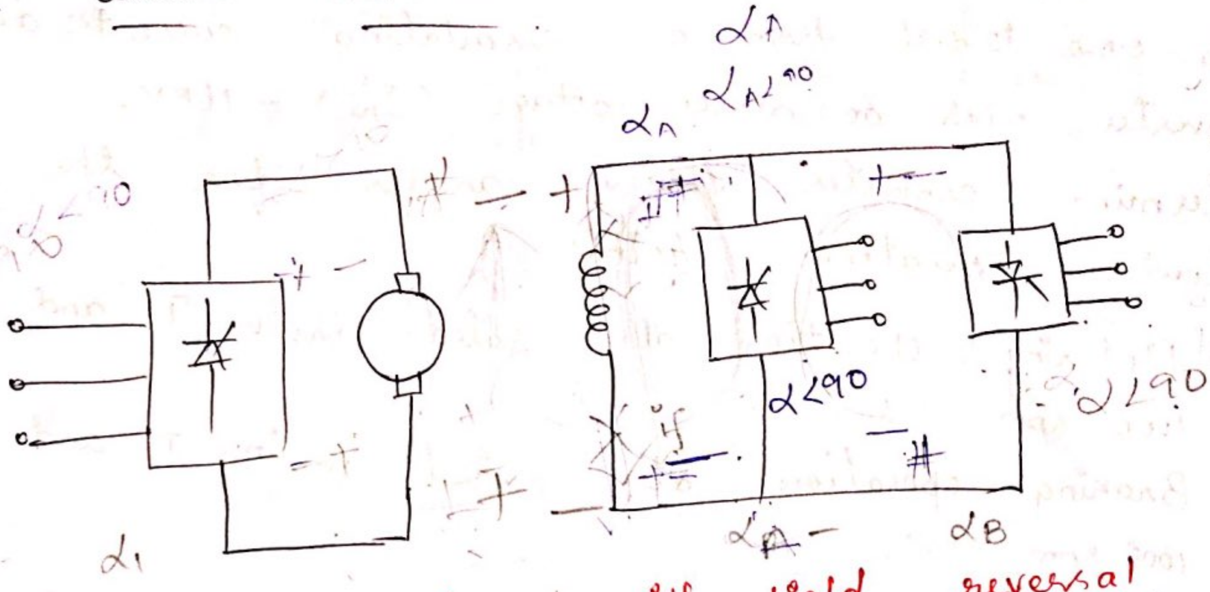
Refer Bimbra.




i) circulating current mode / simultaneous mode.

$$\alpha_A + \alpha_B = 180$$

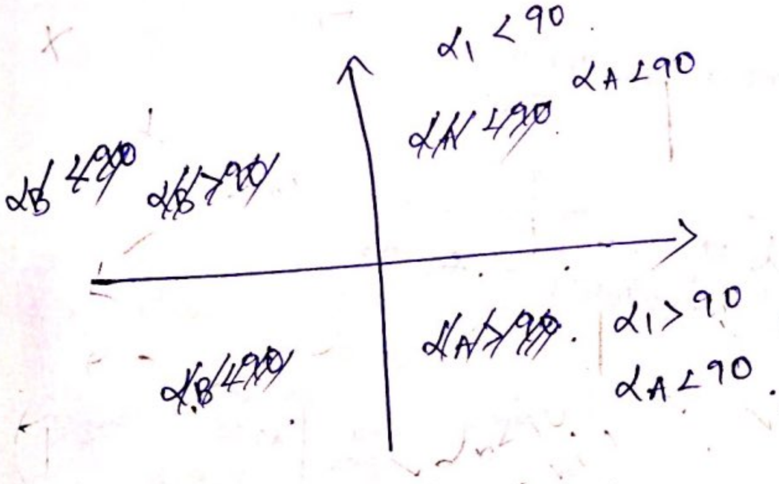
Field current Reversal



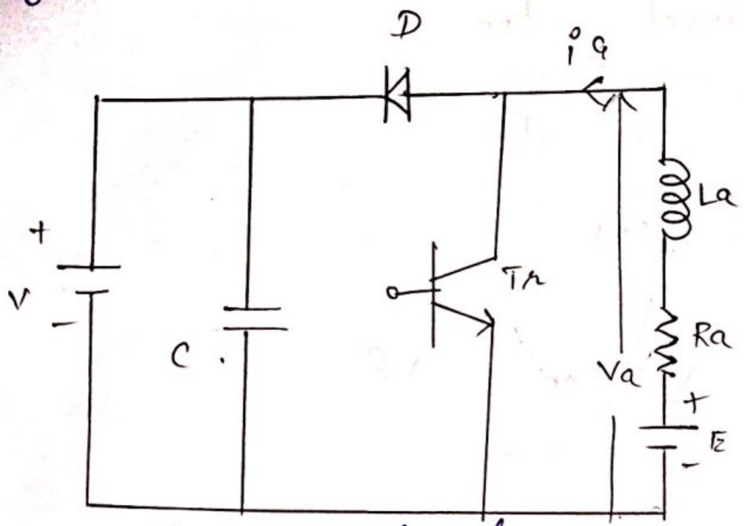

Four quadrant drive with field reversal.

* With If in one direction, → Quadrants I and IV
* When If is reversed → Quadrants II and III.

→ The dual converter operates with non-simultaneous control.



Regenerative Braking.




**Energy Storage interval**

→ When Tr is on ( $0 \le t \le t_{on}$ ), the o/p voltage is zero. $v_o = v_a = 0$.

→ Though $v_a = 0$, voltage E drives current thro La and Tr.

→ La stores energy during ton.

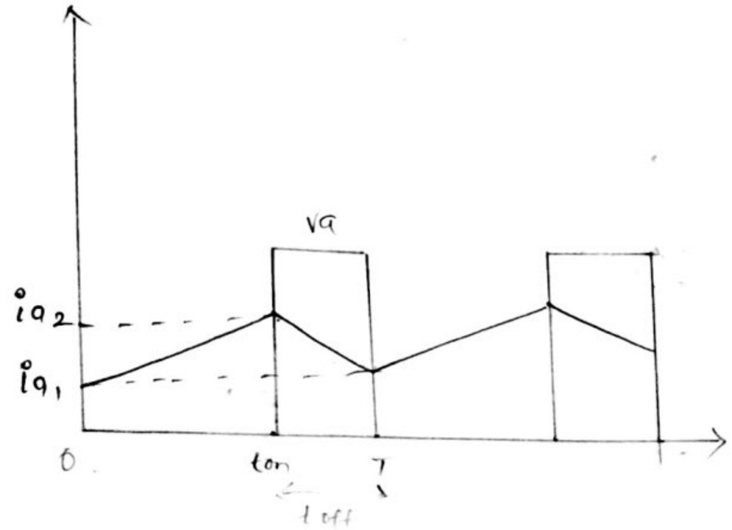
→ ia ↑s from $i_{a1}$ to $i_{a2}$.

**Duty interval:-** ( $t_{on} \le t \le T$ )

→ When Tr is off, $v_o = E + L_a \frac{di_a}{dt} = V$

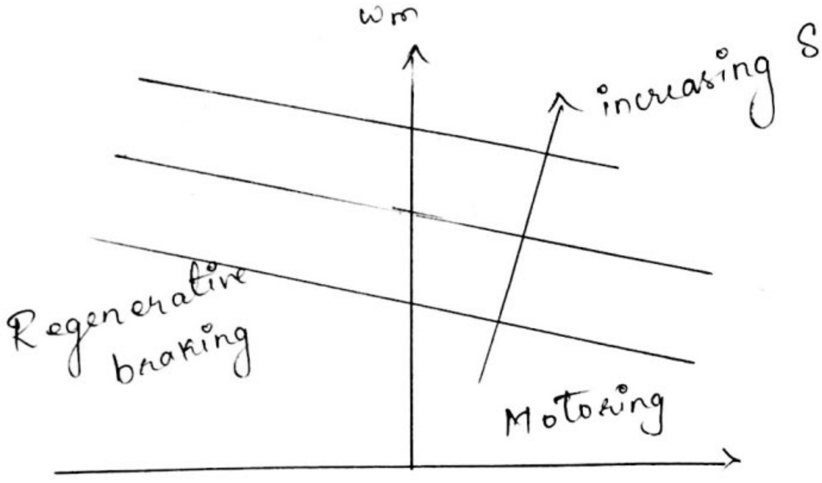
bcoz of this, D is forward biased and begins conduction, thus allowing power flow to the source.

→ ia flows thro D, and source V and reduces from $i_{a2}$ to $i_{a1}$.




$$\delta = \frac{\text{duty interval}}{T} = \frac{t_{off}}{T} = \frac{T - t_{on}}{T}$$

$$V_a = \frac{1}{T}\int_{t_{on}}^{T} \qquad V_a = \frac{1}{T}\int_{t_{on}}^{T} v \, dt = \frac{V}{T}(T - t_{on})$$




$$V_a = V\left(1 - \frac{t_{on}}{T}\right) = V(1-\delta) \qquad V_a = V\delta$$

where $\delta = 1 - \frac{t_{on}}{T}$.

$E_g = K\omega_m$

$T = -K I_a$ (∵ $I_a$ is reversed)

$$\omega_m = \frac{V_a + i_a R_a}{K} = \frac{V(1-\delta)}{K} + \frac{R_a T}{K^2}$$

$$\omega_m = \frac{V\delta}{K} + \frac{R_a T}{K^2}$$

1a) Operation with unbalanced source voltage, and single phasing

Let Va, Vb and Vc be unbalanced supply voltage.

They set of unbalanced voltages can be resolved into 3ϕ balanced +ve sequence Vp, -ve sequence Vn and zero sequence Vo (symmetrical components relationships)

$$V_p = \frac{1}{3}\left[V_a + \alpha V_b + \alpha^2 V_c\right]$$

$$V_n = \frac{1}{3}\left[V_a + \alpha^2 V_b + \alpha V_c\right]$$

$$V_o = \frac{1}{3}\left[V_a + V_b + V_c\right].$$

$$\alpha = e^{j120^\circ} \Rightarrow \cos 120 + j \sin 120.$$

Assume m/c without neutral connection.

→ +ve sequence voltage have same phase sequence as that of original system.

→ -ve sequence voltage - opposite phase sequence.

→ in the absence of neutral connection, zero sequence line voltages are zero.

Calculate motor performance for +ve and -ve sequence separately.

* Resultant performance of motor can be obtained by using super-position principle.

## POSITIVE SEQUENCE.

→ +ve sequence voltage produce an air-gap flux which rotates at syn speed in forward direction.

Let $\omega_m$ - forward direction.

$$S = \frac{\omega_{ms} - \omega_m}{\omega_{ms}}$$

$$S\omega_{ms} = \omega_{ms} - \omega_m$$

$$\omega_m = \omega_{ms} - S\omega_{ms}$$

$$\boxed{\omega_m = \omega_{ms}(1-s)} \quad \text{— (1)}$$

Equivalent ckts are same,

$$\therefore I'_{rp} = \frac{V_p}{\left(R_s + \frac{R'_r}{S}\right) + j\,(X_s + X'_r)} \quad \text{— (2)}$$

$$T_p = \frac{3}{\omega_{ms}} \left[ \frac{V_p^2 \, R'_r / S}{\left(R_s + \frac{R'_r}{S}\right)^2 + (X_s + X'_r)^2} \right] \quad \text{— (3)}$$

## NEGATIVE SEQUENCE.

-ve sequence produces air gap flux which rotates at syn speed in reverse direction.

$$S_n = \frac{-\omega_{ms} - \omega_m}{-\omega_{ms}}$$

$$= \frac{-\omega_{ms} - [\omega_{ms}(1-S)]}{-\omega_{ms}} \leftarrow \text{using (1)}$$

$$= \frac{-\omega_{ms} - \omega_{ms} + \omega_{ms} S}{-\omega_{ms}} = 1+1-S = 2-S$$

$$\therefore \boxed{S_n = 2 - S} \quad - (4)$$

Eqn (4) represents slip for -ve sequence. Replace S by (2-S) in rotor current and torque equations:

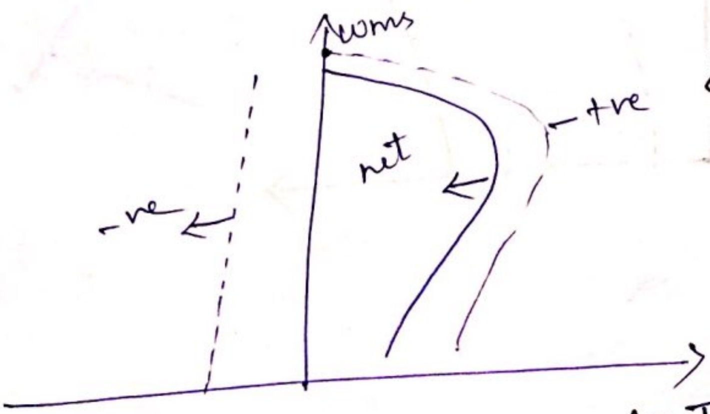
$$I'_{rn} = \frac{V_n}{R_s + \frac{R'_r}{(2-S)} + j(X_s + X'_r)} \quad - (5)$$

$$T_n = -\frac{3}{\omega_{ms}} \left[ \frac{V_n^2 R'_r / (2-S)}{\left[R_s + \frac{R'_r}{(2-S)}\right]^2 + (X_s + X'_r)^2} \right] \quad - (6).$$

Rotor current $\Rightarrow I_r'^2 = I_{rp}'^2 + I_{rn}'^2$

$$T = T_p + T_n$$

$$= \frac{3}{\omega_{ms}} \left[ \frac{V_p^2 R'_r / S}{\left(R_s + \frac{R'_r}{S}\right)^2 + (X_s + X'_r)^2} - \frac{V_n^2 R_r^2 / (2-S)}{\left[R_s + \frac{R'_r}{(2-S)}\right]^2 + (X_s + X'_r)^2} \right]$$




Torque capacity is reduced and cu losses are ned to satisfy load T demand, motor will draw more current from the supply.

∴ to prevent burning of the motor, it is not allowed to run for pro-longed period when voltage unbalance is > 5%.

$2\omega_{ms}$ $R_s + \lambda(\ldots$

$$T_{max} = \frac{3 I_r'^2 R_r' / S_m}{\omega_{ms}} \qquad S = S_m = -\frac{R_r'}{\sqrt{R_s^2 + (X_s + X_r')^2}}$$

A 400V, λ-connected 3φ, 6-pole, 50Hz IM has following parameters referred to stator

$R_s = R_r' = 1\Omega$, $X_s = X_r' = 2\Omega$.

For regenerative braking, determine.

(i) max torque (overhauling) it can hold and range of speed for safe operation.

(ii) speed at which it can hold an overhauling load with a torque of 100 N-m.

$$N_s = \frac{120 \times 50}{6} = 1000.$$

$$N_s = \frac{120 f}{P}$$

$$\omega_{ms} = \frac{2\pi \times 1000}{60}$$

$$= 104.71 \text{ rad/sec.}$$

$$\frac{2\pi N_s}{60} = \omega_{ms}$$

$$\frac{120 f \times 2\pi \times N_s}{60.}$$

$$N_s = \frac{60 \times \omega_{ms}}{2\pi}$$

$$= \frac{30\,\omega_{ms}}{\pi}$$

$$S_m = -\frac{R_r'}{\sqrt{R_s^2 + (X_s + X_r')^2}} = -\frac{1}{\sqrt{1 + (2+2)^2}}$$

$$= \frac{-1}{4.123} = -0.2425$$

$$\boxed{S_m = -0.2425}$$

$$I_r'^2 = \frac{V^2}{\left(R_s + \frac{R_r'}{S}\right)^2 + (X_s + X_r')^2} = \frac{(400/\sqrt{3})^2}{\left[1 + \frac{1}{(-0.2425)}\right]^2 + (2+2)^2}$$

$$= \frac{53\,333.33}{9.7575 + 16} = 2070.594\text{ A}.$$

$$\boxed{I_r' = 45.5\text{ A}}$$

$$T_{max} = \frac{\frac{3 I_r'^2 R_r'}{S}}{\omega_{ms}} = \frac{\frac{3 \times (45.5)^2 \times 1}{(-0.2425)}}{104.71} = -244.59.$$

$$\boxed{T_{max} = -244.59\text{ Nm}.}$$

$$N_m = (1-S)\,N_s = \left[1 - (-0.2425)\right]1000.$$

$$= 1.2425\,(1000)$$

$$\boxed{N = 1242.5\text{ rpm}.}$$

(ii) $T_{max} = 100\text{ Nm}.$

$$T = \frac{3R_r'}{\omega_{ms}\, S} \frac{V^2}{\left(R_s + \frac{R_r'}{S}\right)^2 + (X_s + X_r')^2}$$

$$100 = \frac{3\,(1)}{104.71\,(S)} \left[\frac{(400/\sqrt{3})^2}{\left(1 + \frac{1}{S}\right)^2 + 16}\right]$$

$$100 = \frac{0.02}{S} \left[\frac{230.9^2}{1 + \frac{1}{S^2} + \frac{2}{S} + 16}\right]$$

→ Inner current loop is provided to limit the converter & motor current or torque below a safe limit.

## Supply Frequency Control (V/f const)

$$N = N_s(1-s)$$
$$= \frac{120f}{P}(1-s)$$

f changes → $N_s$ changes → s changes → N changes.

Let $E_1$ be the induced voltage in stator winding of IM

$$E_1 = 4.44 f \phi T K$$

K – winding factor
T – no of turns in stator winding
f – i/p supply fre.

$$E_1 \propto f\phi$$

$$\frac{E_1}{\phi} \propto f$$

$f\downarrow$, $E_1$ – const, $\phi\uparrow$.

→ The increase in flux will saturate the motor
→ This will ↑, magnetizing current, distort line voltage and current, ↑s cu loss and core loss, produces noise.
→ ∴ ↑ in flux in undesirable from the consideration of saturation effects.

∴ the variable fre control at rated air-gap fre is generally carried out with fre flux by varying terminal voltage such that $\frac{V}{f}$ ratio is maintained const.

For rated voltage and fre,

$$T_{max} = \frac{3}{2\omega_{ms}} \left[ \frac{V^2}{R_s \pm \sqrt{R_s^2 + (X_s + X_r')^2}} \right] \quad -(1)$$

$$\omega_{ms} = \frac{4\pi f}{P} \; ; \; X_s = 2\pi f L_s, \; X_r' = 2\pi f L_r'$$

$$= \frac{3}{2\left(\frac{4\pi f}{P}\right)} \left[ \frac{V^2}{R_s \pm \sqrt{R_s^2 + (2\pi f L_s + 2\pi f L_r')^2}} \right]$$

$$= \frac{3P}{8\pi f} \left[ \frac{V^2}{R_s \pm \sqrt{R_s^2 + 4\pi^2 f^2 (L_s + L_r')^2}} \right]$$

$$= K \frac{V^2}{f \times f} \left[ \frac{1}{\frac{R_s}{f} \pm \sqrt{\frac{R_s^2}{f^2} + 4\pi^2 (L_s + L_r')^2}} \right]$$

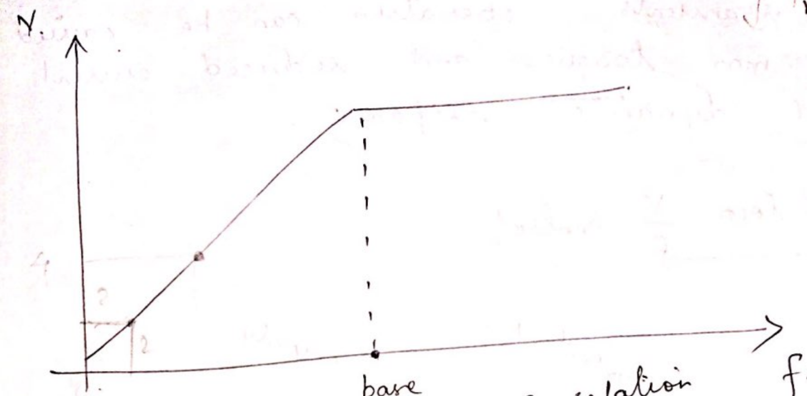
$$= K \left[ \frac{\left(\frac{V}{f}\right)^2}{\frac{R_s}{f} \pm \sqrt{\left(\frac{R_s}{f}\right)^2 + 4\pi^2 (L_s + L_r')^2}} \right] \quad -(2)$$

When f is not low,

$$\frac{R_s}{f} << 2\pi (L_s + L_r')$$

$$T_{max} = \pm \frac{K \left(\frac{V}{f}\right)^2}{8\pi (L_s + L_r')} \quad — (3)$$

$T_{max} \propto \frac{K}{f}$



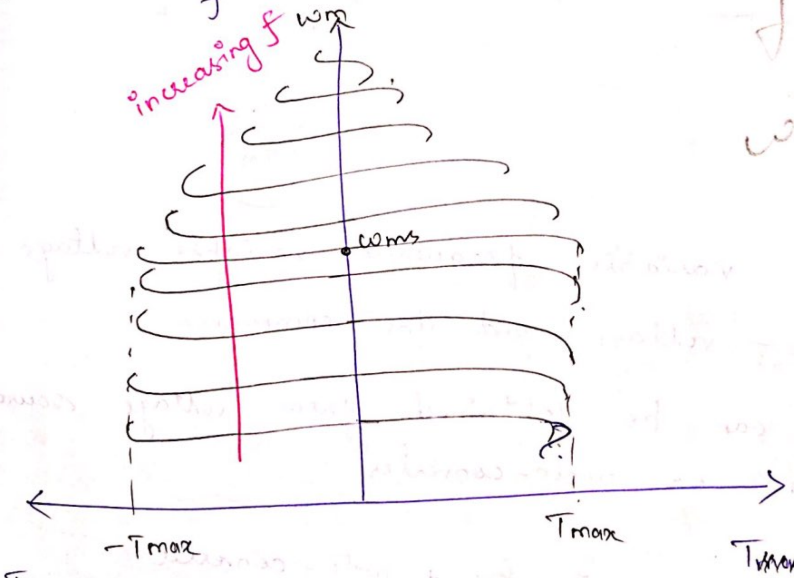

V-f relation

→ with const $\frac{V}{f}$ ratio, motor develops max torque

$f \propto \omega_m$

$\omega_{ms} = \frac{4\pi f}{P}$

$\omega_{ms} \propto f$



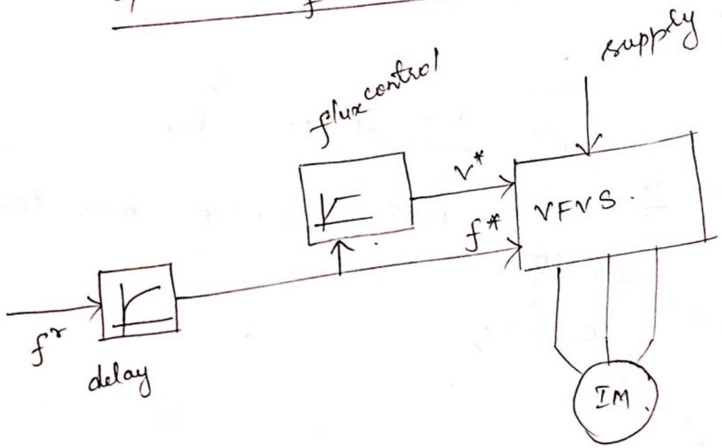

Speed- torque char.

Advantages :-

→ Speed control and braking available from zero to above base speed.

→ during transients operation can be carried out at max torque and reduced current thus good dynamic response.

Open-loop $\frac{V}{f}$ control




VFVS - variable frequency variable voltage source.

$V^*$, $f^*$ - voltage and fre commands.

VFVS - can be obtained from voltage source inverter or cyclo-converter.

Voltage source inverter + cyclo-converter
and
closed-loop control → ppt.

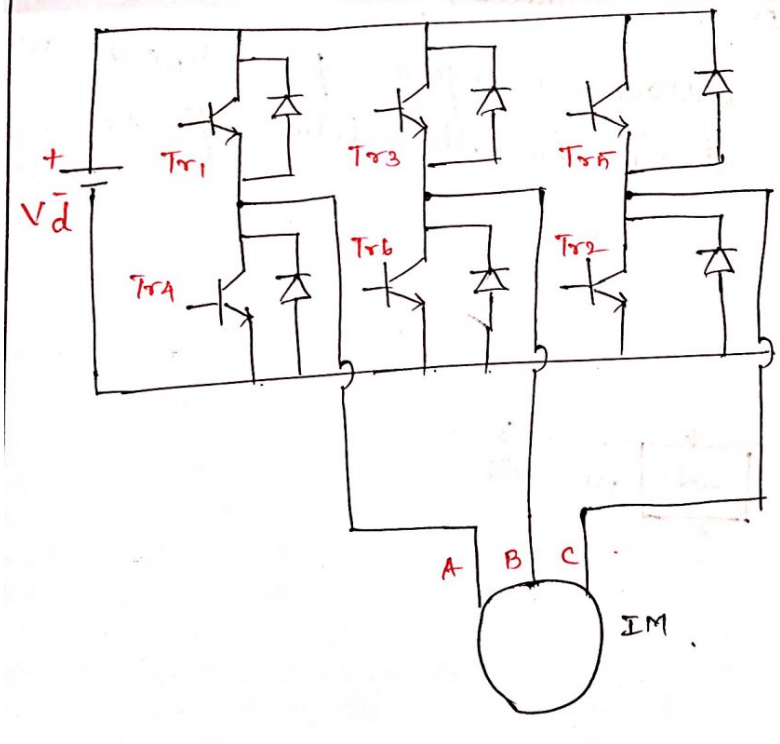
current source inverter

## Voltage Source Inverter Control :- VSI

Variable frequency and variable voltage supply for IM control can be obtained either from a voltage source inverter (VSI) or a cycloconverter.

### VSI IM Drives:-

⇒ VSI allows a variable fre from dc supply. Transistor inverter fed IM drive is shown in the below figure.



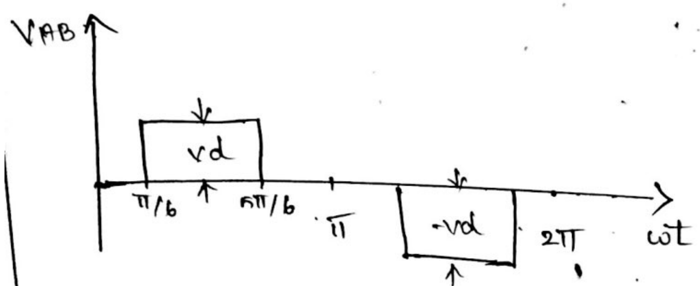
⇒ instead of transistors, any other self commutated devices [MOSFET (low voltage and low power), IGBT, GTO, IGCT - high power level can be used].

⇒ VSI can be operated as stepped wave inverter or a PWM inverter.

* For a given time period T (one cycle), each device is ON for T/2 duration, in which all the devices are switched in the sequence of their numbers with a time difference of T/6.

* frequency is varied by varying T and o/p voltage is varied by varying dc i/p voltage (chopper is required).

The line voltage waveform for stepped wave inverter is shown in the below figure.



The o/p line voltage and phase voltage are given by following expressions :-

$$V_{AB} = \frac{2\sqrt{3}}{\pi} V_d \left[\sin\omega t - \frac{1}{5}\sin 5\omega t - \frac{1}{7}\sin 7\omega t + \frac{1}{11}\sin 11\omega t + \frac{1}{13}\sin 13\omega t \ldots\right]$$

$$V_{AN} = \frac{2V_d}{\pi}\left[\sin\omega t + \frac{1}{5}\sin 5\omega t + \frac{1}{7}\sin 7\omega t\right]$$

The rms value of fundamental phase voltage,

$$V = \frac{V_{AN}}{\sqrt{2}} = \frac{\sqrt{2}}{\pi} V_d .$$

Drawbacks of stepped wave inverter fed IM drive :-

[large harmonics of low frequency].

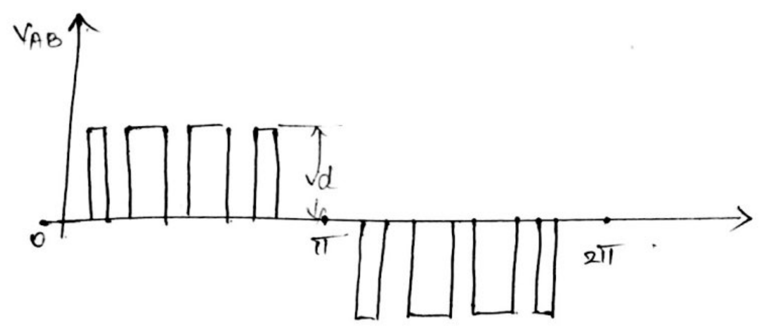
i) Large amt of low fre harmonics - high motor losses - derating of motor

ii) Results in jerky motion of the rotor due to harmonic pulsating torque.

iii) Harmonic current component is more at low speeds - results in overheating - limiting lowest speeds to around 40% of rated value

All the above mentioned drawbacks are eliminated using pulse width modulation Technique

The line voltage for PWM inverter is shown below,



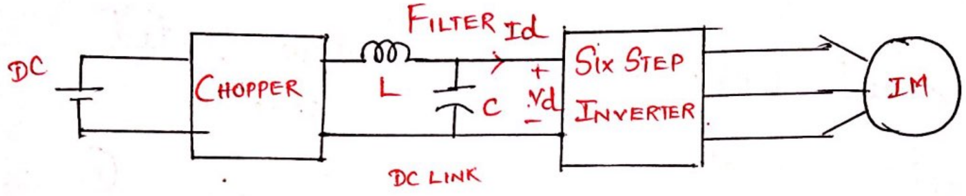

Since o/p can be directly varied by PWM, no arrangement is required for variation of i/p voltage.

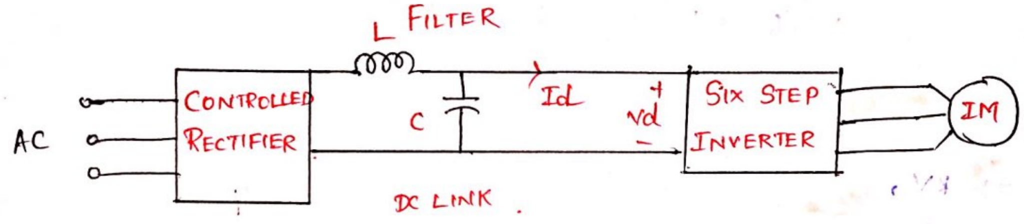
The fundamental component of O/P voltage is give by

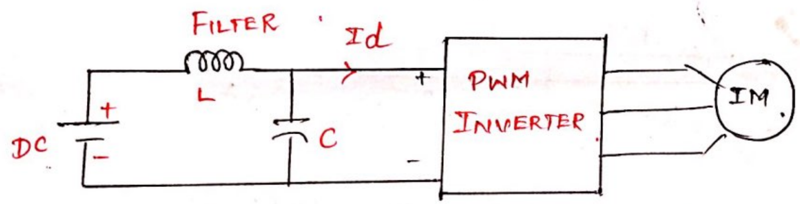
$$V = \frac{m V_d}{2\sqrt{2}}.$$

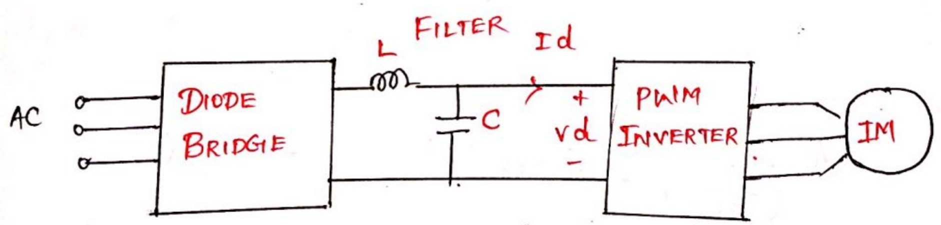
where "m" is the modualation index.

The various configurations of VSI controlled IM drives are shown below,




-*- for braking and multiquadrant operation of VSI IM drive refer slides (PPT).

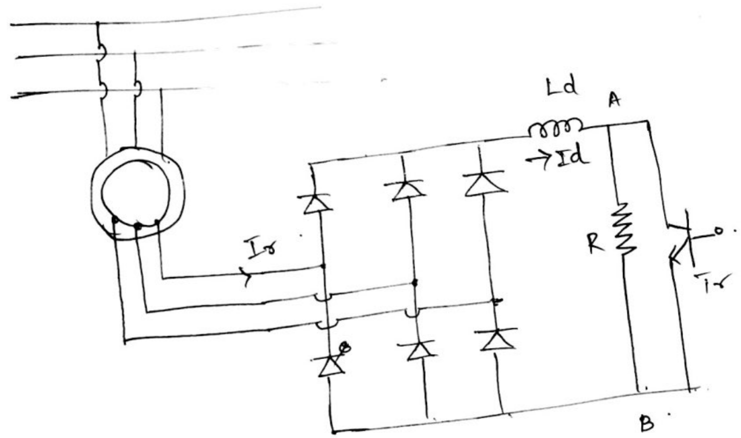
Rotor Resistance Control :

$$T \propto \frac{V^2 R_r'}{S}$$

$$T \propto \frac{R_r'}{S}$$

$R_r' \uparrow$, to maintain const torque, $S \uparrow$, $N \downarrow$.

**Static Rotor Resistance Control**




→ The value of $R_{AB}$ across A and B terminal can be varied by varying the duty ratio of Tr.

→ Thus rotor ckt resistance is varied.

→ Ld is to reduce ripple and discontinuity in the dc link current.

$$R_{AB} = (1-\delta)R.$$

$\delta = \frac{T_{on}}{T} =$

$\delta = 0 \rightarrow R.$

$\delta = 1 \rightarrow 0.$

power consumed by $R_{AB}$,

$$P_{AB} = I_d^2 R_{AB} = I_d^2 R(1-s)$$

$$I_r = \sqrt{2/3}\, I_d .$$

$$I_d^2 = \frac{3}{2} I_r^2$$

Power consumed $P_{AB} = I_d^2 R(1-s)$

$$= \frac{3}{2} I_r^2 R(1-s)$$

$P_{AB}$ per phase $= \frac{1}{2} I_r^2 R(1-s)$

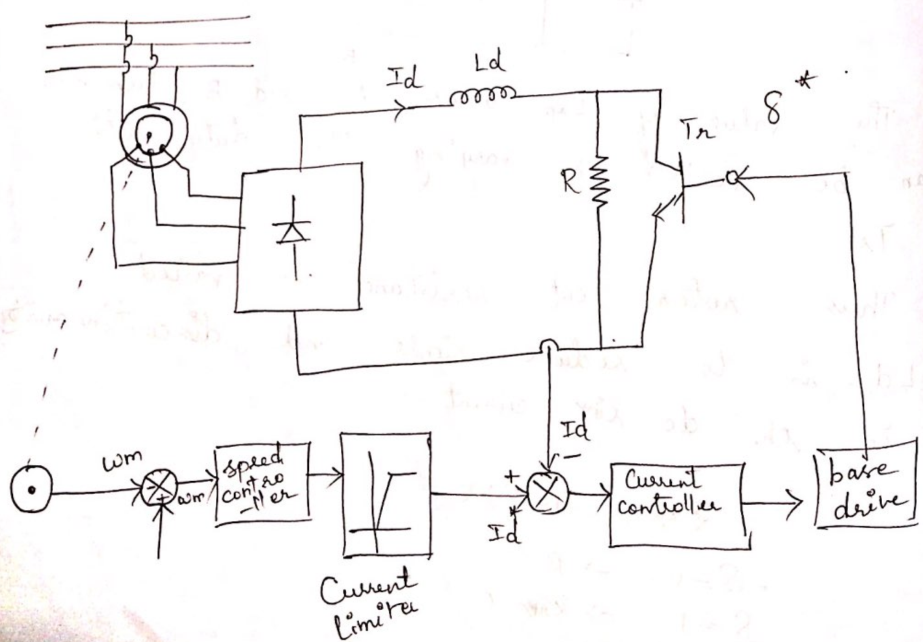
Total ckt R per phase $= R_{rT}$

$$= R_r + 0.5R(1-s)$$

when $s = 1$, $R_{rT} = R_r$

$s = 0$, $R_{rT} = R_r + 0.5R$

Closed Loop Speed Control



the process of pulling rotor into step with the rotating field is called pull in or synchronisation.

Starting :-

1) start syn motor as IM with field unexcited

Pullin :- already defined.

→ things to note

→ starting current can be high (starters)

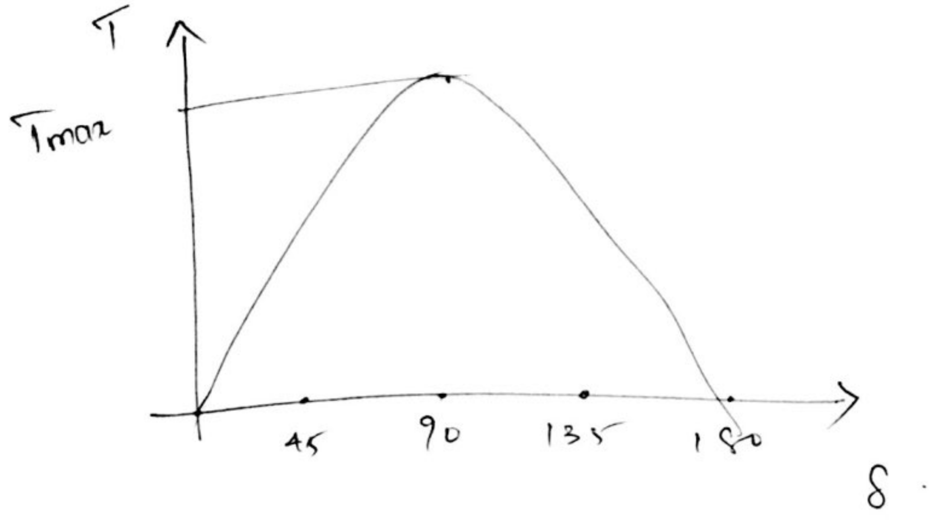
→ during acc as an IM, bcoz of large no of turns in field winding, the induced voltage may reach several thousands - insulation breakdown - to avoid this suitation, field ckt should be closed thro small discharge R before dc excitation.

Transients :

$T = T_{max} \sin \delta$

steady state stability / dynamic stability

$T_{max} = \frac{3VE}{\omega_{ms} X_s}$




$$T_m = T_L + J\frac{d\omega_m}{dt} \approx 0$$

$T_L$ is slowly applied.

<u>Dynamic Stability</u>

$$T = T'_{max} \sin\delta$$

$$T'_{max} = \frac{3VE'}{X'_s \omega_{ms}}$$

$$T_m = T_L + J\frac{d\omega_m}{dt}$$

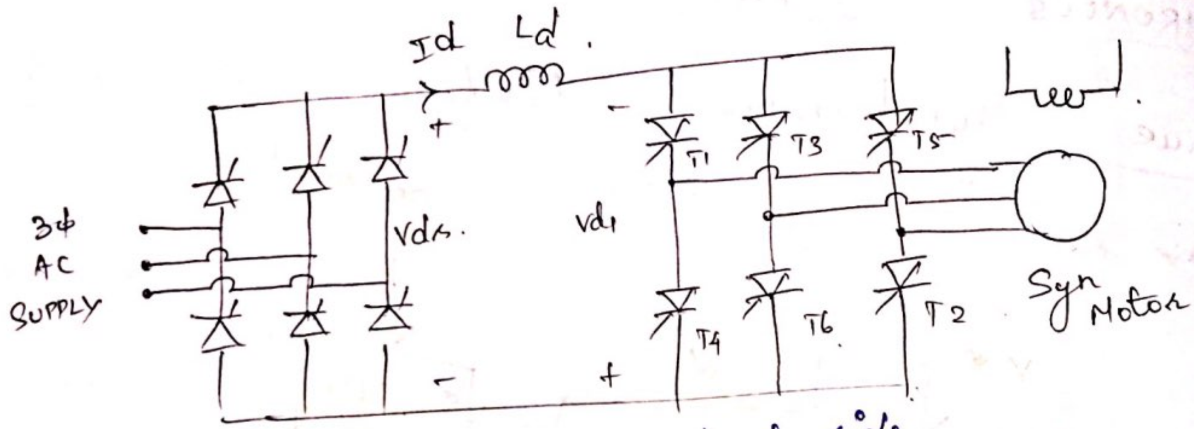
$$= T_L + T_a + T_d$$

$T_a$ - acceleration torque - $K_j \frac{d^2\delta}{dt^2}$

$T_d$ - damping " - $K_d \frac{d\delta}{dt}$

$$\therefore K_j \frac{d^2\delta}{dt^2} + K_d\frac{d\delta}{dt} + T_L - T'_{max}\sin\delta = 0.$$

Self - controlled synchronous motor drive employing load commutated thyristor inverter




Large power drives - wound field SM

Medium power drives - PM SM.

Source - side converter - line commutated thyristor converter.

↳ $0 < \alpha_s < 90$ - rectifier → (+ve) Vds and (+ve) Id.

↳ $90 < \alpha_s < 180$ - inverter → (-ve) Vds and (+ve) Id.

When synchronous motors operates in leading pf, the thyristors (load side) can be commutated by the motor induced voltages in the same way as thyristors of line - commutated converters. Commutation of thyristors by induced load voltage is known as load commutation.

Motoring operation :- $0 < \alpha_s < 90$ & $90 < \alpha_l < 180$.

Regenerative braking :- $90 < \alpha_s < 180$ & $0 < \alpha_l < 90$.

* Speed can be changed by control of line side converter firing angle.
* When working as an inverter, the $\alpha$ has to be less than 180° to take care of commutation overlap.

$$\beta_l = 180° - \alpha_l$$

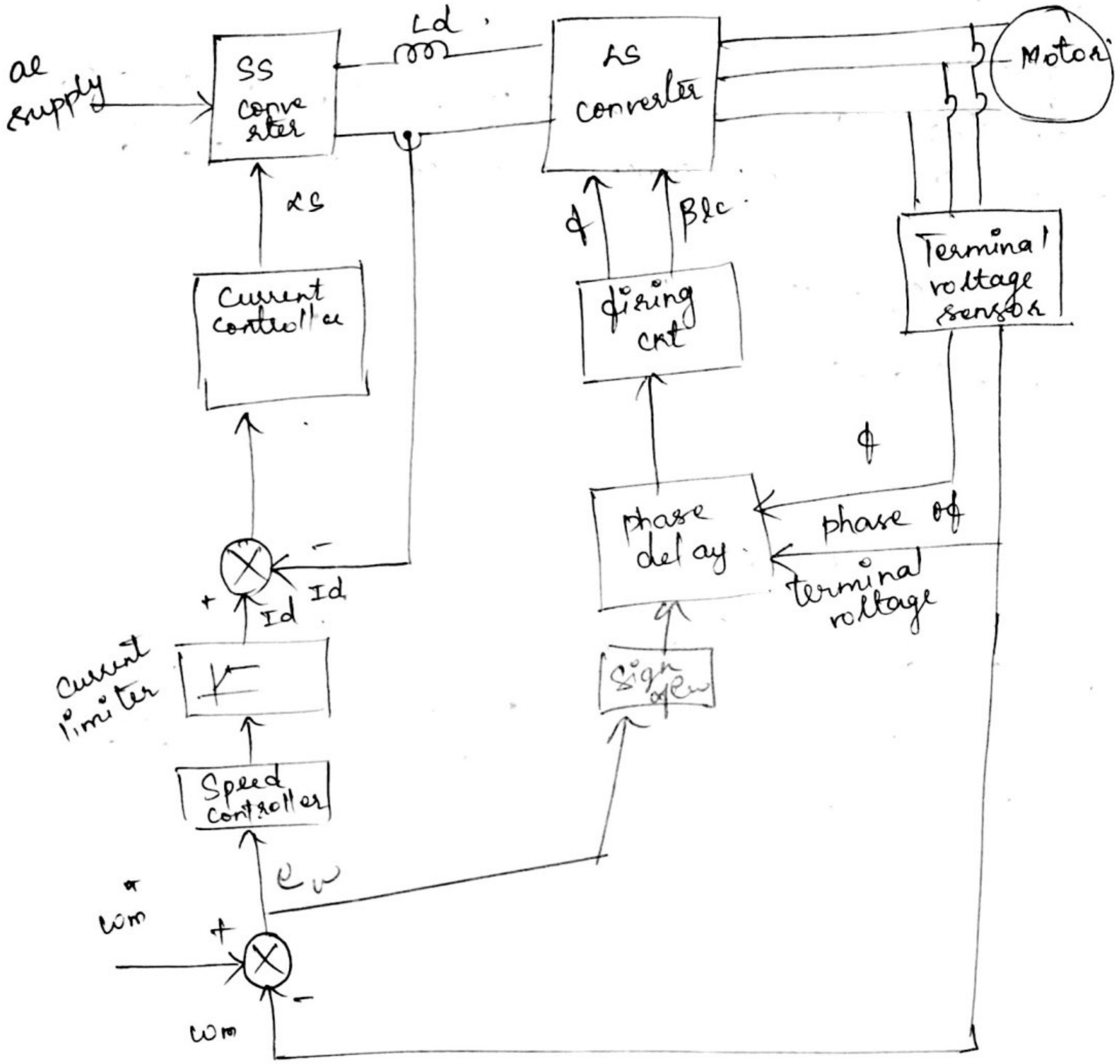
$\beta_l$ - commutation lead angle for load - side converter.

$$\gamma = \beta_l - \mu$$

$\mu$ - commutation over-lap.

$\gamma_{min}$ - thyristor under commutation can be reverse biased for this time duration.

$$I_s = \frac{\sqrt{6}}{\pi} I_d.$$



ac supply
SS converter
Ld
LS converter
Motor
αs
φ
βlc
Current controller
firing ckt
Terminal voltage sensor
φ
phase delay
phase of terminal voltage
Id
Id
Current limiter
Sign of eω
Speed controller
eω
ωm*
ωm