Unit-4.

Stator side control of 3-ϕ induction motor drive

Disadvantages of DC motors (or) DC drives:-

1) Cost is very high.
2) Weight or inertia of DC motor is high.
3) Regular maintenance is required.
4) The DC drives cannot be employed in explosive environment.
5) As the semiconductor technology is improving AC drives are mostly preferred to overcome the disadvantages of DC drives.
6) In AC drives, induction motor is widely used and the stator side voltage control is achieved by varying the voltage which will control the speed of the induction motor.
7) Synchronous speed of induction motor

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

8) By controlling the frequency, the speed can be controlled but the drawback is core goes to saturation.
9) In order to avoid saturation effect, the voltage is also varied proportional to the frequency which is called variable voltage and variable frequency control.

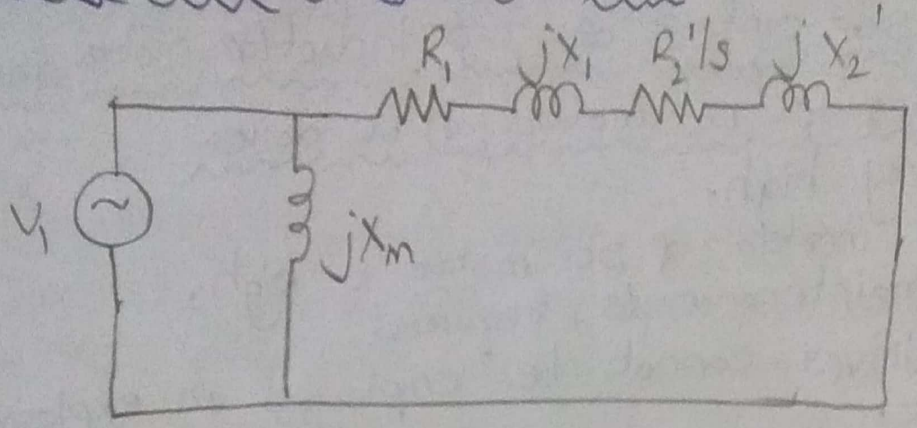
So, in these two control techniques, inverters are used especially square wave inverter and PWM inverter.

10) The square wave inverter is used for variable voltage and constant frequency applications and PWM inverter used for variable voltage and variable freq controllers.

* Stator side control is mostly used in squirrel cage induction motor.

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Steady state Analysis of 3φ I/M :-



Z = Impedance of the equivalent ckt

$$Z = (R_1 + R_2'/s) + j(X_1 + X_2')$$

Current flowing through the I.M

$$I_2' = \frac{V}{|Z|} = \frac{V}{\sqrt{(R_1 + R_2'/s)^2 + (X_1 + X_2')^2}}$$

Rotor Cu loss $= 3(I_2')^2 R_2'$

Air gap power $= \frac{\text{Rotor Cu loss}}{\text{slip}}$

$$P_{ag} = \frac{3(I_2')^2 R_2'}{s}$$

Mechanical power developed

$P_{in} = P_{ag} - $ Rotor losses

$$= \frac{3(I_2')^2 R_2'}{s} - 3(I_2')^2 R_2'$$

$$P_{in} = \left(\frac{1-s}{s}\right) \cdot 3(I_2')^2 R_2' = P_{ag}(1-s).$$

Power of the machine is given by the product of speed and developed

$$P_{ag} = \omega T_d$$

Torque developed.

$$T_d = \frac{P_{ag}}{\omega} = \frac{3(I_2')^2 R_2'}{s\omega}$$

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$$T_d = \frac{3 \cdot \frac{V^2}{(R_1 + R_2'/s)^2 + (X_1 + X_2')^2} \cdot R_2'}{s\omega}$$

The max torque is calculated by diff the torque eq w.r.t slip and equating to zero.

$$\frac{dT_d}{ds} = 0.$$

$$T_d = \frac{3 \cdot V^2 s\omega \, R_2'}{(R_1 + R_2'/s)^2 + (X_1 + X_2')^2}$$

$$\frac{3V^2 \omega R_2'}{(R_1 + R_2'/s)^2 + (X_1 + X_2')^2} = 0.$$

$$3V^2 \omega R_2' = 0.$$

$$\frac{3V^2}{\omega} \cdot \frac{d}{ds}\left[\frac{R_2'}{s((R_1 + R_2'/s)^2 + (X_1 + X_2')^2}\right] = 0$$

$$\frac{3V^2}{\omega}\left[\frac{0 - R_2'\left[\frac{d}{ds}\left[s(R_1 + R_2/s)^2 + s(X_1 + X_2')^2\right]\right]}{3\left[(R_1 + R_2'/s)^2 + (X_1 + X_2')^2\right]}\right] = 0$$

$$R_2'\left[\frac{d}{ds}\left[s(R_1 + R_2'/s)^2 + s(X_1 + X_2')^2\right]\right] = 0$$

$$\frac{d}{ds}\left[s \cdot \left(\frac{sR_1 + R_2'}{s}\right)^2 + (X_1 + X_2')^2\right] = 0$$

$$\frac{d}{ds}\left[\frac{1}{s} \cdot \left[(sR_1)^2 + (R_2')^2 + 2sR_1R_2'\right]\right] + (X_1 + X_2')^2 = 0$$

$$\frac{d}{ds}\left[s\left(R_1^2 + \frac{R_2'^2}{s^2} + \frac{2R_1R_2'}{s}\right) + s(X_1 + X_2')^2\right] = 0$$

$$R_1^2 - \frac{(R_2')^2}{s^2} + 0 + (X_1 + X_2')^2 = 0$$

$$\frac{(R_2')^2}{s^2} = R_1^2 + (X_1 + X_2')^2$$

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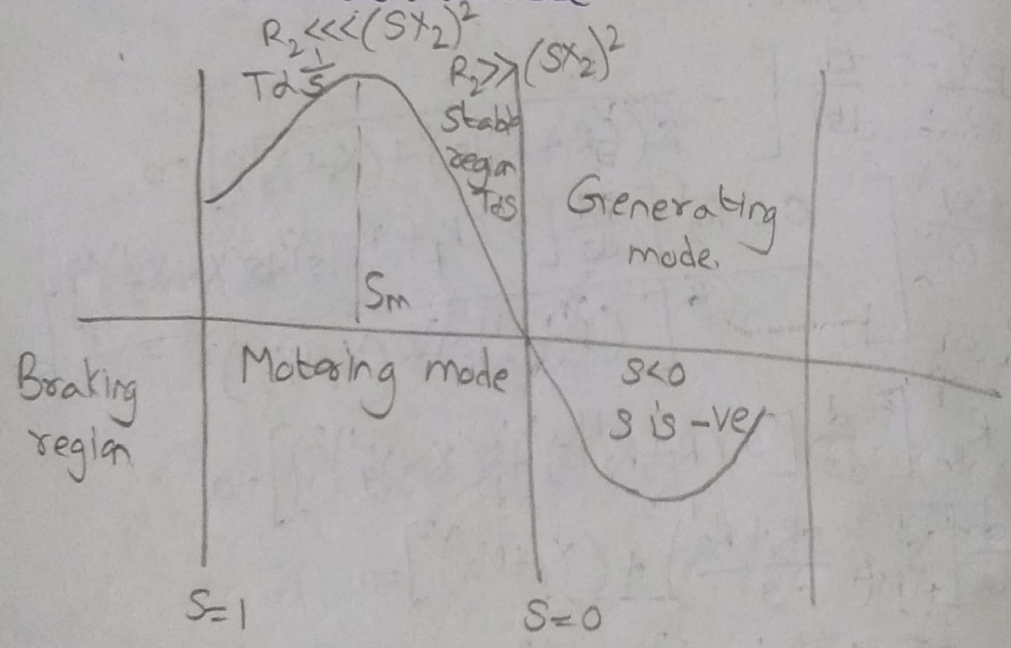
$$S^2 = \frac{(R_2')^2}{R_1^2 + (X_1 + X_2')^2} \Rightarrow S_{max} = \frac{R_2'}{\sqrt{R_1^2 + (X_1 + X_2')^2}}$$

$$\therefore T_{max} = \frac{3V^2 R_2'}{\omega \left[\frac{R_2'}{\sqrt{R_1^2 + (X_1 + X_2')^2}}\right]\left[\left\{R_1 + \frac{\frac{R_2'}{R_2'}}{\sqrt{R_1^2 + (X_1 + X_2')^2}}\right\}^2 + (X_1 + X_2')^2\right]}$$

$$\cong \frac{3V^2 R_2'}{\omega \left[\frac{R_2'}{\sqrt{R_1^2 + (X_1 + X_2')^2}}\right]\left[R_1 + R_1^2 + 2(X_1 + X_2')^2\right]}$$

$$T_{max} = \frac{3V^2\left(\sqrt{R_1^2 + (X_1 + X_2')^2}\right)}{\omega\left(R_1 + R_1^2 + 2(X_1 + X_2')^2\right)}$$

Torque-slip characteristics -



The torque obtained in the I|m depends on slip. In the stable region, the torque is directly proportional to the slip when it reaches & exceeds to the max torque. Torque is inversely proportional to slip.

The gen torque eq is given by

$$T = \frac{KSE_2^2 R_2}{R_2 + (SX_2)^2}$$

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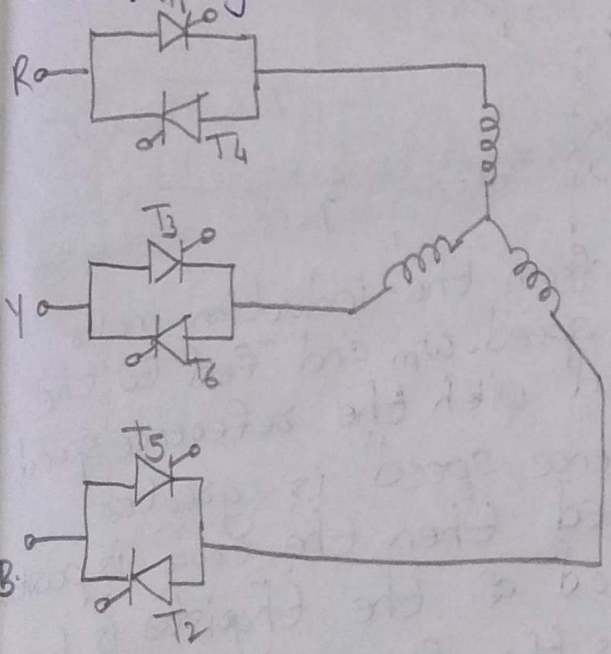
In motoring mode, the slip is in between 0 and 1 and the motor will be operated in stable region.
In generating mode, the speed of the machine is greater than synchronous speed in the same direction as that of the rotating magnetic field. The slip is negative.
In braking mode, the slip is greater than 1 where the direction of the rotor is in opposite direction. Therefore, slip is given by

$$S = \frac{N_s - (-N_r)}{N_s}$$

$S > 1$.

Stator voltage control:-

By connecting a 3-ϕ AC voltage regulator to the stator winding of the induction motor, the voltage is controlled



$$T = \frac{kV^2}{Z}$$

Torque equation $\Rightarrow T = k \cdot \frac{V^2}{Z}$

As $T \propto V^2$, the minute change in the voltage will reduce more torque

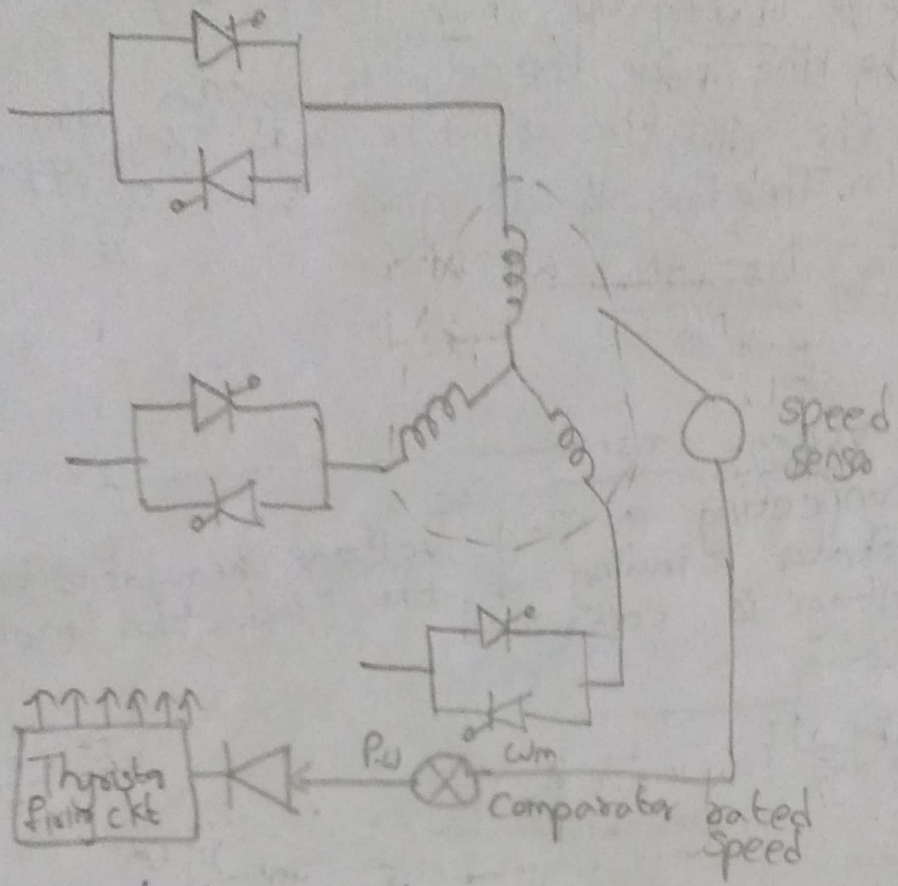
Stator voltage control is used only for low rated motors as the speed is decreased slip increases. thereby efficiency decreases

$$\eta = \frac{P_m}{P_{ag}} = \frac{P_{ag}(1-s)}{P_{ag}} = 1-s.$$

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Stator v/g control is applicable for domestic loads, like fans, pump etc.

Closed loop speed control of an induction motor using stator voltage control



The speed is sensed from the induction motor which is the actual speed ω_m and fed to the comparator and compared with the reference speed.

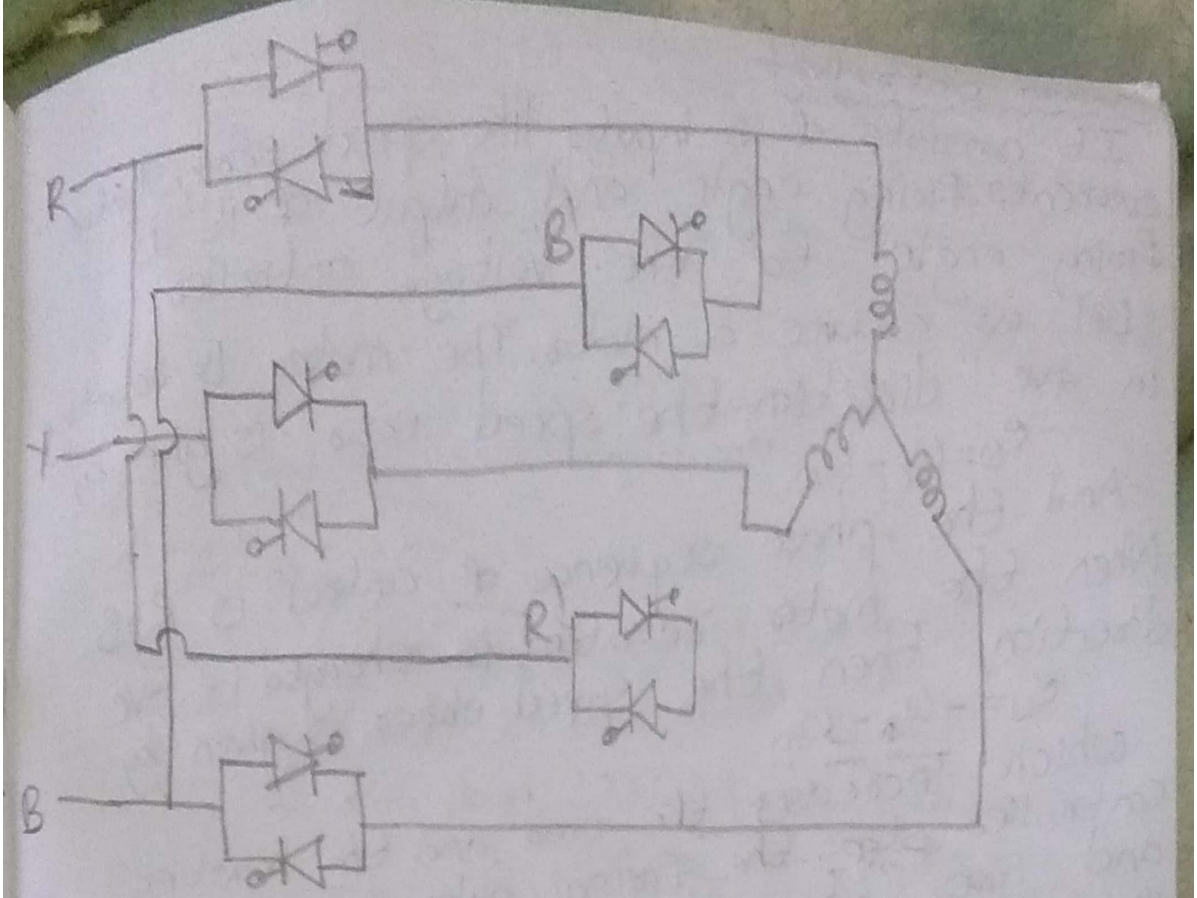
Whenever the reference speed is greater than the actual speed then the error is positive.

∴ The conduction period of the thyristor is to be increased whereas the firing angle is reduced.

Whenever the reference speed is less than the actual speed then the error is negative.

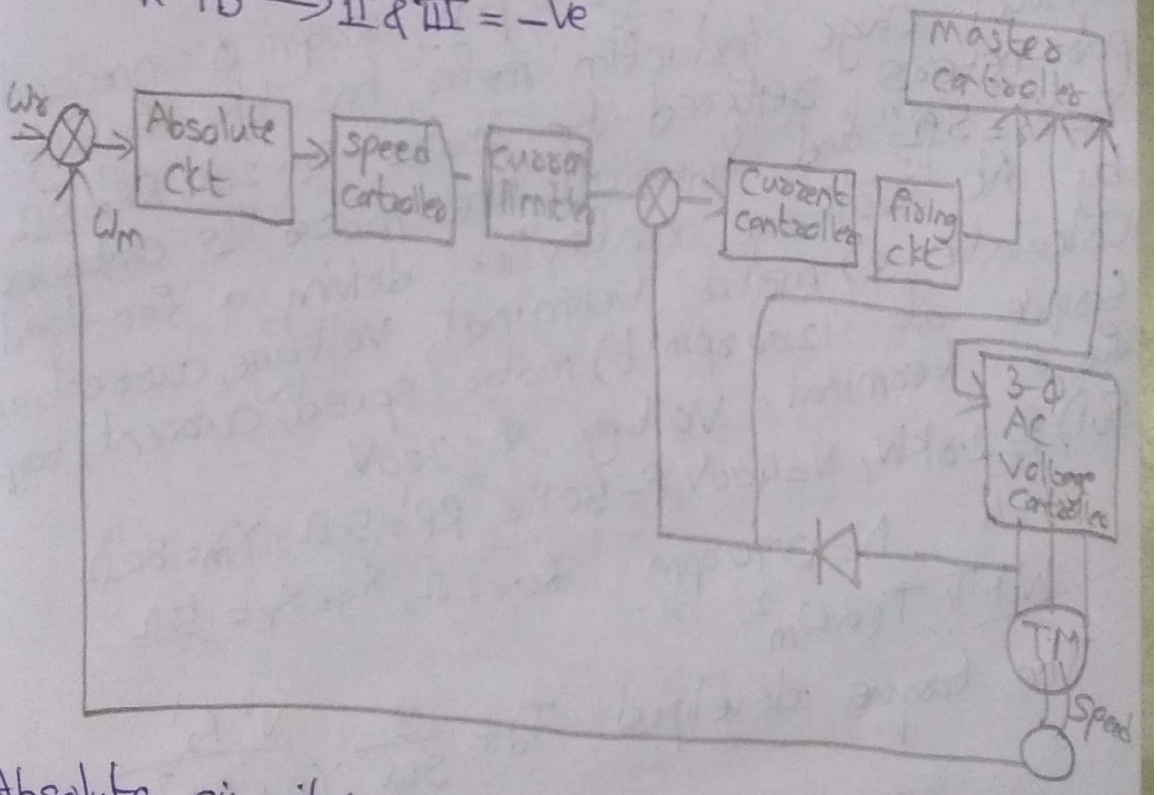
Therefore the conduction period of the thyristor is to be decrease (or) reduce whereas the firing angle is increased.

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RYB → I & IV = +ve

R'YB → II & III = −ve



Absolute circuit :-

It is used to convert the negative error to positive because the speed controller requires only +ve error.

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Master controller:-

It consists of 3 inputs like speed error, stator currents, firing angle and output of it is firing angle to the voltage controller.

Let us assume a motor. The motor is rotating in +ve direction, the speed error is given by

$e_\omega = \omega_r - \omega_m$.

And the phase sequence of control is RYB When the motor rotation is changed i.e -ve direction then the speed error is given by

$e_\omega = -\omega_r - \omega_m$.

which increases the error and the master controller stop the firing pulse to RYB sequence and gives the signal to R'YB'

* A 2.8 KW, 400V, 50Hz 4 pole 1370rpm Δ connected Squirrel cage induction motor has the following parameters refered to stator $R_c = 2\Omega$, $RR' = 5\Omega$ $X_s = X_r = 5\Omega$ and $X_m = 80\Omega$ the motor is controlled by AC voltage controller driving a fan load. Calculate a) motor terminal voltage, current and torque at 1200 rpm b) motor speed, current, torque for a terminal voltage of 300V.

Sol) $P = 2.8kW$, $V = 400V$, $f = 50Hz$, $RR' = 5\Omega$, $X_m = 80\Omega$

$P = 4$ $N = 1370rpm$ $R_c = 2\Omega$, $X_s = X_r = 5\Omega$

W.K.T $T_d \propto \omega_m^2$

The torque developed $T_d = \frac{3}{s\omega_s} \cdot \frac{V^2 R_2'}{\left(R_1 + \frac{R_2'}{s}\right)^2 + (X_1 + X_2')^2}$

$s = \frac{120f}{P} = \frac{120 \times 50}{4} = 1500rpm$

$\omega_s = \frac{2\pi N_s}{60} = \frac{2\pi \times 1500}{60} \Rightarrow$

$\frac{\pi}{50} = 157 rad/sec$

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$$S=\frac{N_s-N_r}{N_s}=\frac{1500-1370}{1500}=0.0867$$

$$\therefore \text{Torque developed } T_d=\frac{3}{(0.0867)(157)}\cdot\frac{(400)^2(5)}{\left(2+\frac{5}{0.0867}\right)^2+(5+5)^2}$$

$$=48.16\ N\text{-}m$$

W.K.T, $T_L=k\omega_m^2$.

$T_L=k\cdot\omega_s(1-s)^2$.

where ω_s is constant

$\therefore T_L=k(1-s)^2$.

W.K.T at full load, load torque = developed torque.

$T_L=T_d$.

$48.16=k(1-0.0867)^2$

$K=57.7$

(a) at $N_r=1200$ rpm

$$S=\frac{N_s-N_r}{N_s}=\frac{1500-1200}{1500}=0.2$$

Load torque $T_L=k(1-s)^2$

$=57.7(1-0.2)^2$

$=36.9\ N\text{-}m$

At full load $T_L=T_d$

$$36.9=\frac{3}{s\omega_s}\cdot\frac{V_2R_2'}{\left(R_1+\frac{R_2'}{s}\right)^2+(X_1+X_2')^2}$$

$$36.9=\frac{3}{(0.2)(157)}\cdot\frac{V^2\times5}{\left(2+\frac{5}{0.2}\right)^2+(5+5)^2}$$

$V^2=36.9(5.76\times10^4)$

$V=253V$

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$$I_L = \frac{V}{Z} = \frac{253}{Z}$$

$$= \frac{253}{\left(R_1 + \frac{R_2'}{s}\right) + j\,(X_1 + X_2')}$$

$$= \frac{253}{\left(2 + \frac{5}{0.2}\right) + j\,(5+5)} \Rightarrow \frac{253}{27 + 10j}$$

$$= (8.24 - j3.5)\,A$$

$\therefore I_L = I_w$ (working component)

magnetizing component of the load current

$$I_m = \frac{V}{jX_m} = \frac{253}{j80} = -j3.16$$

∴ The total load current

$$I = I_L + I_m = 8.24 - j3.5 - 3.16$$

$$= 8.24 - j6.66A$$

b) at 300V the developed torque is given by

At 300V

$$T_d = \frac{3}{s\omega_s} \cdot \frac{V^2 R_2'}{\left(R_1 + \frac{R_2'}{s}\right) + (X_1 + X_2')}$$

$$= \frac{3}{50\pi} \cdot \frac{(300)^2 .5}{\left(2 + \frac{5}{s}\right)^2 + (5+5)^2}$$

$$= \frac{27 \times 10^3}{s(\pi)\left[\frac{25}{s^2} + \frac{20}{s} + 104\right]}$$

At that motor is connected to the fan type load.

$$T_L = K(1-s)^2$$

where $K = 57.7$

$$T_L = 57.7\,(1-s)^2$$

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W.K.T, at full load $T_L = T_d$.

$$57.7(1-s)^2 = \frac{27\times10^3}{s(\pi)\left[\frac{25}{s^2}+\frac{20}{s}+104\right]}$$

$$= \frac{27\times10^3\times s}{\pi(104s^2+20s+25)}$$

$$104s^4 - 188s^3 + 89s^2 - 17.9s + 2.5 = 0$$

$$s = 0.147$$

Then $s = \frac{N_s - N_r}{N_s}$

$$N_r = N_s(1-s)$$

$$N_r = 1500(1-0.147)$$

$$N_r \cong 1280 \text{ rpm}$$

$$T_L = k(1-s)^2$$

$$T_L = 57.7(1-0.147)^2 = 41.98 \text{ N-m.}$$

$$I = \frac{V}{Z}.$$

$$= \frac{300}{\left(R_1+\frac{R_2'}{s}\right)+j(X_1+X_2')} \Rightarrow \frac{300}{\left(2+\frac{5}{0.147}\right)+j(5+5)}$$

$$= \frac{300}{36+j10}$$

$$= (7.73-2.1j)\text{ A}$$

$I_L = I_w$ (working component)

magnetizing component of the load current

$$I_m = \frac{V}{jX_m} \Rightarrow \frac{300}{j80} = -j3.75$$

The total load current,

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$I = I_L + I_m$

$= 7.73 - j2.1 - j3.75$

$= 7.73 - j5.89A$

* A 240V 50Hz 4pole star connected 3-ϕ I/m has the following parameters $R_1 = 0.25\Omega$, $X_1 = 0.36\Omega$. $X_m = 17.3\Omega$, $R_2' = 0.6\Omega$ and $X_2 = 0.36\Omega$, the speed of the motor is controlled by a 3-ϕ voltage control from 1400rpm to 600rpm the motor drives a fan load the equation is given by $\left(\frac{1.4}{10^3}\right)\omega_m^2$. Calculate per unit load impedance

Sol) $V = 240V$, $f = 50Hz$, $P = 4$, $R_1 = 0.25\Omega$, $X_1 = 0.36\Omega$

$X_m = 17.3\Omega$ $R_2' = 0.6\Omega$ $X_2 = 0.36\Omega$, $T_L = \left(\frac{1.4}{10^3}\right)\omega_m^2$

$S = \frac{120f}{P} = \frac{120 \times 50}{4} = 1500rpm$

$S = \frac{N_S - N_r}{N_S} = \frac{1500 - 1400}{1500} = 0.06$.

Stator impedance $Z_1 = R_1 + jX_1 = 0.25 + j0.36\Omega$

Rotor impedance $Z_2 = \frac{R_2}{S} + jX_2 = 10 + j0.36\Omega$

$\therefore$ Total impedance $Z = Z_1 + Z_2 = (10.25 + j0.72)\Omega$

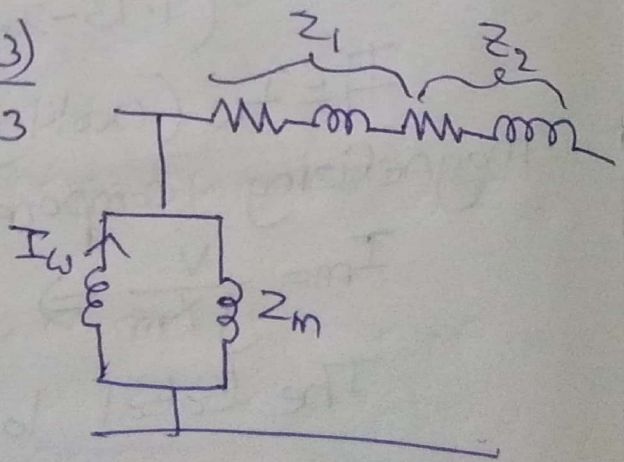
I/P impedance $= (Z_1 + Z_2) / Z_m$.

i/p impedance $= Z_{i/p}$

$= \frac{(10.25 + j0.72)(j17.3)}{10.25 + j0.72 + j17.3}$

$= (7.137 + j4.75)\Omega$

$= 8.57 \angle 33^\circ$



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Mechanical power developed $P_m = (1-s) P_{ag}$

$$T_L \cdot \omega_m = (1-s)\frac{3 I_2'^2 R_2'}{s}$$

$$(I_2')^2 = \frac{s \cdot T_L \cdot \omega_m}{3(1-s)R_2'}$$

W.k.T, $T_L = \frac{1.4}{10^3}\omega_m^2$

where

$$\omega_m = \frac{2\pi N}{60} = \frac{2\pi \times 1400}{60} = 146.6 \text{ rad/sec}$$

$$T_L = \frac{1.4}{10^3} \times (146.6)^2$$

$$T_L = 30.08 \text{ N-m}$$

$$I_2' = \sqrt{\frac{(0.06)(30.08)(146.6)}{3(1-0.06)\,0.6}} = 12.5\text{A}.$$

b) At $N_r = 600$ rpm

$$s = \frac{N_s - N_r}{N_s} = \frac{1500-600}{1500} = 0.6$$

Stator impedance $Z_1 = R_1 + jX_1 = (0.25 + j0.36)\,\Omega$

Rotor impedance $Z_2 = \frac{R_2'}{s} + jX_2 = \left(\frac{0.6}{0.6} + j0.3\right)\Omega$

$= (1 + j0.36)\,\Omega$

Total impedance $Z = Z_1 + Z_2 = (0.25 + j0.36) + (1 + j0.36)$

$= (1.25 + j0.72)\,\Omega$

I/P impedance $= (Z_1 + Z_2) \,|\, Z_m$.

$$= \frac{(1.25 + j0.72)(j17.3)}{1.25 + j0.72 + j17.3}$$

$$= (1.146 + j0.77)\,\Omega$$

$$= 1.36 \angle 0.59\,\Omega$$

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Mechanical power developed $P_m = (1-s) P_{ag}$

$$T_L \cdot \omega_m = (1-s) \cdot \frac{3 I_2'^2 R_2'}{s}$$

$$(I_2')^2 = \frac{s \cdot T_L \cdot \omega_m}{3(1-s) R_2'}$$

W.k.T, $T_L = \frac{1.4}{10^3} \times \omega_m^2$

where $\omega_m = \frac{2\pi \times 600}{60} = 62.83$ rad/sec

$$T_L = \frac{1.4}{10^3} \times (62.83)^2 = 5.52$$

$$I_2' = \sqrt{\frac{0.6 \times 5.52 \times 62.83}{3 \times 0.6 \times (1-0.6)}}$$

$I_2' = 17\Omega$

At 1400rpm

Rotor per unit current = $\frac{\text{Actual value}}{\text{Base value}}$

$$= \frac{1.25}{\left(\frac{240}{8.57}\right)} = 0.44$$

For 600rpm

Rotor per unit current = $\frac{17}{\left(\frac{240}{1.38}\right)} = 0.09$.

Variable frequency characteristics of Induction motor

Emf equation of $I/m = 4.44 \phi f t$.

Where emf is directly proportional to flux and frequency.

* When the frequency increases the emf of the voltage will also increase upto a point called saturation point where the torque is maintained constant.

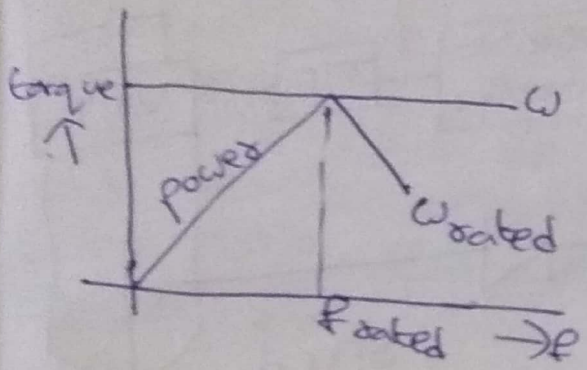
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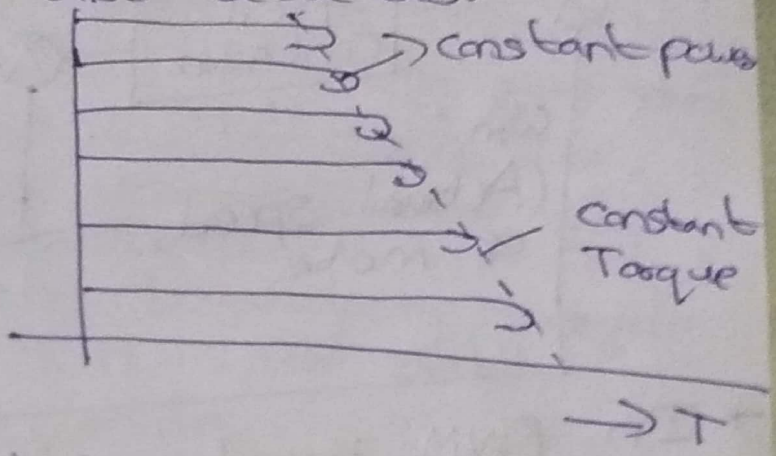
* To maintain the voltage is constant flux will be decreased which results in reduction in torque will increased.

Control of induction motor by variable frequency as the frequency is increased the speed changes and torque is maintained constant until rated frequency because voltage is proportional to frequency

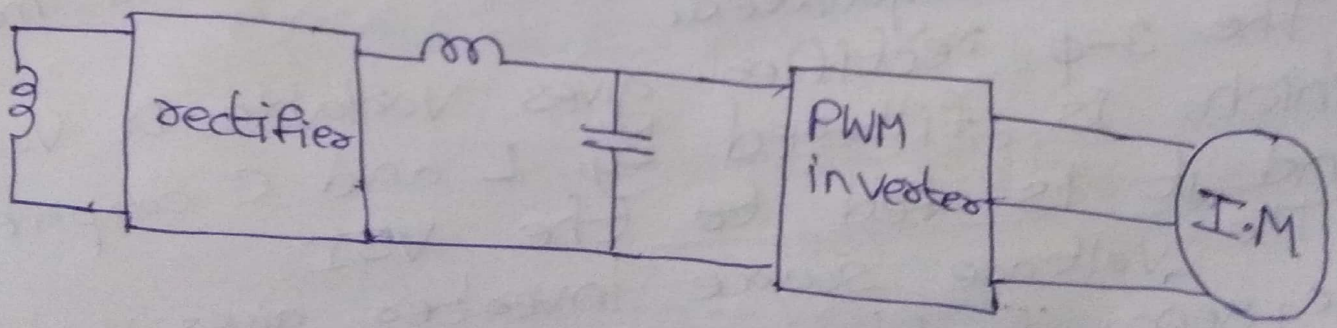
When the frequency increased the starting torques are equal to maximum torque at certain frequency.

When the frequency is greater than rated frequency at constant voltage the flux decreases the torque also decreases.

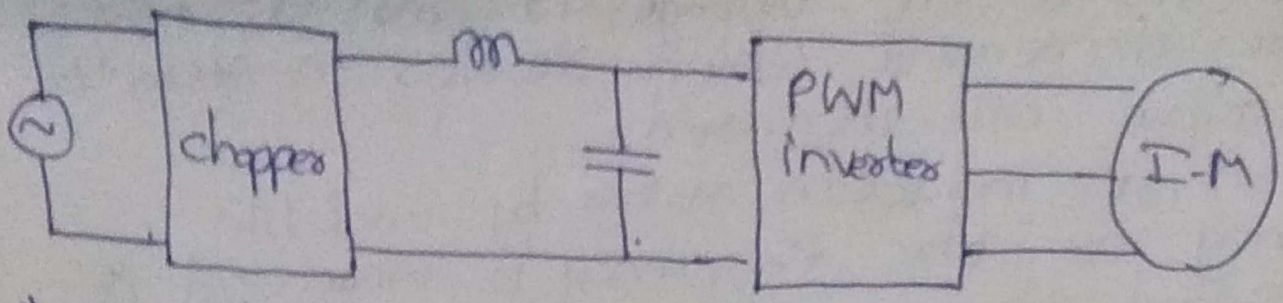




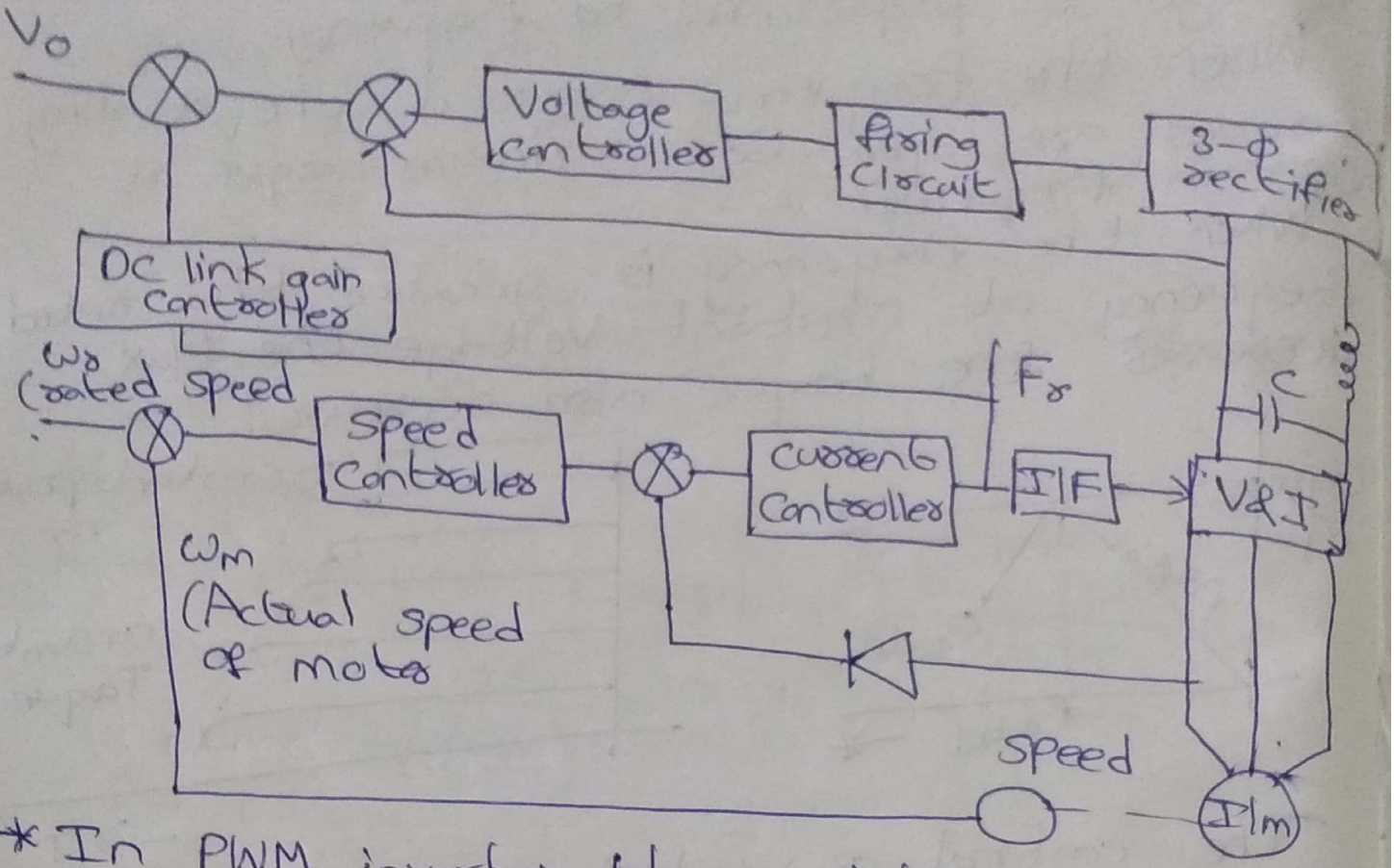
The control of induction motor by voltage source inverter can be done in varies methods like chopper is connected to the PWM inverter or a rectifier is connected to the inverter



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* Closed loop speed control of Induction motor :-



* In PWM inverter the variable voltage and variable frequency and the harmonic content in PWM inverter can be reduced by Sinusoidal pulse width modulation
* By 120°, 180° conduction the induction motor speed will regulated.
* The 3-ϕ rectifier gives variable DC voltage which is filtered by L and C components and it is fed to the VSI.
* The voltage source inverter gives variable frequency to the Induction motor.

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* This method is used for any desired speed i.e, ω_m is set to ω_r by the controller. The current controller generates two signals V_δ and V_e.
* The V_δ is composed with desired voltage and the error is fed to the voltage controller which sense the command signals to the firing circuit to generate firing pulses at an angle 'α' based on reference voltage
* The f_r is fed to the I/F controller till the actual frequency of the induction motor is equal to f_r (reference frequency).

Problem :-

* A 440V, 50Hz, 4 pole 1420 rpm Δ connected squirrel cage I/m as the following parameters $R_1 = 0.35\Omega$, $R_2' = 0.4\Omega$, $X_1 = 0.7\Omega$, $X_2' = 0.8\Omega$. The motor is fed from voltage source inverter and it is operated at constant V/F controlled upto 50Hz. Calculate the breakdown torque for a frequency at 75Hz for both motoring and braking modes.

Sol) Motoring mode

$$\text{Torque } T_{max} = \frac{3}{2k\omega_s} \cdot \frac{V^2}{R_1 + \sqrt{R_1^2 + k^2(X_1 + X_2')^2}}$$

$$k = \frac{f}{f_r} = \frac{75}{50} = 1.5$$

For motoring mode:

$$\omega_s = \frac{2\pi \times N}{60} = \frac{2\pi \times 1420}{60} = 148.70 \text{ rad/sec}$$

$$T_{max} = \frac{3}{2 \times 1.5 \times 148.70} \times \frac{(440)^2}{(0.35) + \sqrt{(0.35)^2 + (1.5)^2 (0.7 + 2.25)^2}}$$

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$T_{max} = 495.5$ N-m.

Braking mode $= \frac{3}{2k\omega_s} \cdot \frac{V^2}{R_1 - \sqrt{R_1^2 + k^2(X_1+X_2')^2}}$

$\Rightarrow \frac{3}{2\times1.5\times148.7} \cdot \frac{(440)^2}{0.35 - \sqrt{(0.35)^2 + (1.5)^2 \times (0.7+0.8)^2}}$

$T_{max} = -675.6$ N-m.

Let V & f be the operating voltage and frequency V_r & V_e be the rated voltage and rated frequency.

K is constant of frequency and voltage

$K = \frac{f}{f_r}$ (or) $K = \frac{V}{V_r}$.

$f < f_r$:

The actual current or rotor current is given by

Rotor current $I_2 = \frac{kV_r}{\sqrt{\left(R_1 + \frac{R_2'}{s}\right)^2 + k^2(X_1+X_2')^2}}$.

Developed torque. $k = \frac{f}{f_r} < 1$

$T_d = \frac{3}{s \cdot k\omega_s} \cdot \frac{k^2 V_r^2 R_2'}{\left(R_1 + \frac{R_2'}{s}\right)^2 + k^2(X_1+X_2')^2}$

Maximum torque

$T_{max} = \frac{3}{2k\omega_s} \cdot \frac{k^2 V_r^2}{R_1 + \sqrt{R_1^2 + k^2(X_1+X_2')^2}}$

$f > f_r$: $k = \frac{f}{f_r} > 1$.

Rotor current

$I_2 = \frac{V}{\sqrt{\left(R_1 + \frac{R_2'}{s}\right)^2 + k^2(X_1+X_2')^2}}$.

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Developed torque

$$T_d = \frac{3}{sK\omega_s} \cdot \frac{V^2 R_2'}{\left(R_1 + \frac{R_2'}{s}\right)^2 + K^2(X_1 + X_2')^2}$$

max torque

$$T_{max} = \frac{3}{2K\omega_s} \cdot \frac{V^2}{R_1 + \sqrt{R_1^2 + K^2(X_1 + X_2')^2}}$$

Problem :-

* A 3-ϕ star connected 50Hz, 4 pole induction motor has the following parameters referred to stator. $R_1 = R_2 = 0.034\Omega$, $X_1 = X_2 = 0.018\Omega$. The motor is controlled by variable frequency controlled with constant V/F control. Determine the following for an operating frequency of 15Hz. Calculate 1) Breakdown torque as the ratio of rated frequency for motoring and motoring modes 2) Starting torque and rotor current in terms of their rated frequencies

Sol) $R_1 = R_2' = 0.034\Omega$, $X_1 = X_2' = 0.018\Omega$ $f = 50Hz$, $f = 15Hz$.

$$K = \frac{f}{f_r} = \frac{15}{50} = 0.3$$

f - operating frequency, f_r = rated frequency.

$$\omega_s = \frac{2\pi N}{60}$$

$$T_{max} = \frac{3}{2K\omega_s} \cdot \frac{K^2 V_r^2}{R_1 + \sqrt{R_1^2 + K^2(X_1 + X_2')^2}}$$

$$= \frac{3}{2 \times 0.3 \times \omega_s} \cdot \frac{(0.3)^2 V_r^2}{(0.034) + \sqrt{(0.034)^2 + (0.3)^2 \cdot (0.018 + 0.018)^2}}$$

$$T_{max} = \frac{V^2}{\omega_s}(6.458)$$

at $K = \frac{50}{50} = 1$

$$T_{max} = \frac{V^2}{\omega_s}(17.96)$$

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$$\frac{T_{max} \text{ at } K=0.3}{T_{max} \text{ at } K=1} = \frac{6.458}{17.96} = 0.359$$

T_{max} at $K=0.3 = 0.359 \times T_{max}$ at $K=1$

As $K<1$

at $K=0.3$

$$I_r = \frac{KV_s}{\sqrt{\left(R_1 + \frac{R_2'}{s}\right)^2 + K^2(X_1+X_2')^2}}$$

$$= \frac{0.3 \times V_s}{\sqrt{\left(0.03 + \frac{0.034}{1}\right)^2 + (0.3)^2 \times (0.018+0.018)^2}}$$

at $K=1$

$$I_r = \frac{1 \times V_s}{\sqrt{\left(0.034 + \frac{0.034}{1}\right)^2 + 1^2(0.018+0.018)^2}}$$

$$T_d = \left(\frac{3}{sk\omega_s}\right) \cdot \frac{K^2 V_s^2 R_2'}{\left(R_1 - \frac{1R_2}{s}\right)^2 + K^2(X_1+X_2)^2}$$

At T_{st}, $s=1$, $K=0.3$

$$T_{st} = \frac{3}{1 \times 0.3\omega_s} \times \frac{(0.3)^2 \times V_s^2 \times 0.034}{\left(0.034 + \frac{0.034}{1}\right)^2 + (0.3)^2 (0.018+0.018)^2}$$

=

At $K=1$, $T_{st}=9$

$$T_{st} = \frac{3}{1 \times 1 \times \omega_s} \frac{1^2 \times V_s^2 \times 0.034}{\left(0.034 + \frac{0.034}{1}\right)^2 + \omega^2 (0.018+0.018)^2}$$

=

$$\frac{I_r \text{ at } K=0.3}{I_r \text{ at } K=1} =$$

I_r at $K=0.3 =$ _____ $\times I_r$ at $K=1$

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$\frac{T_{st} \text{ at } K=0.3}{T_{st} \text{ at } K=1} = \_\_\_\_$

T_{st} at $K=0.3 = \_\_\_\_ \times T_{st}$ at $K=1$

Braking and multi quadrant operation of voltage source inverter induction motor drives:-

The power input into the motor is given by

$P_{in} = 3VI_s \cos\phi$

V - Fundamental component of motor phase voltage

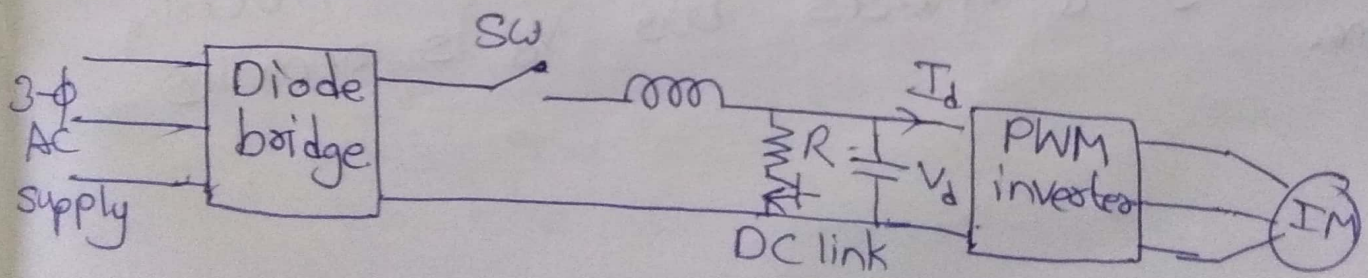
I_s - Fundamental component of motor phase current

ϕ is angle b/w V & I_s.

* In motoring operation $\phi < 90$. So P_{in} is positive i.e, the power flows from the inverter to the machine.
* A reduction in frequency makes the synchronous speed less than the rotor speed and the relative speed b/w the rotor conductor and air gap rotating field reverses
* When $\phi > 90$, the power flow reverses the machine works as generator feeding power into the inverter which in turn fed power into DC link.
* The regenerative braking is obtained when the power flowing from the inverter DC link it is usefully employed.

Dynamic braking:-

In Dynamic braking the power flowing from inverter to the DC link is wasted on resistance.



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* For dynamic braking switch Sw and self commuted switch are used. Here transistor in series with braking resistance R_b connected across the DC link are added to the drive.
* When the operation of the motor is shifting from motoring to braking switch is opened.
* Generated energy flowing into the DC link charges the capacitor thereby its voltage will rise.
* When it crosses set value the switch Sw will be closed and connects the resistance across the link.
* The generative power and part of energy stored in the capacitor flowing through resistance and DC link voltage reduces
* When it falls to its normal value switch Sw is opened thereby closing and opening Sw based on the value of the DC link voltage generator energy is dissipated in resistance is given by dynamic braking.

Regenerative braking:-

When machine operation shifts from motoring to braking I_d reverses and flows into the DC supply feeding the energy to the source.

For regenerating braking the power supplied to the DC link must be transfered to the DC supply.

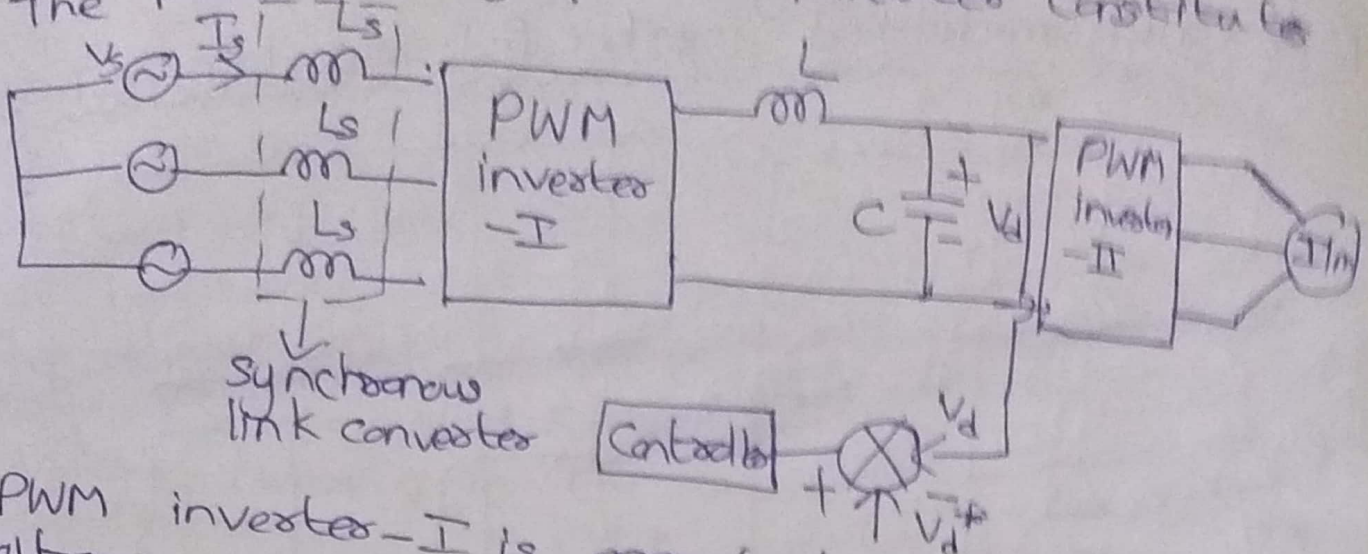
When the operation shifts from motoring to braking, I_d reverses but V_d is remains same.

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Principle of operation:

The regenerative drive with synchronous link converter (SLC) and PWM inverters.

The inductors L_s & PWM inverter constitute

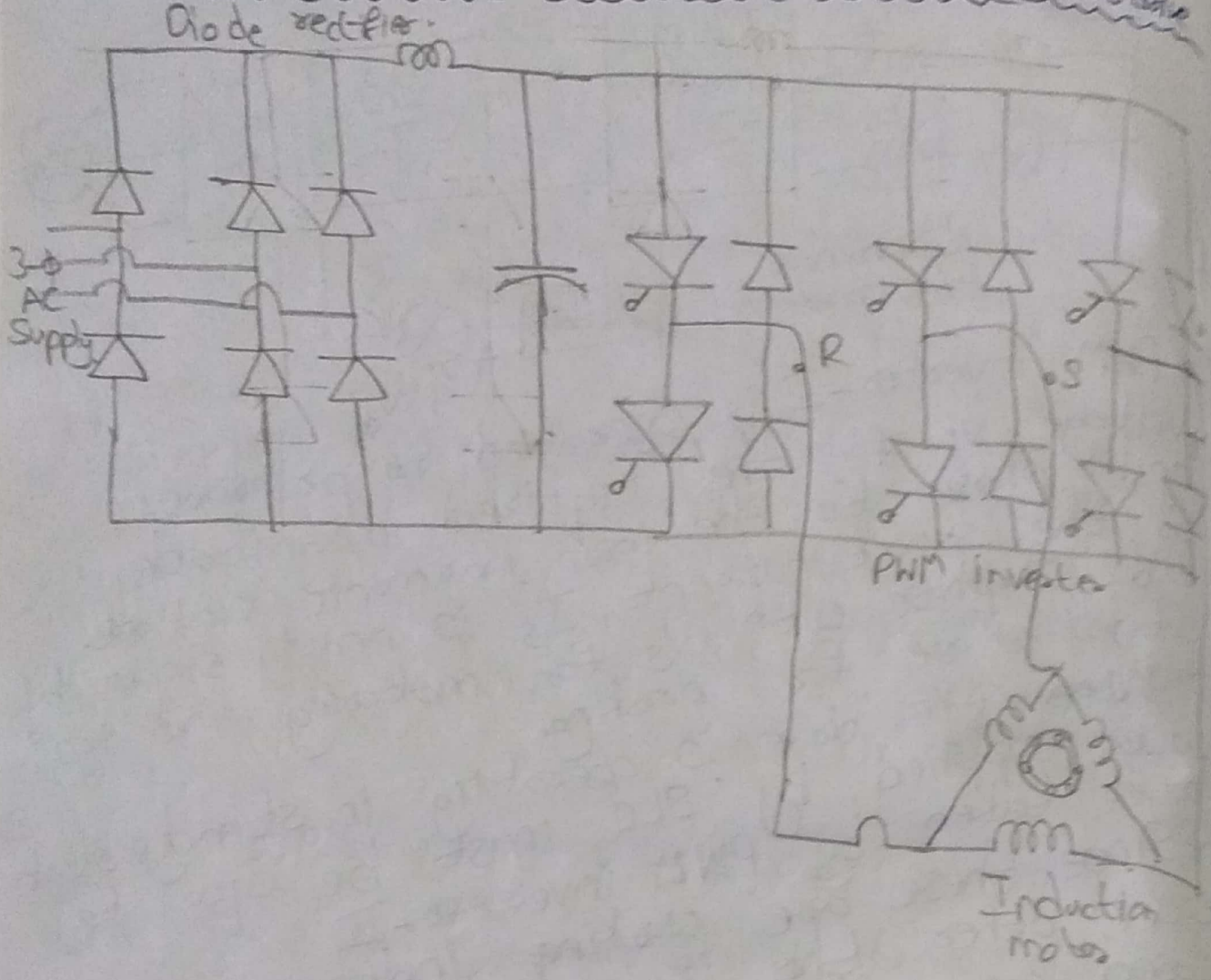


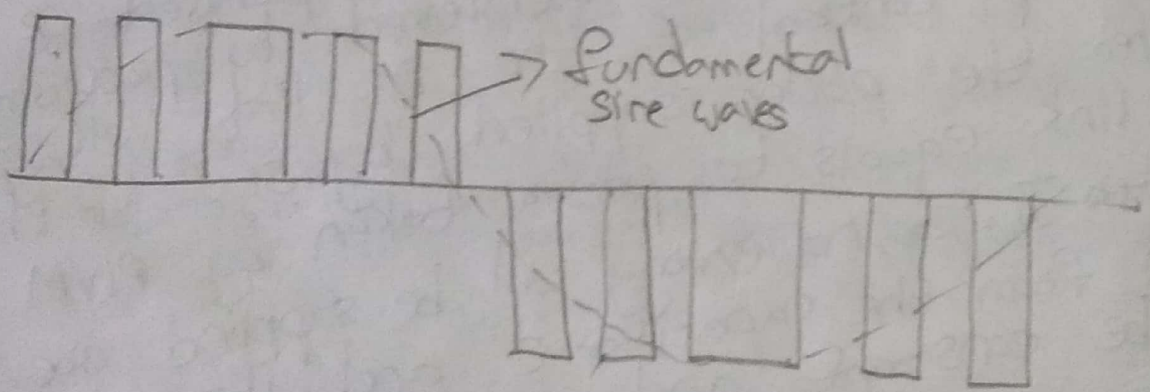
* PWM inverter-I is operated to produce voltage V_i of the required magnitude and phase so the low harmonic content. So the source current I_s is nearly sinusoidal and Inphase with V_s for motoring and 180° outer phase for braking.
* When the drive is operating in steady state power supplied by SLC must be equal to power taken by PWM inverter-II
* Since these are working independent of each other this is achieved by providing closed loop control of the DC link voltage
* When the power supplied by SLC to the DC link equals to power taken by PWM inverter-II. So, no energy will be supplied or taken from the capacitor C and its voltage will be constant and equal to the reference value V_d^*
* Closed loop voltage control will increase the value of I_s and thereby the power supplied to the DC link will also increased

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*Since SLC works as Boost converter the closed loop control of DC link voltage provides the drive with right through capability against voltage sag and under voltage.

Pulse width modulated inverter fed induction motor drive





Ideal line voltage with low freq ratio

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The demerits of 6 step inverter drive like more number of semiconductor devices, harmonics and poor power factor are eliminated in PWM inverter drives. When supply is AC, output of diode bridge has less harmonic content and filter components are not bulky and the drive response is fast.

Drive is free from torque pulsations at low speeds and has higher efficiency due to low harmonics in the inverter output voltage. The disadvantages are complex control circuitry and higher switching losses.

Voltage control in the square wave inverter has been external to the inverter by means of a phase controlled rectifier on the line side. The inverter is supplied with constant DC voltage and is controlled to have variable output voltage.

With this operation, the inverter can be extended upto 0 frequency as the commutation is effective at all the frequency.

With this control, the output voltage is no longer a square wave but a pulsed wave. The principle of operation modulation and output voltage waveform is shown in the above fig.

Features of PWM inverter induction motor drive

1) The inverter has constant DC link voltage and employees PWM principle for both voltage control and harmonic eliminator
2) The o/p voltage waveform is improved with reduced harmonic content. The amplitude of torque pulsations is minimal even at low speeds.
3) Parallel operation of many inverters on the same DC bus
4) Uninterrupted operation is possible when a buffer is used.
5) The power factor of the system is good

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6) Control is complicated
7) Size of the filter will be reduced.
8) Efficiency may be effected by the switching losses.
9) Open loop operation is possible and the drive has a very good dynamic and transient response.
10) Selected harmonic elimination harmonic technique may be employed to eliminate lower order harmonics.
11) It finds the application in low to medium power upto 450 KVA.
12) Transistors may be used in place of thyristors

* A star connected squirrel cage I/m has the following ratings and parameters 400V, 50Hz, 6 Pole 1500rpm $R_1=2\Omega$, $RR'=3\Omega$, $X_1=X_R'=4\Omega$. Motor is controlled by a voltage source inverter at constant V/f ratio. The inverter allows a frequency of 50Hz Calculate the starting torque and the starting current.

Sol) $f=50Hz, P=6, V_s=400, R_1=2\Omega, R_2'=3\Omega, X=4\Omega$

$$T_{st}=\frac{3}{\omega_s}\times\frac{V_s^2}{\left(R_1+\frac{R_2'}{s}\right)^2+(X_1+X_2')^2}\times\frac{R_2'}{s}.$$

$$\omega_s=\frac{2\pi N_s}{60}$$

$$N_s=\frac{120f}{P}=\frac{120\times50}{6}=1000\ rpm$$

$$\omega_s=\frac{2\pi(1000)}{60}=104.72$$

T/st = At the time of starting $S=1$.

$$\therefore T_{st}=\frac{3}{104.72}\times\frac{(400/\sqrt{3})^2}{\left(2+\frac{3}{1}\right)^2+(4+4)^2}\times\frac{3}{1}$$

$$=51.5\ N-m.$$

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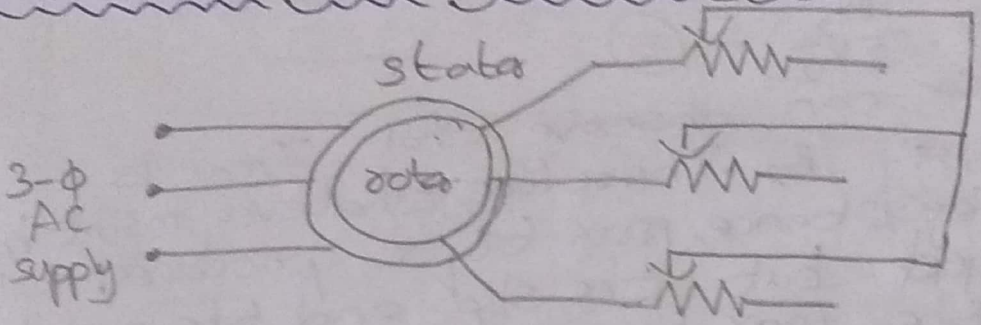
$$I_{st} = \frac{V_{ph}}{\sqrt{\left(R_1 + \frac{R_2'}{s}\right)^2 + (X_1 + X_2')}}$$

$$= \frac{(400/\sqrt{3})}{\sqrt{(2+3)^2 + (4+4)^2}} = \frac{400/\sqrt{3}}{\sqrt{25+64}} = 24.47A$$

Unit-5

Rotor side control of 3-ϕ induction motor drive.

Conventional rotor resistance control:



*

In this method, external resistance can be added with the help of brushes and slip ring arrangement in series with each phase of the rotor winding.

By controlling the rotor resistance per phase, motor starting torque, speed etc are also controlled. It is known that in slip ring induction motor resistance can be added externally in the rotor windings.

Let R_2 = rotor resistance per phase.

W.k.T, $T \propto \frac{sE_2^2 R_2}{R_2^2 + (sX_2)^2}$ ——(1)

Now, external resistance is added in each phase of the rotor through slip rings

Let R_2' = new rotor resistance per phase

The corresponding torque

$$T' \propto \frac{sE_2^2 R_2'}{(R_2')^2 + (sX_2)^2}$$ ——(2)

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At the time of starting, slip = 1. Then T and T' become

$$T \propto \frac{E_2^2 R_2}{R_2^2 + X_2^2} \quad -(3), \qquad T' \propto \frac{E_2^2 R_2'}{(R_2')^2 + (X_2)^2} \quad -(4)$$

W.k.T, the max torque is attained by the motor at $s = \frac{R_2}{X_2}$

$$\therefore T_{max} = \frac{\frac{R_2}{X_2} \cdot E_2^2 R_2}{R_2^2 + \left(\frac{R_2}{X_2} \cdot X_2\right)^2} = \frac{R_2 \cdot E_2^2 \cdot R_2}{X_2 \cdot 2R_2^2}$$

$$T_{max} = \frac{E_2^2}{2X_2} \quad -(5)$$

From eq(5), we can observe that T_{max} is independent of R_2. Therefore, whatever might be the rotor resistance, max torque produced will not be changed but the slip and the speed at which the max torque occurs will depend on R_2

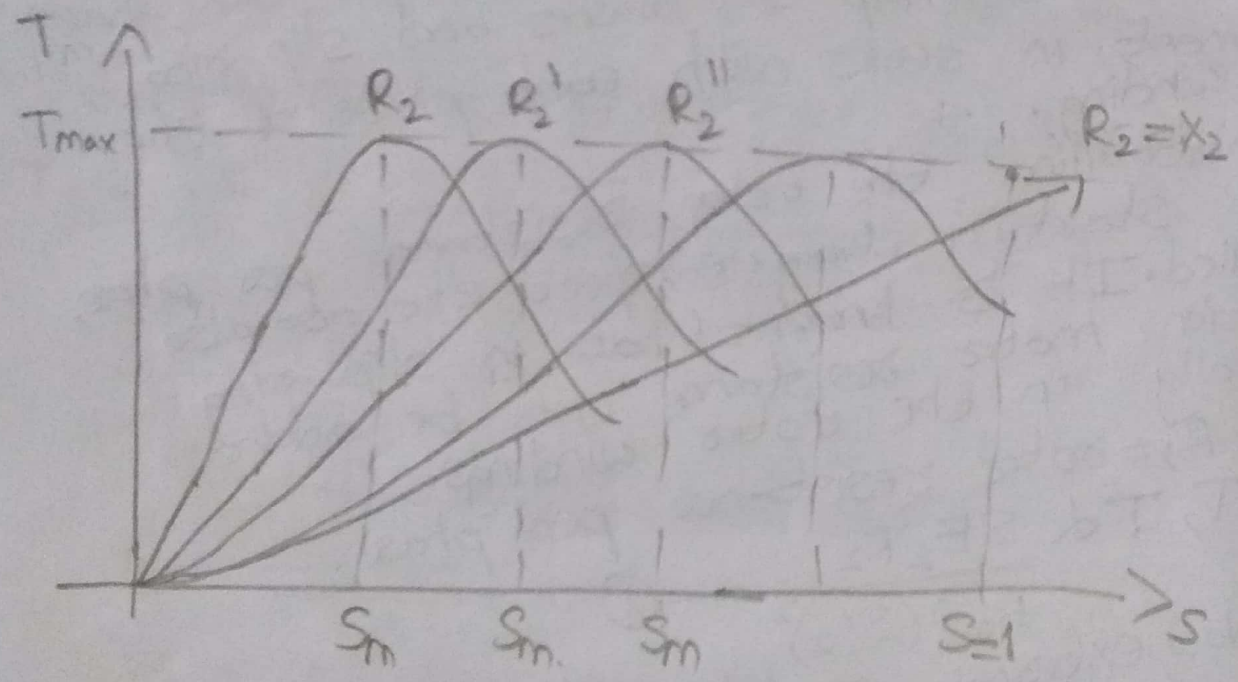
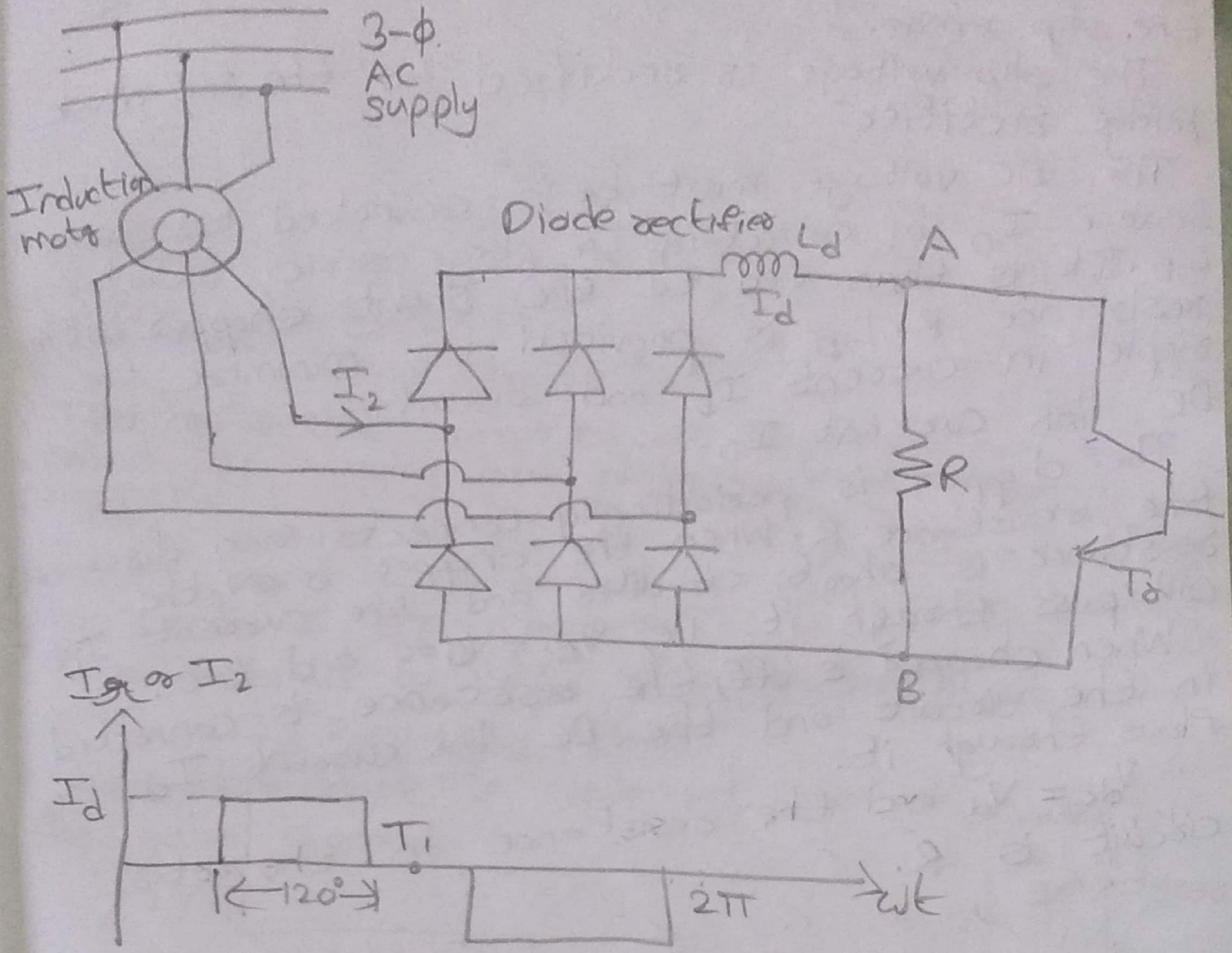


Fig: Speed torque characteristics.

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The condition for getting starting torque is equal to maximum torque $R_2 = X_2$

Static rotor resistance control :-



Rotor current waveform

Instead of varying rotor resistance mechanically it can be varied statically by using the principle of chopper which gives stepless and smooth variation of resistance and consequently the motor speed

The external resistance may be replaced by a 3-ϕ diode rectifier and a chopper where the transistor operates as the chopper switch

This method of speed control is inefficient because the slip energy is wasted in rotor circuit resistance. However, the advantages are high starting torque with low starting current

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and improves power factor with a wide range of speed control. The stator of the machine is directly connected to the line power supply and in the rotor circuit slip voltages are available across the slip rings.

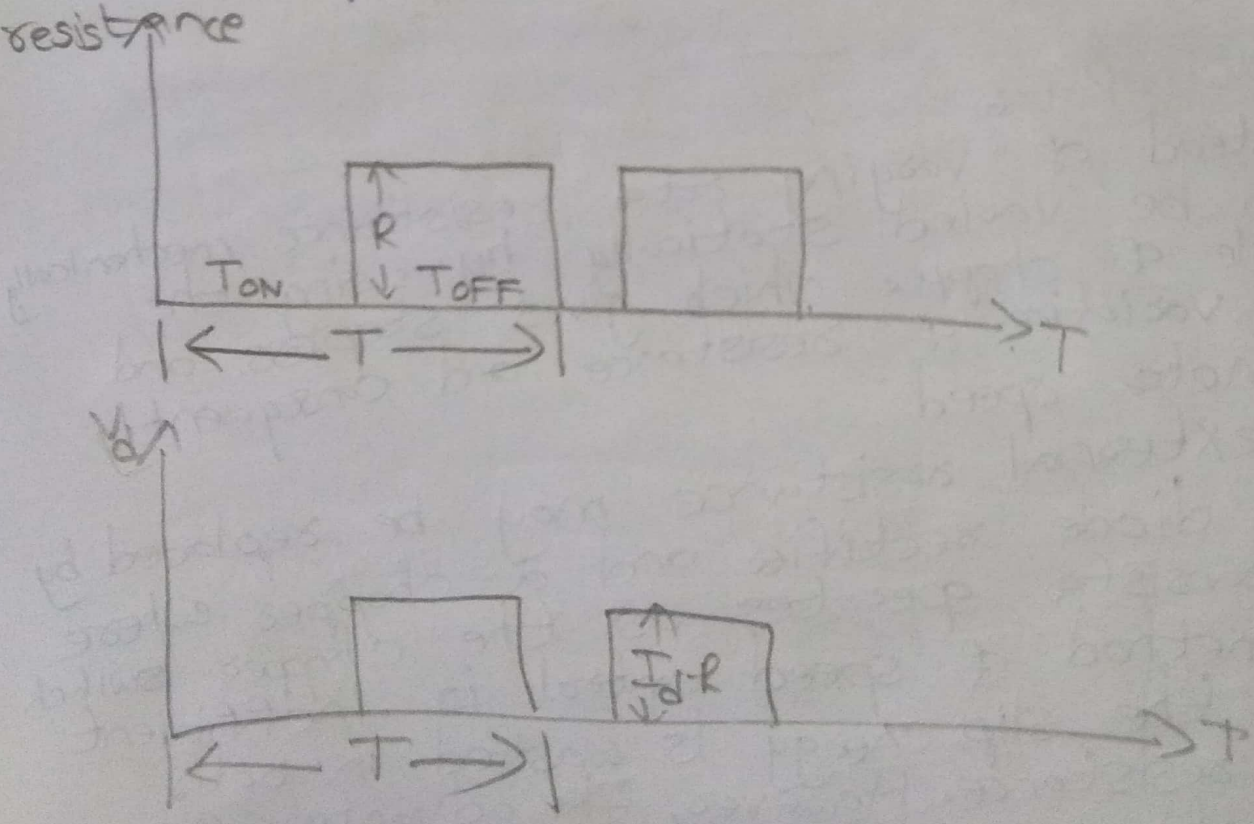
The slip voltage is rectified by the 3-ϕ diode bridge rectifier.

The DC voltage ~~must be~~ is converted to current source I_D by connecting the large series inductor L_D. It is then fed to the shunt chopper with resistance R. L_D is provided to minimize the ripple in current I_D and discontinuous in the DC link current I_D.

The chopper is periodically connects and disconnects the resistance R. When the chopper is ON, the resistance is short circuited and the current I_D will pass through it. i.e, $V_{dc} = V_d = 0$ and $R = 0$.

When chopper is off, the resistance is connected in the circuit and the DC link current I_d flows through it.

$\therefore V_{dc} = V_d$ and the resistance in the rotor circuit is R.



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The effective external resistance

$$R_{eff} = \frac{1}{T}\int_0^T R(t)\,dt$$

$$= \frac{1}{T}\left[\int_0^{T_{ON}} 0\,dt + \int_{T_{ON}}^{T} R\,dt\right]$$

$$= \frac{R}{T}\left[t\right]_{T_{ON}}^{T} = \frac{R(T-T_{ON})}{T}$$

$$R_{eff} = R\left(1-\frac{T_{ON}}{T}\right) = R(1-\alpha).$$

where α = duty cycle

T = Time period = $T_{ON} + T_{OFF}$

The effective rotor circuit resistance can be varied by varying the duty cycle α of the chopper.

∴ The torque developed and the speed of the machine can be controlled by the variation of duty cycle of the chopper.

Power consumed by the effective resistance

$$P_{AB} = I_d^2 R_{eff} = I_d^2 R(1-\alpha)$$

when the ripple is neglected, the rms value of the rotor current is

$$I_2 = \sqrt{\frac{1}{\pi}\int_0^{2\pi/3} I_d^2 \cdot d(\omega t)}$$

$$= \left[\frac{I_d^2}{\pi}\left(\frac{2\pi}{3}\right)\right]^{1/2} = I_d\sqrt{\frac{2}{3}}$$

or

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

The total resistance across the bridge is

$$R_{eff}^{**} = R_d + R_{eff}$$

where R_d is the resistance of the inductor L_d

$$\therefore R_{eff}^{**} = R_d + R(1-\alpha)$$

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The per phase power consumption by resistance R_{eff}^* is

$$P_e = I_d^2 \cdot R_{eff}^* / 3$$
$$= I_d^2 [R_d + R(1-\alpha)] / 3.$$

Sub the value of I_d in the above eq.

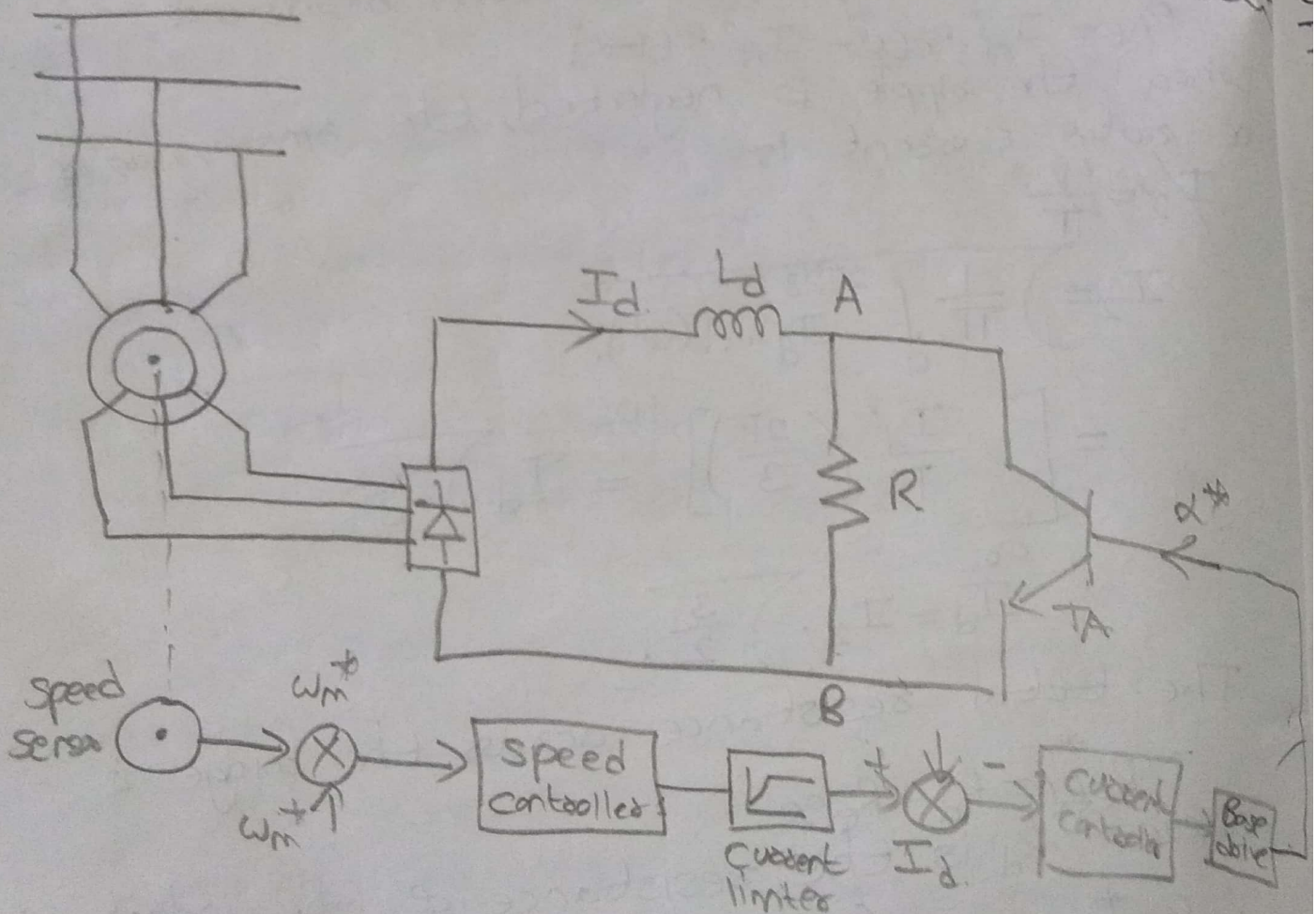
$$P_e = \frac{I_2^2}{3} \cdot \frac{3}{2} [R_d + R(1-\alpha)]$$

$$P_e \text{ per phase} = \frac{I_2^2}{2} [R_d + R(1-\alpha)]$$

∴ The equivalent to the power dissipation resistance, $\frac{R_d + (1-\alpha)R}{2}$ caused by the RMS rotor current I_2

∴ The effective value of resistance per phase is given by $R_{eff}^* = 0.5 [R_d + R(1-\alpha)]$

Closed loop speed control with static rotor resistance



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For satisfying the steady state performance & transient performance of IIm, a closed loop control is normally used. The transistor chopper circuit allows the external rotor resistance to be varied statistically. and steplessly and it also provides a low cost variable speed drives with a very good dynamic response.

The rotor slip power is converted into DC by using diode bridge rectifier and feeds through a smooth ring inductor L_d to a resistor R.

(L_d is provided to minimize ripple I_d discontinuous in DC link current. The chopper periodically connects and disconnects the resistance R

When the chopper is in ON position, the resistance is short circuited and the current I_d passes through it

$\therefore V_{dc} = V_d = 0$. (chopper is in ON then R=0)

When the IGBT chopper is off, the resistance is connected in the circuit and the DC link current I_d flows through it.

$\therefore V_{dc} = V_d$)

Single transistor chopper is connected across the resistor. The chopper is on and off in control circuit. The control signal can be obtained from sensing of speed and current. Actual speed is fed back from a tacho generator coupled to the slip ring induction motor. and compared with the reference voltage i.e, set speed.

The error is passed through the speed controller and current limiter which will set the desired current reference. The actual current can be obtained from current sensing circuit and compared with actual current as well as set current.

The error output goes to the current control and drives the circuit

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The current feedback loop adjust the current of the system by controlling the chopper. By controlling the chopper i.e, by switching on and off, the effective value of the rotor resistance can be determined and thus controls the motor speed by charging its torque speed characteristics

Advantages of static rotor resistance control over conventional rotor resistance:-

1) Smooth and stepless control
2) Fast response
3) Less maintenance
4) Compact size
5) Simple closed loop control.

6) Slip power recovery scheme:-

This system is mainly used for speed control of slip ring induction motor. The conventional methods of voltage control and rotor resistance control have more efficiency particularly at low speeds

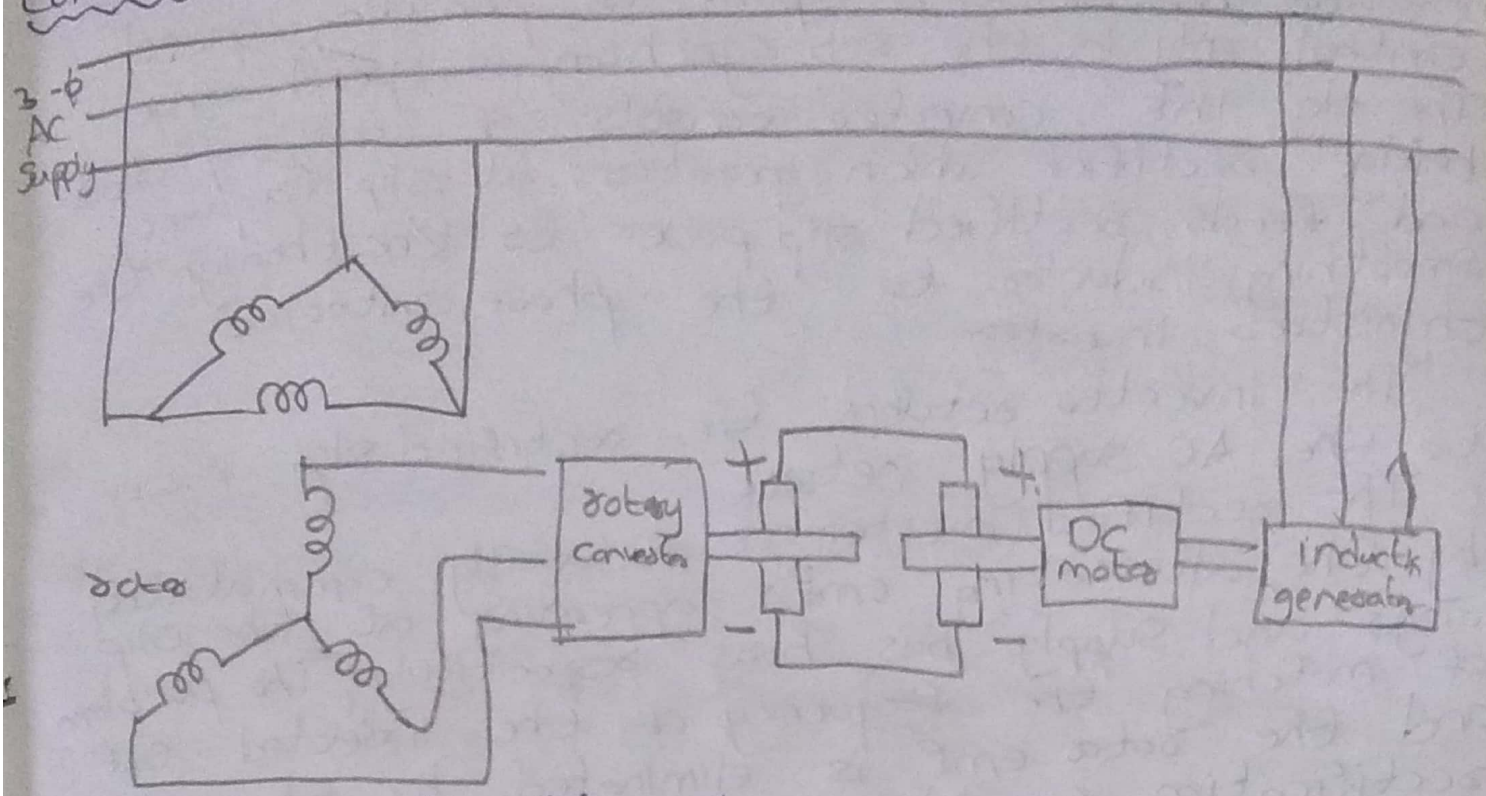
∴ It finds in limited applications. The slip power is wasted in the rotor resistance. Instead of wasting slip power, it can be converted by various schemes for the control of speed of slip ring induction motor.

Slip power recovery system can be classified into two types.

(i) Scherbius system — Conventional, Static
(ii) Kramer system

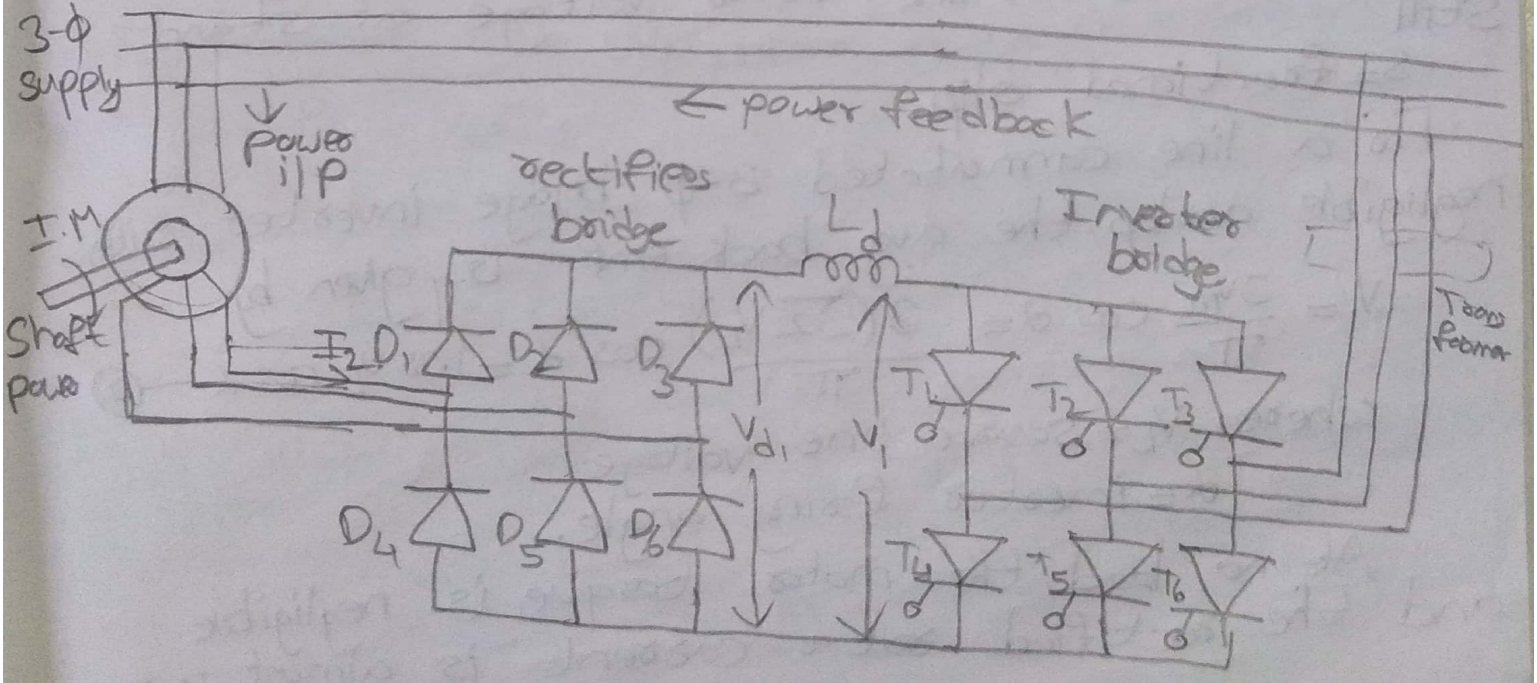
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Conventional Scherbius system



In this method, the rotary converters convert slip power into DC power and the DC power is fed to the DC motor. The DC motor is coupled with induction generator where the induction generator converts mechanical energy into electrical energy and return it to the supply line. The SRIM speed can be controlled by varying the field regulator of the DC motor.

Static Scherbius system / drive



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This scheme is known as sub-synchronous converter cascade because it is capable of providing speed control only in the sub synchronous speed range. The dc link converter consists of a 3-ϕ diode bridge rectifier which operates at slip frequency and feeds rectified slip power through the smoothing inductor to the phase controlled thyristors inverter.

The inverter returns the rectified slip power to the AC supply network.

The rectifier & inverter are naturally commutated by the alternating emf's appearing at the slip rings and supply bus bars respectively. The problem of matching the frequency of the induced emf and the rotor emf is eliminated by the rectification of the slip rings voltage because at an adjustable dc back emf can now be used at the injected voltage for speed control.

If commutation overlap is neglected, the output of 3-ϕ uncontrolled bridge rectifier

$$V_{dc} = \frac{3V_m}{\pi} = \frac{3(\sqrt{2}V_L)}{\pi} = 1.35 V_r \cdot S \quad \text{---(1)}$$

where V_m = max value of the line voltage

$V_r = V_L$ = line to line rotor voltage at stand still

S = fractional slip

For a line commutated 3-ϕ bridge inverter with negligible overlap, the avg back emf is given by

$$V_i = \frac{3V_m}{\pi}\cos\alpha = \frac{3(\sqrt{2}V_L)}{\pi}\cos\alpha = 1.35 V_L \cos\alpha \quad \text{---(2)}$$

where V_L = source line voltage

α = inverter firing angle.

At no load, the motor torque is negligible and the rectified rotor current is almost zero.

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∴ The two direct voltages of eq ① & ② must balance

$$V_{dc} + V_1 = 0.$$

$$1.35\, V_r \cdot S + 1.35\, V_L \cos\alpha = 0$$

$$S = \frac{-1.35\, V_L \cos\alpha}{1.35\, V_r} = \left(-\frac{V_L}{V_r}\right)\cos\alpha = |a|\cos\alpha \quad \text{— (3)}$$

where a = effective stator to rotor turns ratio

∴ Speed control is obtained by simple variation of the inverter firing angle

If the transformer turns ratio for the utility side relative to the inverter side is denoted by "aT".

Then AC line voltage applied to the inverter terminals is $\left(\frac{V_L}{aT}\right)$

$$\therefore S = \frac{a}{aT}(\cos\alpha) \quad \text{— (4)}$$

In order to develop motor torque, a rotor current is required and the rectified rotor voltage must force the current flow against the inverter back emf.

As the I/m is loaded, the speed falls slightly so that the resulting rotor voltage can overcome the voltage drop in the rotor winding and in the DC link circuit.

∴ Fundamental rotor slip power = DC line power

$$S \cdot P_{ag} = V_1 \cdot I_d$$

$$\Rightarrow P_{ag} = \frac{V_1 \cdot I_d}{S}$$

W.k.T, $P_{ag} = T\omega_s$

$$T = \frac{P_{ag}}{\omega_s} = \frac{\left(\frac{V_1 I_d}{S}\right)}{\omega_s}$$

$$T = \frac{V_1 I_d}{S\omega_s} \quad \text{— (5)}$$

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Sub. eq(2) in eq(5)

$$T = \frac{1.35 V_L \cos\alpha \cdot I_d}{S.\omega_s} \quad \text{---(6)}$$

Sub $S = a\cos\alpha$ (eq(3)) in (6)

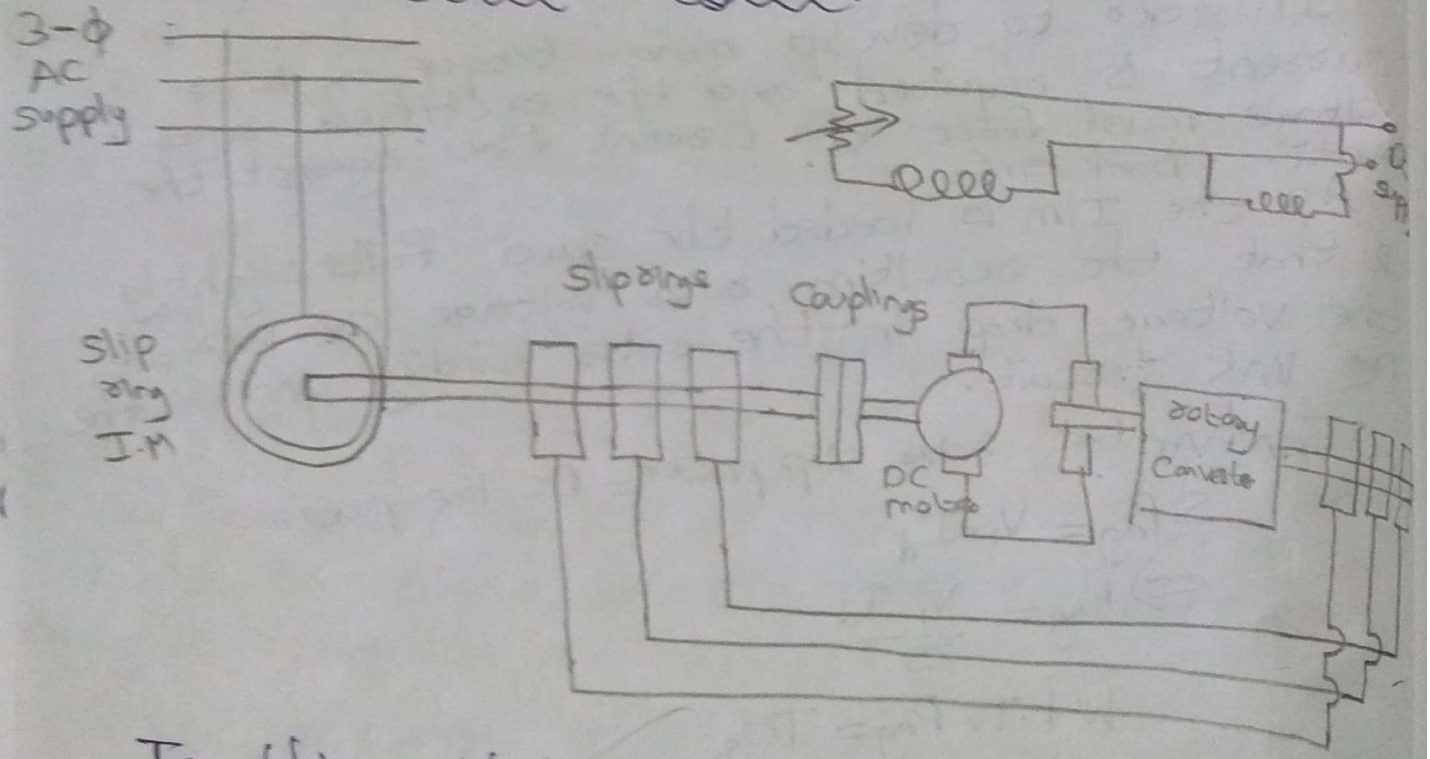
$$T = \frac{1.35 V_L \cos\alpha \cdot I_d}{a\cos\alpha \cdot \omega_s}$$

$$\therefore \boxed{T = \frac{1.35 V_L I_d}{a\omega_s}}$$

Disadvantages of sub ~~sync~~ synchronous cascade drive:-

* Only real power can be transferred through the DC link. Therefore the reactive power of the motor is entirely separated from the stator. So, the stator current can must be at lagging power factor.

* Conventional Kramer system:-



In this method, induction motor is controlled by injecting a voltage in rotor circuit. It is necessary for injecting a voltage to have the frequency same as the slip frequency. When we insert a voltage which is in phase opposition, to the induced rotor emf, it amounts to increase the

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rotor resistance.
Whereas inserting a voltage which is in phase with the induced rotor emf and is equivalent to decreasing its resistance. Therefore, by changing the injected emf and the rotor resistance, speed can be controlled.

When power is extracted from the rotor of the main induction motor and supply to the synchronous converter which supplies DC power to the auxilary DC machine.

This will now operate as a DC motor and develop an additional torque.

∴ The total torque developed = Torque developed by I/m and DC motor.

∴ We get high torque at low speed separate excitations are used for DC machine and the synchronous converter.

Change in excitation of the synchronous converter will regulate the power factor of the AC input This intern will change the power factor of the main induction motor.

The DC excitation of the auxilary DC machine is increased, it will tend to reduce its speed.

∴ Main I/m will drive the Auxilary DC machine which is operating as DC generator.

The DC power generated is converted to power at slip frequency by the synchronous converter and fed into the rotor circuit of the main I/m

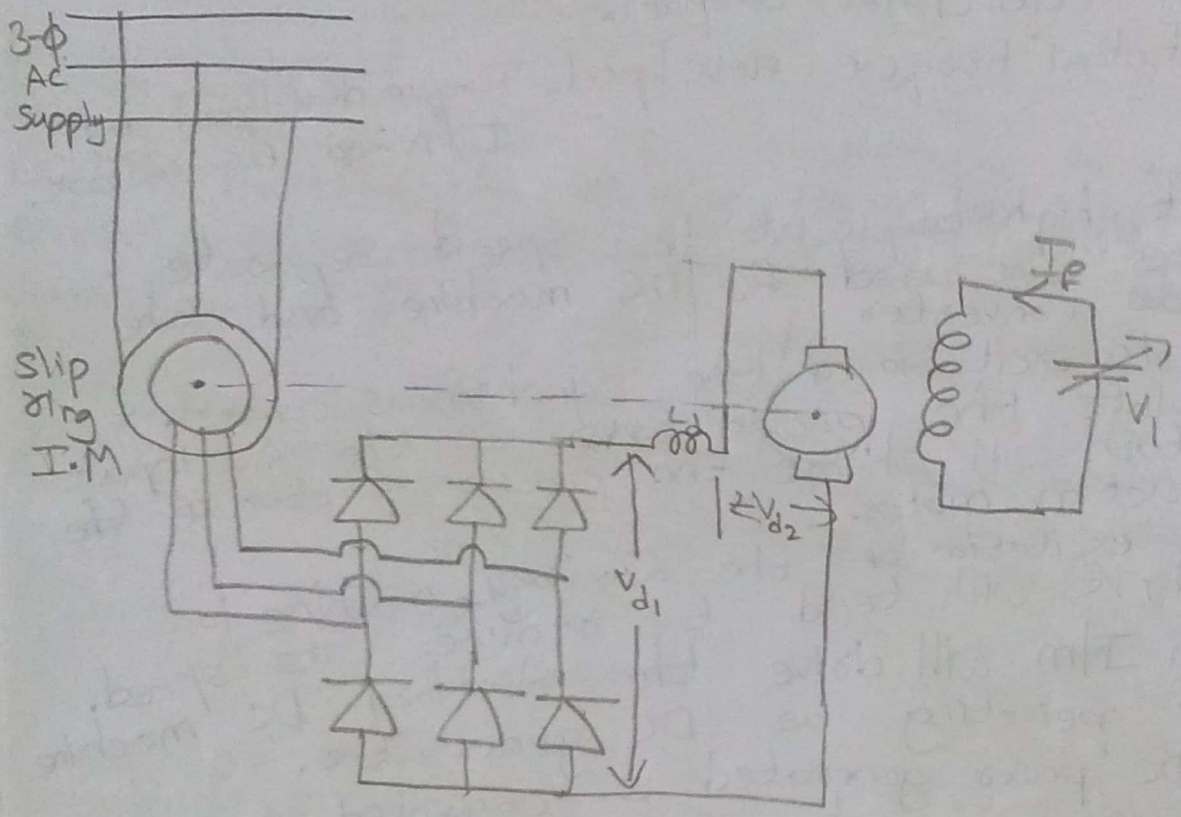
∴ The speed of the I/m will increase. Sum of the torque developed by the I/m will be consumed by the DC machine operating as a generator.

∴ The cascaded set with excessive excitation of auxilary DC machine will run at high speed and with low torque.

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Advantages:-

* Any speed within the working range can be obtained instead of other method of speed controller.
* If the rotary converter is over excited, it will take lead current which compensate the lagging current drawn by main rotor and hence improve the power factor of the system, such a system is employed for large motors.
* Static kramer drive



Rotary slip power is converted into DC by a diode bridge as shown in the fig. The DC power is now fed to DC motor which is mechanically coupled to induction motor. The torque supplied to load is sum of the torque produced by the induction and DC motors.

Speed control is obtained by controlling field current of DC motor. The steady state operation is obtained when $V_{D_1} = V_{D_2}$ i.e, at A and B for field current I_{f_1} and I_{f_2}

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Speed control is possible from synchronous speed to around half of the synchronous speed. When larger speed range is required, diode bridge is replaced by thyristor bridge.

Now, the relationship blw V_{D_1} and V_{D_2} and the speed can be altered by controlling firing angle of the thyristor rectifier.

Problem:-

A 440V 3-ϕ 50Hz 6 pole 945 rpm delta connected IIm has the following parameters referred to the stator side $R_s = 2\Omega$. $R_r = 2\Omega$. $X_s = 3\Omega$. $X_r = 4\Omega$ when driving a fan load of rated voltage and rated speed, the motor speed is controlled by stator voltage control. Determine motor terminal voltage, current and torque at 800 rpm.

Sol) Synchronous speed of motor

$$N_s = \frac{120f}{P} = \frac{120 \times 50}{6} = 1000 \text{ rpm}$$

Rotor speed $N_r = 945$ rpm

$$\therefore \text{slip} = \frac{N_s - N_r}{N_s} = \frac{1000 - 945}{1000} = 0.055.$$

$$T = \frac{3}{\omega_{ms}} \cdot \frac{E_2^2 (R_r'/s)}{\left(R_s + \frac{R_r'}{s}\right)^2 + (X_s + X_r')^2}$$

$$\omega_{ms} = \frac{2\pi N_s}{60} = \frac{2\pi (1000)}{60} = 104.7 \text{ rad/sec}$$

$$T = \frac{3}{104.7} \cdot \frac{(440)^2 (2)/(0.055)}{\left(2 + \frac{2}{0.055}\right)^2 + (3+4)^2} = 3140.9 \text{ N-m.}$$

$$= 132.693 \text{ N-m}$$

At steady state, load torque

$$T_L = T = k(1-s)^2.$$

$$132.63 = k(1-0.055)^2$$

$$k = 148.52$$

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At 800 rpm, $T_L = k(1-s)^2$

$= 148.52(1-s)^2$

$s = \frac{N_s - N_r}{N_s} = \frac{1000-800}{1000} = 0.2$

$T_L = 148.52(1-0.2)^2 = 95.05\ N\text{-}m$

$T_L = \frac{3}{\omega_{ms}} \cdot \frac{V_2^2 \cdot R_2/s}{\left(R_1 + \frac{R_2}{s}\right)^2 + (X_1 + X_2')^2}$

$95.05 = \frac{3}{\left(\frac{2\pi \times 1000}{60}\right)} \cdot \frac{V_2^2 \left(\frac{2}{0.2}\right)}{\left(2 + \frac{2}{0.2}\right)^2 + (3+4)^2}$

$V_2 = 253.26V$

$I_2' = \frac{V_2}{(R_1 + \frac{R_2'}{s}) + j(X_1 + X_2')} = 15.72 - j9.172 = 18.2 \angle -30.35$

$I_{2(L)}' = \sqrt{3} \times I_2'$

$I_2' = \frac{253.26}{\left(2 + \frac{2}{0.2}\right)^2 + (3+4)j} = 15.72 - j9.172 = 18.2 \angle -30.35^\circ$

$I_{2(L)}' = \sqrt{3} \times I_2' = \sqrt{3} \times 18.2 = 31.52A$

*A 3-ϕ 400V 4 pole 50Hz star connected I/m has the following parameters referred to the stator, $R_2' = 0.2\Omega$, $X_2' = 0.35\Omega$. Stator impedance and the magnetising branch can be ignored when driving the load with its torque proportional to the speed, the motor runs at 1450 rpm. Calculate the magnitude and the

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phase of the voltage referred to the stator to be impressed on the slip rings inorder that the motor may operates at 1200rpm and unity power factor.

Sol) $R_2' = 0.2\,\Omega$, $X_2' = 0.35\,\Omega$, $R_s = 0$, $X_s = 0$

$P = 4$, $V = 400\,V$, $f = 50\,Hz$.

Syn. speed $N_s = \frac{120f}{P} = \frac{120 \times 50}{4} = 1500\,rpm.$

$\omega_{ms} = \frac{2\pi N_s}{60} = \frac{2\pi(1500)}{60} = 157.07\,rad/sec.$

At full load

$$s = \frac{N_s - N_r}{N_s} = \frac{1500 - 1450}{1500} = 0.0344.$$

$$T = \frac{3}{\omega_{ms}} \left[\frac{\left(V^2 \cdot \frac{R_2'}{s}\right)}{\left(R_1 + \frac{R_2'}{s}\right)^2 + (X_1 + X_2')^2} \right]$$

$$= \frac{3}{157.07} \left[\frac{\left(\frac{400}{\sqrt{3}}\right)^2 \left(\frac{0.2}{0.0344}\right)}{\left(0 + \frac{0.2}{0.0344}\right)^2 + (0 + 0.35)^2} \right]$$

$$T = 175.2\,N\text{-}m.$$

Given that $T \propto N$

$$T = k(1 - s)$$

$$175.2 = k(1 - 0.0344)$$

$$k = \frac{175.2}{1 - 0.0344} = 181.44.$$

$$T = k(1 - s)$$

$$T = 181.44(1 - s)$$

at 1200rpm, $s = \frac{1500 - 1200}{1500}$

$$s = 0.2$$

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$$T = 181.44\,(1-0.2)$$

$$T = 145.15\ \text{N-m}$$

$$145.15 = \frac{3XV^2\left(\frac{0.2}{0.2}\right)}{157.07\left[\left(0+\frac{0.2}{0.2}\right)^2+(0+0.35)^2\right]}$$

$$V^2 = \frac{145.15 \times 157.07\left[(1)^2+(0.35)^2\right]}{3}$$

$$V_{Ph} = 92.36\text{V}.$$

$$V_L = \sqrt{3} \times V_{Ph} = \sqrt{3} \times 92.36 = 159.97\text{V}.$$

Unit-6

Speed control of synchronous motor

The speed of synchronous motor is controlled by varying the frequency. The frequency can be varied with the help of, cycloconverters or PWM Inverters.

Power factor is controlled by varying the field currents. Generally voltage source inverters are used for controlling the speed of the synchronous motor. The load commutated inverter is more advantageous than forced commutated inverter because additional circuitry is not required.

Synchronous motor has 3-ϕ winding on stator and field winding on rotor which is excited by DC. Synchronous motor has self starting torque

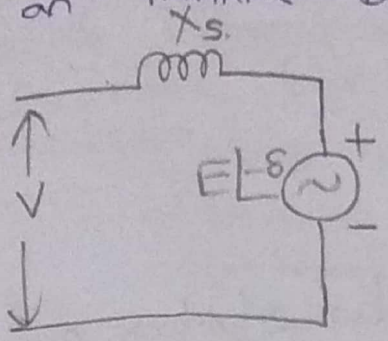
By using Auxilary methods, the motor is self driven. The synchronous motor is of two types

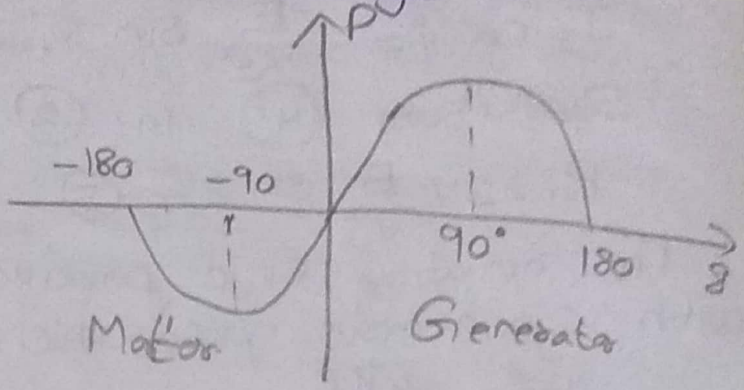
1) Cylindrical rotor type.
2) Salient pole rotor type.

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Cylindrical rotor wound field motor :-

Let us consider that the synchronous machine is acting as a generator and is feeding power to an infinite bus of constant voltage 'V'





Power input to the motor is

$$P_{in} = 3VI_s \cos\phi \quad \text{---(1)}$$

where ϕ is the phase angle of I_s with respect to V

By neglecting stator losses, the power developed is given by

$$P_m = 3VI_s \cos\phi \text{ (by neglecting stator losses)} \quad \text{---(2)}$$

Applying KVL to the loop,

$$V\angle 0^\circ = jI_sX_s + E\angle -\delta \quad \text{---(3)}$$

$$I_s = \frac{V\angle 0 - E\angle -\delta}{jX_s}$$

$$= \frac{V}{X_s}\angle -90 - \frac{E}{X_s}\angle -90-\delta = I_s\cos\phi + jI_s\sin\phi$$

Real component of I_s is

$$I_s\cos\phi = \frac{V}{X_s}.$$

$$I_s\cos\phi + jI_s\sin\phi = \frac{V}{X_s}[\cos 90 - j\sin 90] -$$

$$\frac{E}{X_s}[\cos(90+\delta) - j\sin(90+\delta)]$$

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Equate real parts on both sides

$$I_s \cos\phi = \frac{V}{X_s}\cos 90 - \frac{E}{X_s}\cos(90+\delta)$$

Equate,

$$I_s \cos\phi = \frac{E}{X_s}\sin\delta \quad \text{---(4)}$$

Substitute (4) in (2).

$$P_m = 3V\frac{E}{X_s}\sin\delta \quad \text{---(5)}$$

The rotating field produced by stator moves with synchronous speed which is given by

~~$\omega_{ms} = \frac{4\pi f}{p}$~~

$$\omega_{ms} = \frac{2\pi N_s}{60} = \frac{2\pi \times 120 f}{P \times 60} = \frac{4\pi f}{P} \quad \text{---(6)}$$

where f is the supply frequency

P = no. of poles of the machine

From (5), the variation of power P vs power angle δ (load angle) has a sinusoidal shape and is usually called the power angle characteristic of the cylindrical rotor synchronous machine.

For a steady torque to be produced, rotor field must move as that of the stator field speed.

∴ The rotor also runs at synchronous speed

Torque developed = $\frac{P_m}{\omega_{ms}}$.

$$T = \frac{3VE}{X_s \cdot \omega_{ms}}\sin\delta.$$

For a given field excitation, E is constant

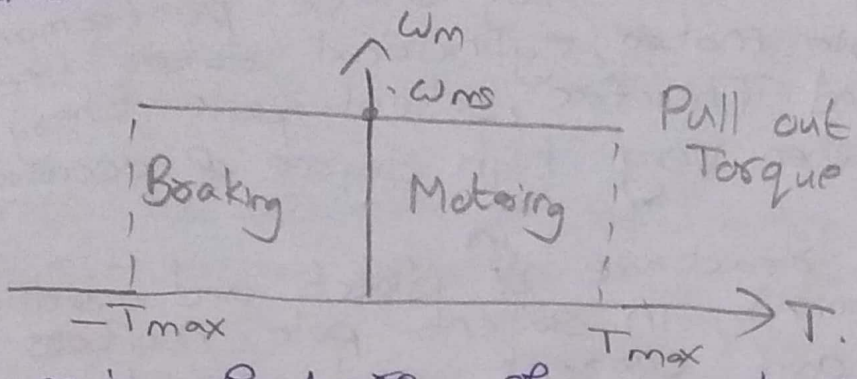
∴ $P_m \propto \sin\delta$ & $T \propto \sin\delta$.

Motoring operation is obtained where δ is positive and E lags behind V whereas regenerative braking is obtained when δ is negative. or E

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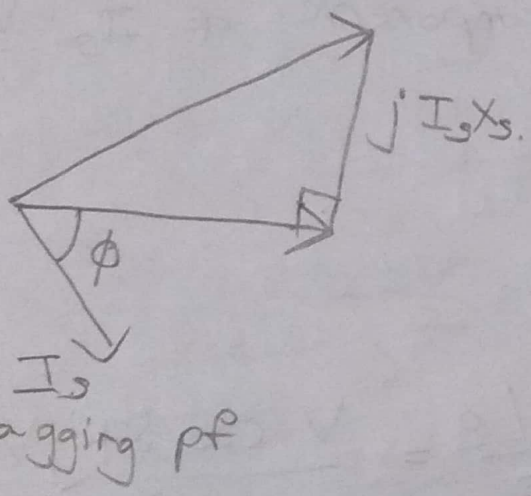
leads V. The max torque (or) pull out torque is reached at $\delta = \pm 90°$. If the max torque exceeds by the machine, it pulls out of synchronism.

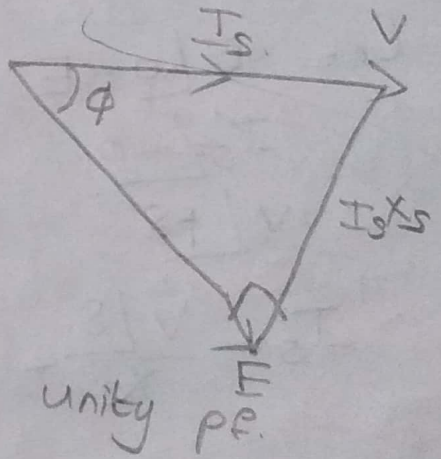
In order to prevent damage due to excessive current automatic circuit breakers are provided to disconnect the machine when it comes out of synchronism.

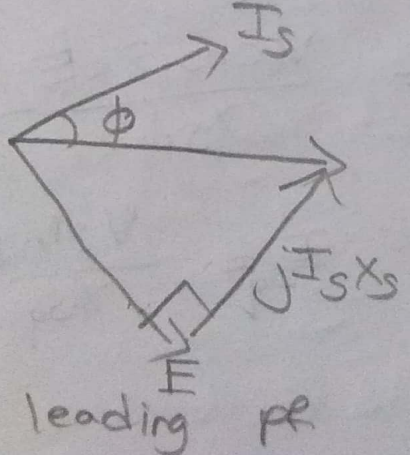


The main feature of wound field motor is that its power factor can be controlled by varying field current or excitation E.

When field excitation is small, the machine operates with a lagging power factor. The power factor can be made unity or leading by increasing the field excitation.







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Salient pole wound field motor :-

Analysis of salient pole motors is difficult when compared to cylindrical rotors because cylindrical rotor motors have uniform air gap whereas in salient pole motors air gap is much greater b/w the poles than along the poles.

In explaining the steady state performance of a salient pole motor, cylindrical rotor theory is reasonably good. Therefore, salient pole theory is required only when very high degree of accuracy is needed.

Synchronous reactance in direct and quadrature axis are different in salient pole motors

∴ The d-q axis current and reactance for a salient pole synchronous motor is exactly same as the salient pole synchronous generator.

Let the stator current = I_s.

Direct axis component of I_s

$$I_s = \frac{V}{X_s}\angle -90^\circ - \frac{E}{X_s}\angle -90-\delta.$$

∴ Direct axis component of $I_s = \frac{V\cos\delta - E}{X_{sd}}$.

Let $E\angle 0 = E$

$I_s \angle -\phi$.

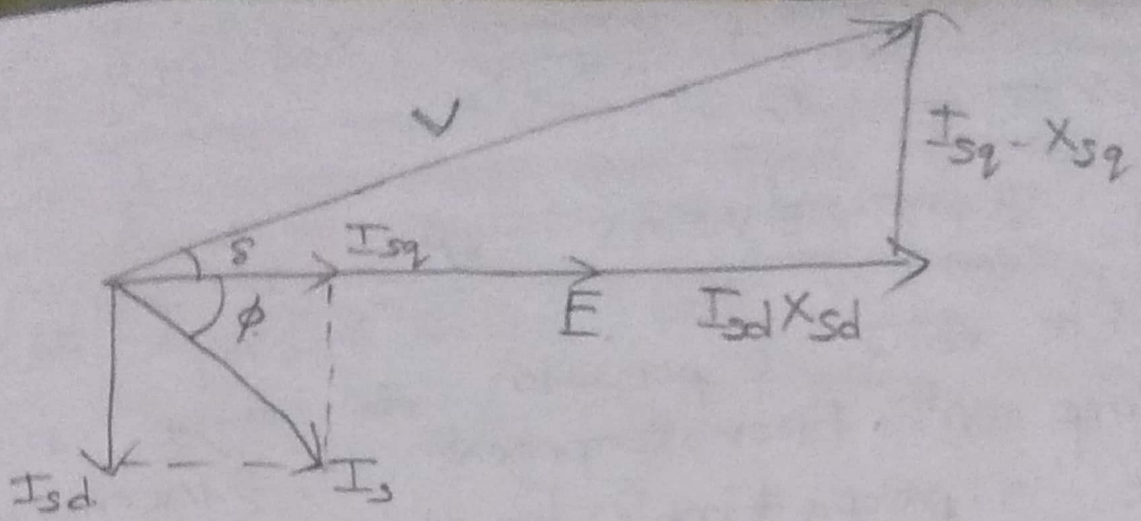
$V\angle +\delta$

$$I_s = \frac{V\angle\delta}{X_s} - \frac{E\angle 0}{X_s} = \frac{V\cos\delta + jV\sin\delta - E}{X_s}$$

Direct axis component of $I_{sd} = \frac{V\cos\delta - E}{X_{sd}}$ — (1)

Quadrature axis component of $I_{sq} = \frac{V\sin\delta}{X_{sq}}$ — (2)

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where X_{sd} = synchronous reactance of direct axis
X_{sq} = synchronous reactance of quadrature axis

Sub eq ① & ②

$$I_s \cos\phi = I_{sq} \cos\delta - I_{sd} \sin\delta \quad \text{---} ③$$

Sub eq ① & ② in eq ③.

~~$I_s \cos\phi \neq V \cos\delta$~~

$$I_s \cos\phi = \frac{V \sin\delta}{X_{sq}} \cos\delta - \left(\frac{V\cos\delta - E}{X_{sd}}\right) \sin\delta$$

$$= \frac{E \sin\delta}{X_{sd}} + \frac{V \sin\delta \cos\delta}{X_{sq}} - \frac{V \cos\delta \sin\delta}{X_{sd}}$$

$$= \frac{E \sin\delta}{X_{sd}} + V \sin\delta \cos\delta \left(\frac{1}{X_{sq}} - \frac{1}{X_{sd}}\right)$$

$$= \frac{E \sin\delta}{X_{sd}} + \frac{V}{2} \sin 2\delta \left(\frac{1}{X_{sq}} - \frac{1}{X_{sd}}\right)$$

$$I_s \cos\phi = \frac{E \sin\delta}{X_{sd}} + \frac{V \sin 2\delta}{2 X_{sd} X_{sq}} (X_{sd} - X_{sq}) \quad \text{---} ④$$

W.k.T $P_m = 3V I_s \cos\phi$. ——— ⑤

Sub ④ in ⑤

$$P_m = 3V \left[\frac{E \sin\delta}{X_{sd}} + \frac{V \sin 2\delta}{2 X_{sd} X_{sq}} (X_{sd} - X_{sq})\right]$$

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$$P_m = 3\left[\frac{EV\sin\delta}{X_{sd}} + \frac{V^2\sin 2\delta}{2X_{sd}X_{sq}}(X_{sd}-X_{sq})\right] \quad \text{--- (6)}$$

W.K.T, $T = \frac{P_m}{\omega_{mo}}$

$$\therefore T = \frac{3}{\omega_{mo}}\left[\frac{EV\sin\delta}{X_{sd}} + \frac{V^2\sin 2\delta}{2X_{sd}X_{sq}}(X_{sd}-X_{sq})\right]$$

In the above expression for torque we have two components. First component i.e, synchronous torque is proportional to $\sin\delta$ & the second component i.e, reluctance torque which is proportional to $\sin 2\delta$.

Permanent magnet motor:-

In small and medium size motors, DC field can be produced by permanent magnets which are called as permanent magnet synchronous motors.

In permanent magnet motor, field excitation is obtained by mounting permanent magnets on the rotor. This eliminates DC source, losses associated with the field winding, frequent maintenance associated with slip rings and brushes in a wound field motor but power factor cannot be changed. (or) Controlled because the field excitation cannot be changed

This type of motors are designed to operate at unity power factor at full load.

Synchronous reluctance motor:-

It has salient poles and they do not have any field winding or permanent magnet on the rotor. The machines have low cost, high efficiency, can be operated at a very high speeds

Air gap flux is produced only by the magnetising current which is drawn from the source because here field excitation is

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not present

Damper winding:-

Damper windings consists of low resistance copper, brass or aluminium bars embedded in slots in the pole faces of salient pole machines. The projecting ends of the bars are connected to short circuiting strips of the same material as used for the bars. Some synchronous motors have an additional winding known as damper winding on the rotor.

It is similar to squirrel cage winding of an induction motor. It is provided to damp the hunting oscillations during transient operation of the motor.

It is also used to start the motor as an induction motor. When the motor runs at synchronous speed, no voltages are induced in the damper winding.

∴ Damper winding has no effect on motor operation

Starting torque:-

It is the ability of the motor to accelerate the load. It is also called as breakaway torque.

Running torque:-

It is the torque developed by the motor under running condition.

Pull-in torque:-

It is the ability of the motor to pull into synchronism.

Pull-out torque:-

It is the ability of the motor to remain in synchronism under rated load conditions. (or) The maximum torque which the motor will develop without pulling out of step. (or) o synchronism is called the pull-out torque.

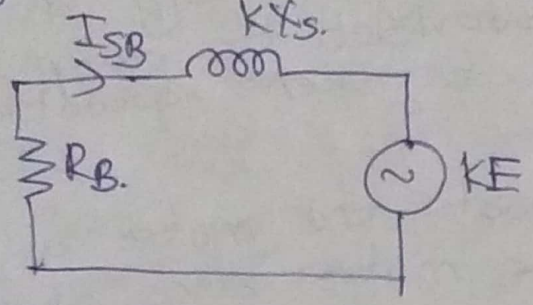
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Braking:

Regenerative braking cannot be used for stopping or decelerating a load. The motor can work in regenerative braking only at synchronous speed.

Dynamic braking is obtained by disconnecting stator from the source and connecting it to 3-ϕ resistor.

Machine works as a synchronous generator and dissipates generated energy through the braking resistor



Where I_{SB} = Braking current

R_B = Braking resistor

K is the per unit speed of the motor given by

$$K = \frac{\omega_m}{\omega_{ms}}$$

Braking current $I_{SB} = \frac{KE}{\sqrt{R_B^2 + (KX_s)^2}}$.

Braking power = $P_B = 3 I_{SB}^2 R_B$

$$P_B = 3 \cdot \frac{(KE)^2}{R_B^2 + (KX_s)^2} \cdot R_B$$

Braking torque $T_B = \frac{P_B}{K\omega_{ms}} = \frac{3(KE)^2 R_B}{K\omega_{ms}(R_B^2 + (KX_s)^2)}$.

∴ For stopping the motor dynamic braking is suitable.

Since, the braking torque is zero at zero speed

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Theoretically plugging can also be employed but practically it is not used because braking torque produced is much smaller compared to dynamic braking toque.

Speed control of synchronous machines:

The speed of synchronous motor can be varied by varying frequency of its source. With the development of semiconductor devices like variable frequency source, high speed compressors, blowers, servo drives are existing.

The speed control of synchronous machine may be achieved by voltage fed inverters, current fed inverters or cycloconverters.

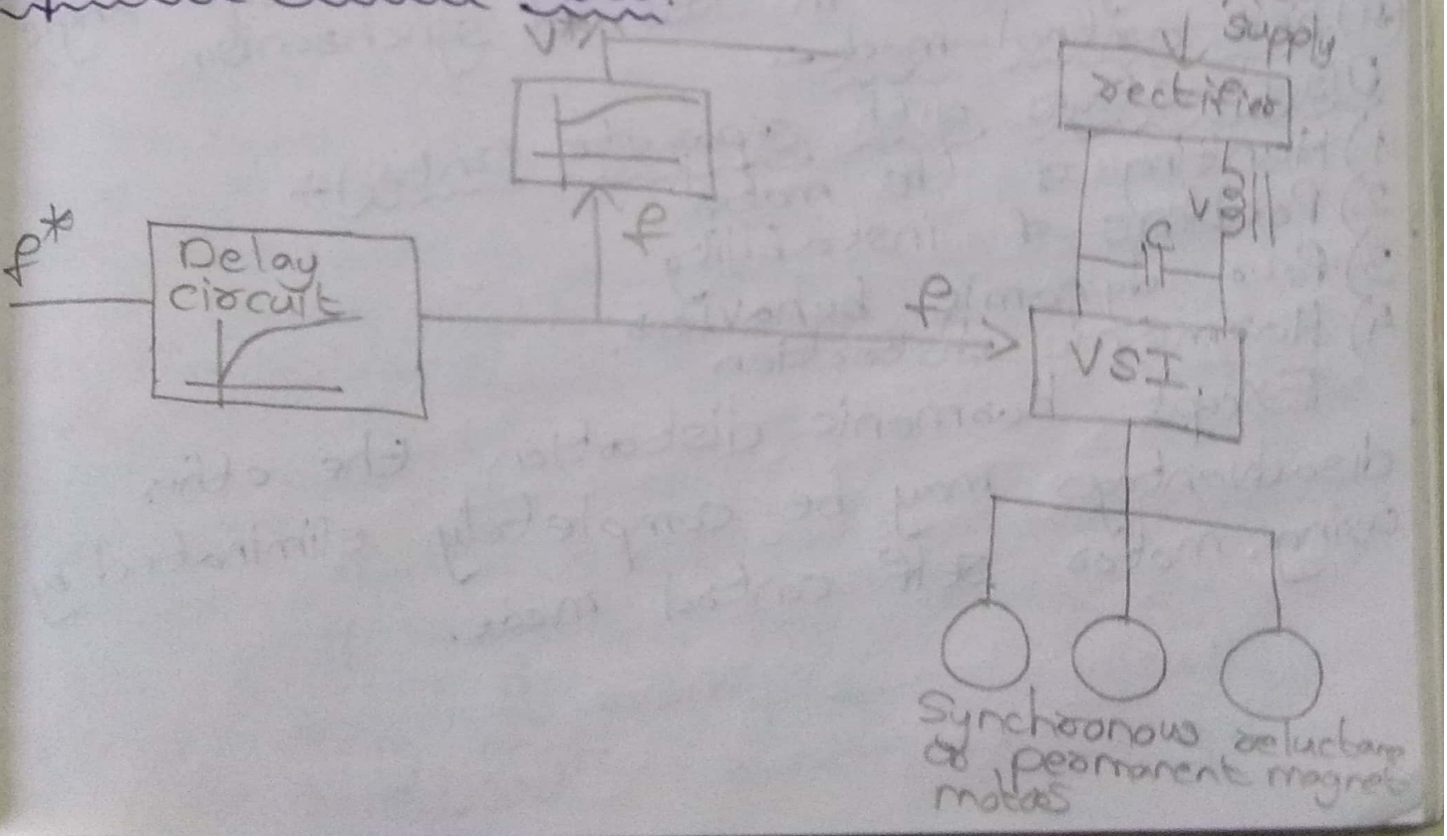
The control can be ~~done~~ categorized into two groups.

1) Scalar control and
2) Vector control.

Scalar control synchronous machine drive system will have two modes of operation.

(i) Separate control mode.
(ii) Self control mode.

Separate control mode:



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The Command frequency passed through the delay unit and delay circuit output. It is applied to the voltage source inverter so that the rotor speed is able to track the changes in frequency.

A flux control block changes stator voltage with frequency V/F to maintain a constant flux below rated speed and a constant terminal voltage above rated speed. The speed can be varied from zero to the full value by gradually varying the frequency.

Beyond the base speed, the DC link voltage saturates and the machine enters into the field weakening. Constant power operation is required. So it enters into constant power region where the torque decreases with an increase in the frequency. If prolonged low operation is required improved cooling is needed.

Speed is being determined by Inverter frequency

Speed changes must be done slowly to avoid possibility of exceeding the pull out torque angle which may result in loss of synchronism

(ii) ~~Self control mode:~~

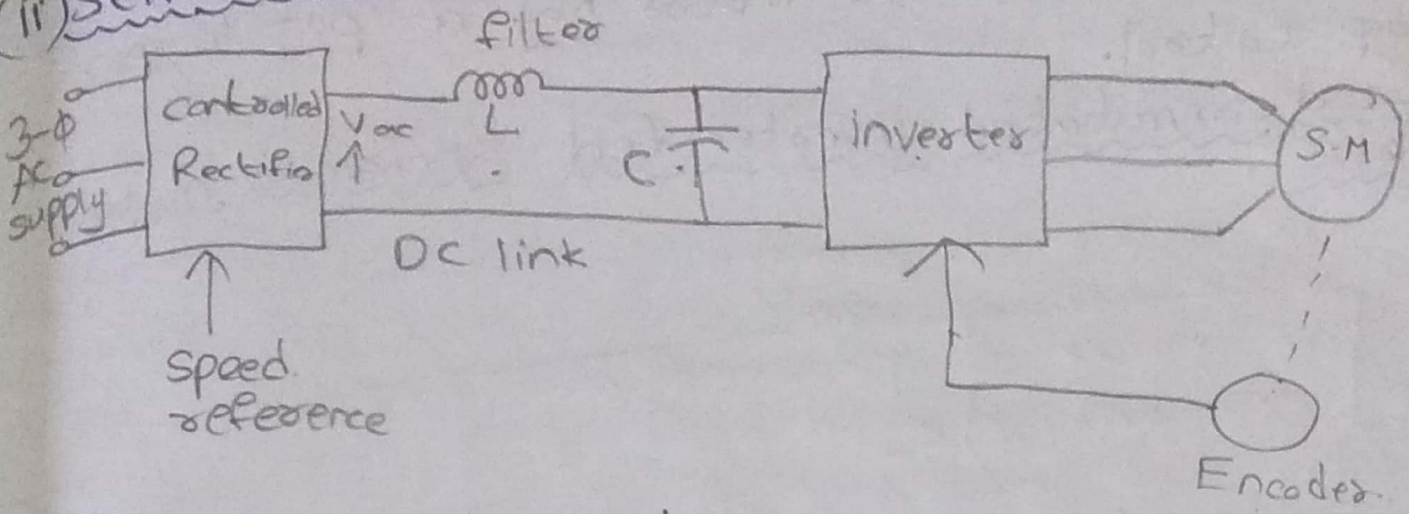
Disadvantages with separate control

1) Hunting of the motor
2) Problems of instability
3) Poor dynamic behaviour.
4) Harmonic distortion

Except harmonic distortion the other disadvantages may be completely eliminated by using motor self control mode.

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(ii) Self control mode:



A self control synchronous motor has analogy with DC motor. When an inverter is employed, the drive is controlled from a DC source, the inverter may be a VSI or CSI.

Depending upon the type of inverter, the DC source may be a controllable current source or controllable voltage source. The inverter output frequency is determined by the rotor speed.

The instance at which the switching devices operate to turn the stator windings ON and OFF are determined by the rotor position dependent signals obtained from an encoder mounted on the rotor shaft.

The stator currents are always switched on at the right time could produce the required torque on the rotor because the inverter knows where the rotor is at every instant of time.

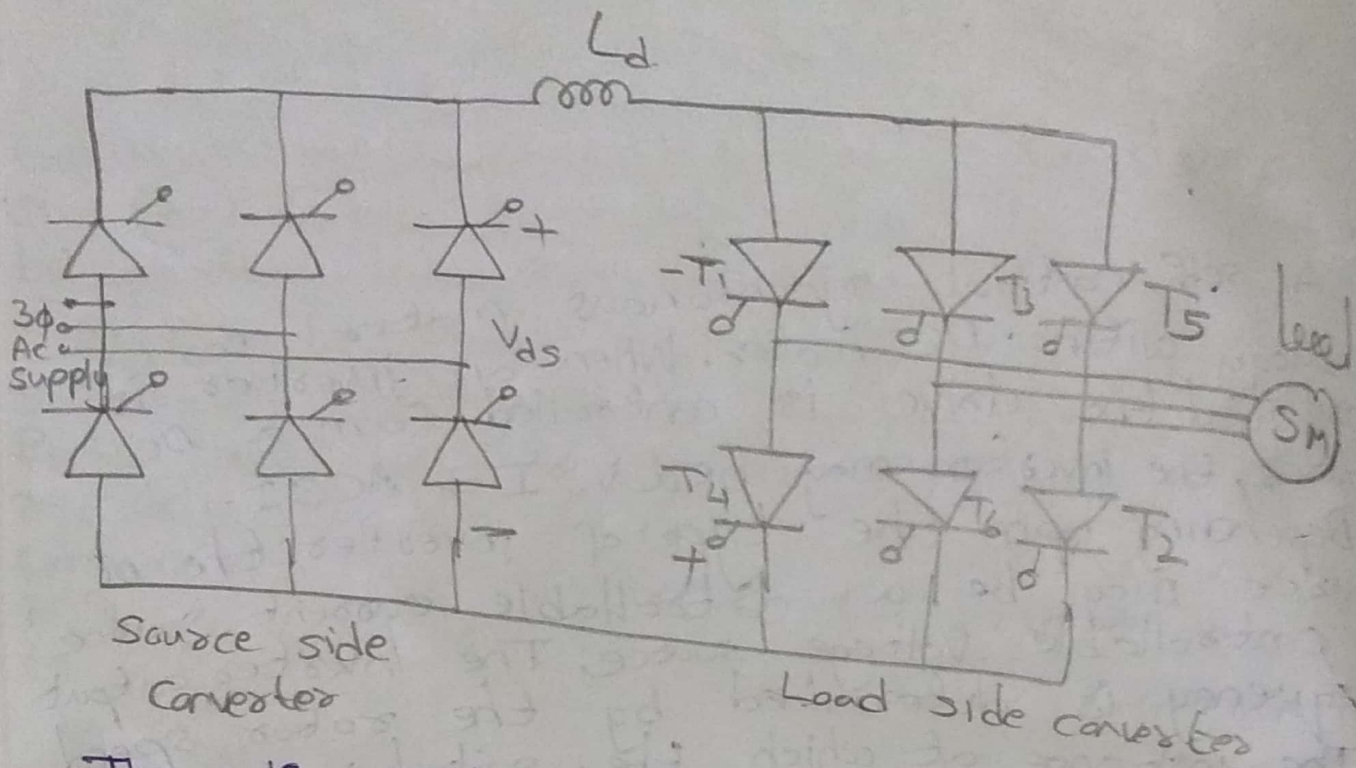
With the application of load, if the rotor slows down, the stator supply frequency automatically requires. Therefore, the rotor remains synchronized with the rotating field.

The speed of the synchronous motor can be controlled by controlling the DC link voltage to the inverter. By varying the controlled rectifier firing angle, the DC link voltage can be controlled.

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At very low speeds, the emf generated is insufficient so the motor may be put in open loop control.

Load commutated inverter fed synchronous motor drive



The self control synchronous motor drive employing a load commutated thyristor inverter. The drive employees two converters

1) Source side converter
2) Load side converter

The source side converter is a six pulse line commutated thyristor.

For $0 \leq \alpha_s \leq 90°$, it works as a line commutated fully controlled rectifier. delivering positive V_{ds} and positive I_d.

For $90° \leq \alpha_s \leq 180°$, it works as a line commutated inverter delivering -ve V_{DS} and $+I_d$.

When synchronous motor operates at a leading power factor by adjusting the

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excitation of synchronous motor. This enables the inverter to operate as load commutated circuit. and is also known as self controlled circuit.

Firing angle is measured by comparison of induced voltages.

Load side converter operates as an inverter, produces negative V_{dL} and carrying +ve I_D for $90° \leq \alpha_l \leq 180°$.

For $0 \leq \alpha_l \leq 90°$, it works as a rectifier giving +ve V_{dl} and $+I_d$

For $0 \leq \alpha_s \leq 90°$ & $90° < \alpha < 180$ with $V_{ds} > V_{dl}$ is source side converter works as a rectifier. and load side converter acts as a inverter.

Now the power flows in reverse direction and the machine operates in regenerative braking. The magnitude of torque depends on $V_{ds} - V_{dl}$.

Speed can be changed by changing load side converter firing angles. Firing pulses are supplied at the instant determined by the rotor position sensor.

When working as an inverter, the firing angle has to be less than 180° to take care of commutation overlap and turn off the thyristors.

Commutation lead angle for the load side converter $\beta_l = 180 - \alpha_l$. If commutation overlap is ignored, the input side AC current lags the voltage by α_l

Motor input current has an opposite phase to converter input current, the motor current will lead its terminal voltage by an angle β_l. Therefore, motor operates at a leading power factor.

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Lower the value of β_l, higher the motor power factor. and lower the inverter rating. The commutation overlap for the load side converter depends on the sub transient inductance of the motor.

The motor is provided by the damper winding in order to reduce the subtransient inductance.

The driver is operated at a fixed value of commutation, lead angle 'β_{lc}'.

For the load side converter working as an inverter $\beta_l = 180$ when working as an rectifier.

If commutation overlap of the thyristor under commutation is denoted by 'μ' then the duration for which the thyristor under commutation is subjected to reverse bias after current through it is zero. i.e, commutation

$\gamma = \beta_l - \mu$.

For successful commutation of thyristor $\gamma = \omega t_q$. where t_q is the turn off time of the thyristors. and ω is the frequency of motor voltage in radians/sec.

Since $\mu \propto I_d$. The DC link current I_d flows through the machine with phase of 120° in each half cycle. Fundamental component of motor phase current

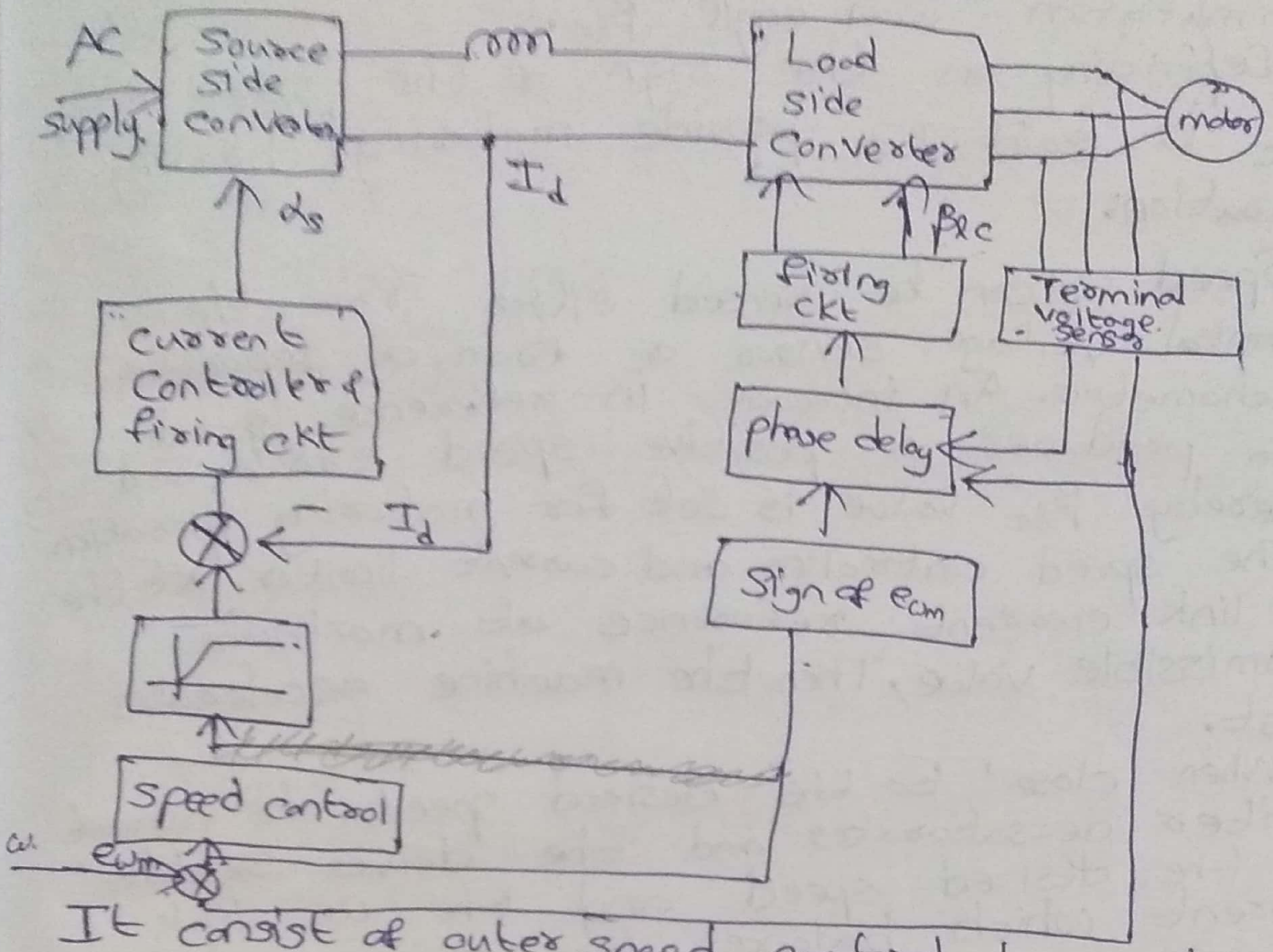
$$I_s = \frac{\sqrt{6}}{\pi} \cdot I_d$$

Load side converter thyristors are fired in the sequence of their numbers with 60° interval.

∴ For the control of load side converter thyristors in all six rotor angle positions are required to detect the induced voltage per cycle.

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Closed loop speed control of load commutated inverter fed synchronous motor drive :-



It consist of outer speed control loop and inner current control loop with a limiter like a DC motor. The phase controlled thyristor rectifier on the supply side of the DC link has a current regulating loop and operates as a current control source. The regulated DC current is delivered through the DC link inductor to the thyristor load commutated inverter which supplies square wave line currents to the synchronous motor.

The terminal voltage sensor generates reference pulse, of the same frequency as the machine ~~terminal~~ induced voltage sensor generates ~~frequency of the~~

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The phase delay circuit shifts the reference pulses suitably to obtain control at a constant commutation lead angle β_{lc}.

Depending on the sign of the speed error β_{lc} is said to provide motoring / braking operation.

Speed ω_m can be sensed either from the terminal voltage sensor or from a separate tachometer. An increase in reference speed ω_m produces a positive speed error and thereby β_{lc} value is set for motoring operation. The speed controller and current limiter set the DC link current reference at maximum permissible value, Then the machine accelerates fast.

When close to the desired speed, the current limiter de-saturates and the drives settle at the desired speed and the DC link current which balances the motor and load torques.

Reduction in reference speed produces a negative speed error.

This sets β_{lc} for regenerative braking operation and the motor decelerates.

When speed error changes sign β_{lc} value is set for motoring operation and the drive settle at the desired speed.

Advantages:-

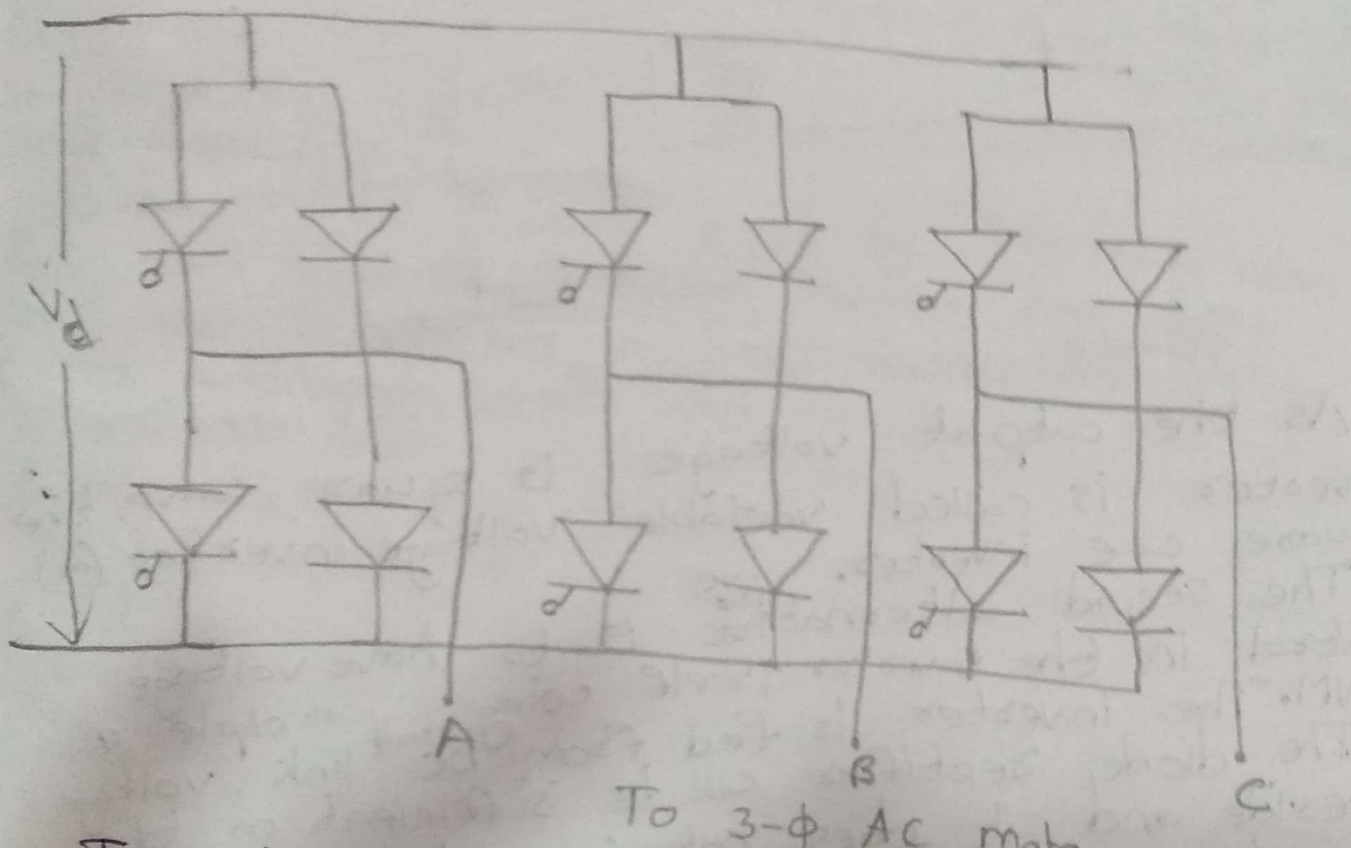
1) High efficiency
2) Four quadrant operation with regenerative braking
3) High power ratings upto 100MW and the ability to run at high speeds.

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Applications

1) Compressors
2) Blowers
3) Fans
4) Pumps
5) Conveyors
6) Steel rolling wheels
7) Main line traction.
8) Ship propulsion and aircraft test facilities

Voltage source inverter fed synchronous motor drive

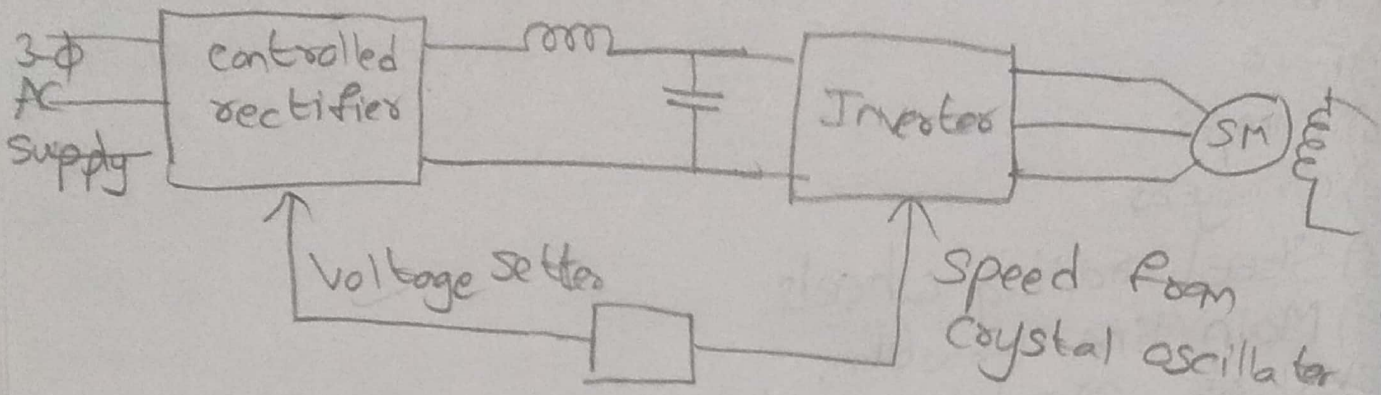


In a typical power circuit of a voltage source inverter, 3 combinations are possible to provide a variable voltage, variable frequency supply to a synchronous motor.

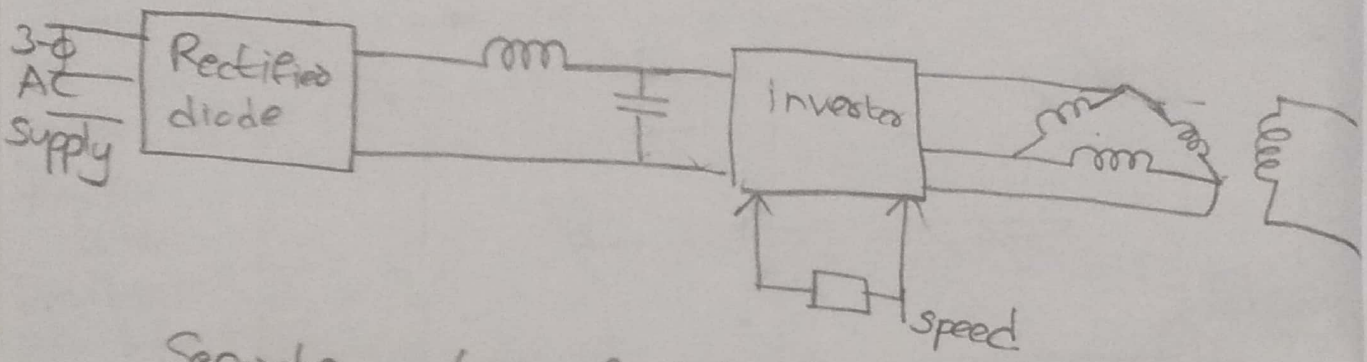
The voltage control can be obtained external to the inverter using a phase control rectifier.

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The link voltage is variable and it is difficult to provide commutation at very low speeds.



Separate control of SM fed from square wave inverter



Separate control of SM fed PWM inverter

As the output voltage is square wave, the inverter is called variable voltage inverter (or) square wave inverter.

The second alternative is to have voltage control in the inverter itself using constant DC link voltage principle of PWM. The inverter is fed from diode rectifier will be sufficient on the lineside and it does not have difficulty for commutation at low speeds.

The third alternative is to interpose a DC chopper in b/w the rectifier and inverter.

Three simple converters are used to give the desired results. It is possible to reduce the size of the DC link inductance by having a synchronous control of the chopper.

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*A VSI feeding the synchronous motor can have either separate control or self control
The speed of the motor is determined by external frequency from crystal oscillator
open loop control system
The motor has instability problems and hunting similar to a conventional motor.
The inverter is controlled by means of firing pulse obtained from a rotor position sensor or induced voltage sensor.
The motor is in commutationless motor mode and has better stability issues or characteristics.
The output voltage of the inverter is non sinusoidal. The behaviour of the motor supplied from the inverter is entirely different from the behaviour of the motor operation on a conventional sinusoidal supply.
When stator current drawn by the motor when fed from the square wave inverter, has sharp peaks and is switched in harmonic content which causes additional losses and heating of the motor.
They also cause pulsating torque which are objectionable at low speeds.
So this method is applicable for medium to high speed applications.
A VSI drive provides reasonably good efficiciency, Converter cost is high and multimotor operation is possible.
Open loop control may give less stability problems at low speeds, whereas commutatorless motor mode is very stable.
PWM drive has a better dynamic response than a square wave drive. This is used in general purpose industrial drives for low and medium powers.

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Due to phase control, the live power factor is very poor. A diode rectifier is sufficient in case of PWM Inverter. The line power factor improves to unity

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