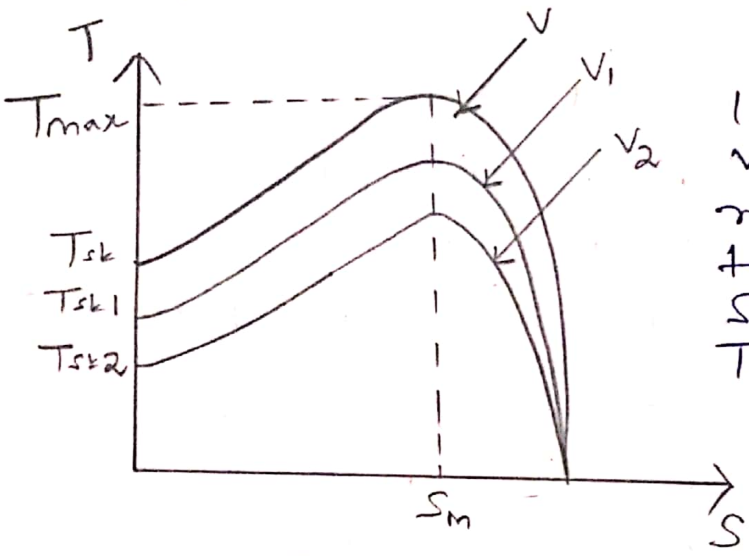
Stator voltage Control:

The Induction Motor speed can be controlled by varying the stator voltage. Supply frequency constant.

$V > V_1 > V_2$



$T \propto V^2$

10% reduction of voltage causes a 19% reduction in developed torque as well as starting and maximum torque.

$$\eta_m = \frac{P_m}{P_{ag}} = 1 - S$$

If the stator Cu loss, friction, windage, core losses are neglected.

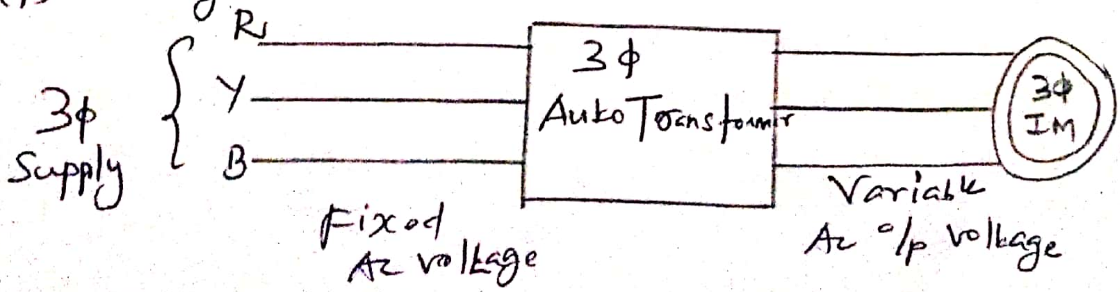
The terminal voltage cannot exceed rated value to prevent the damage of the winding insulation.

This method is suitable is only for speed control below the rated speed.

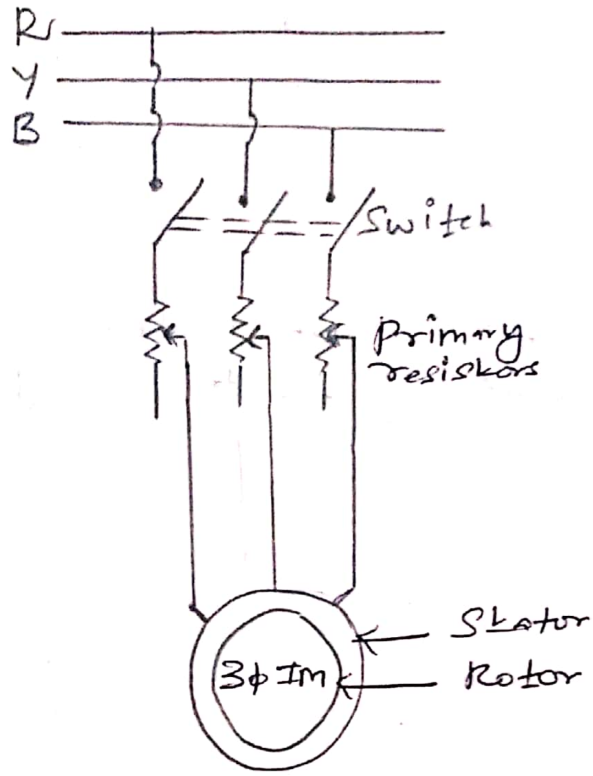
(i) Conventional Method
(ii) Solid state control method

Conventional Method:

(i) Using Autotransformer:

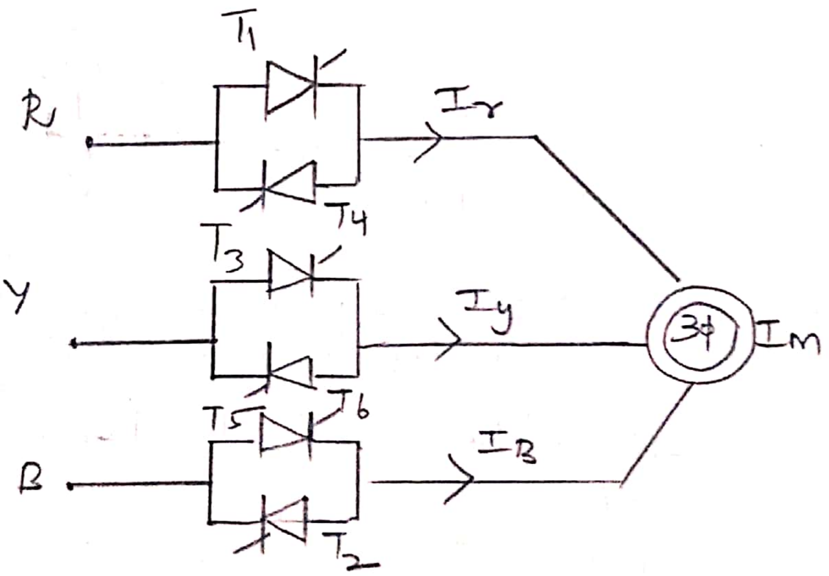


(ii) Primary resistor Connected in Series with Stator Windings



Solid State Speed Control Using 3ϕ AC voltage Controller

operation of [T_1T_6, T_1T_2, T_2T_3, T_3T_4, T_4T_5, T_5T_6]



$0 < \alpha < 60°$:

$$V_o = \sqrt{6}\, V_s \left\{ \frac{1}{\pi} \left[\frac{\pi}{6} - \frac{\alpha}{4} + \frac{\sin 2\alpha}{8} \right] \right\}^{1/2}$$

Adv:-

Control circuit is simple

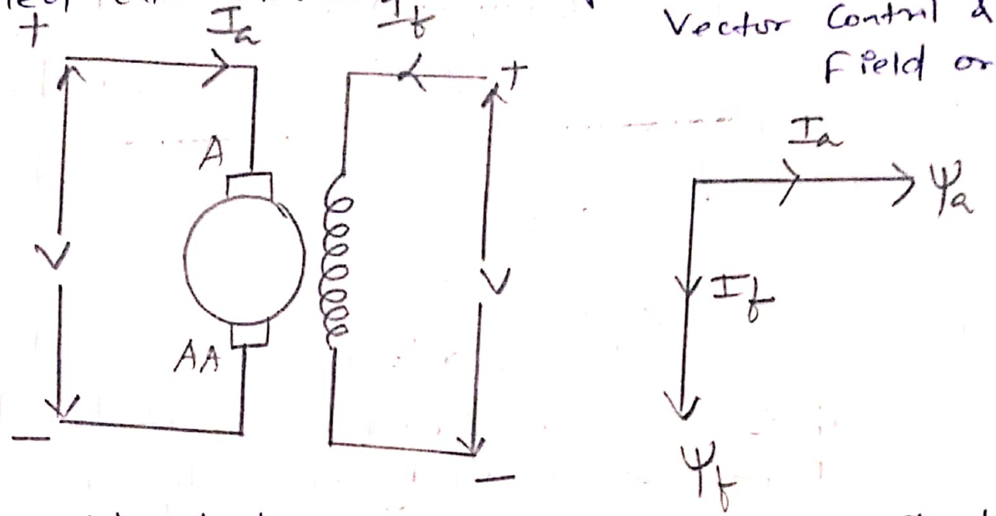
More Compact & less weight

It response time Quick

(i) PF ↓, Eff ↓, Tm ↓, poor starting Conditions.

Vector Controlled Induction Motor drives:

Induction Motor Control methods (Scalar Control) which produce satisfactory steady state performance. But this method gives poor dynamic response. An Induction Motor Exhibits Non linear multivariable and Highly Coupled characteristics. the problem can be solved by Vector Control & Field oriented Control.

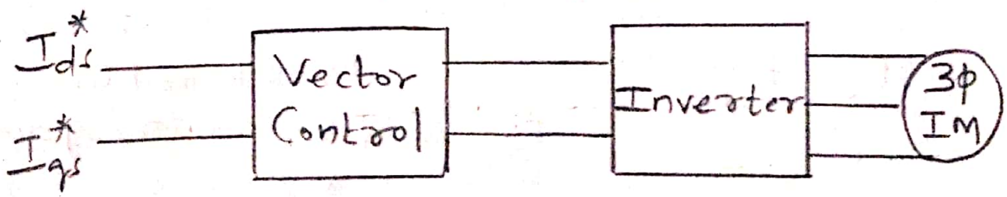


This method of Speed Control of Cage Induction Motor has High dynamic performance that is Comparable to the Characteristics of a Separately Excited DC Motor. Because of DC Machine-like performance, vector Control is also known as decoupling, orthogonal (or) transvector Control.

A Vector Control IM drive Can operate as a Separately Excited DC Motor drive

$$T_d = k_t I_a I_f$$

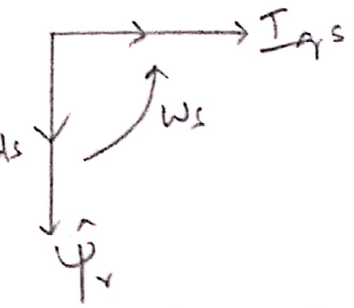
k_t - Torque Constant
I_a - Armature Current
I_f - Field Current



The Construction of DC Machine is such that the Field flux linkage ψ_f produced by I_f is perpendicular to the Armature Flux linkage ψ_a produced by I_a.

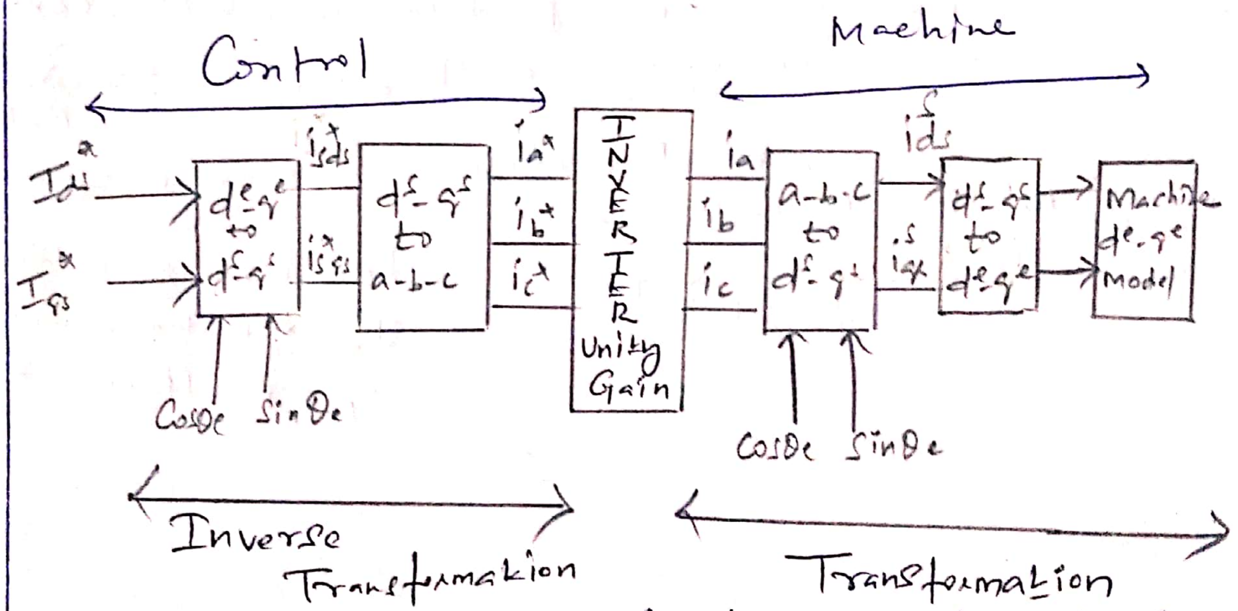
These space vectors which are stationary are orthogonal or decoupled in nature, Due to this a DC Motor has fast transient response. But an IM cannot give such fast transient response due to its inherent coupling problem

Ids - Field Component
Iqs - torque Component



$$T_d = K_m \hat{\varphi}_f I_f$$
$$= K_t I_{ds} I_{qs}$$

DC Machine - like performance can also be extended to an Induction Motor if the Machine is Controlled in a synchronously rotating reference frame (d^e-q^e) where sinusoidal variables appear as DC quantities in the steady state.

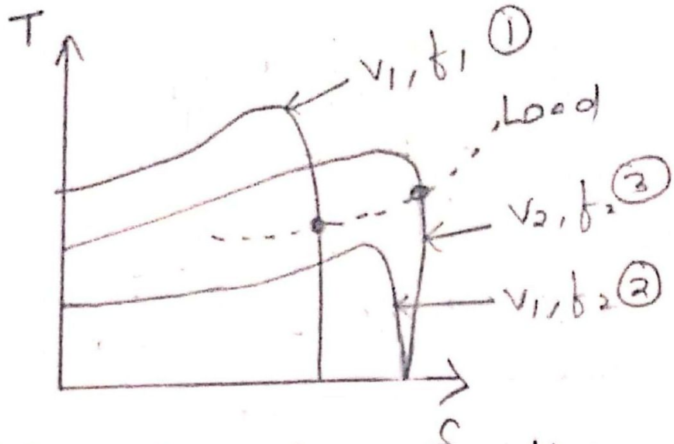


Inverter generates i_a, i_b & i_c in response to the corresponding commands i_a^*, i_b^*, i_c^* are converted to the synchronously rotating frame i_{ds} and i_{qs} these two synchronously rotating frame (i_{ds} and i_{qs}) unit vector components $\cos\theta_e$ and $\sin\theta_e$.

Transformation & Inverse Transformation including the Inverter ideally donot incorporate dynamics.

Voltage/Frequency Control:

V/f Control Method is one of the methods of 3ϕ Control of Induction Motor.

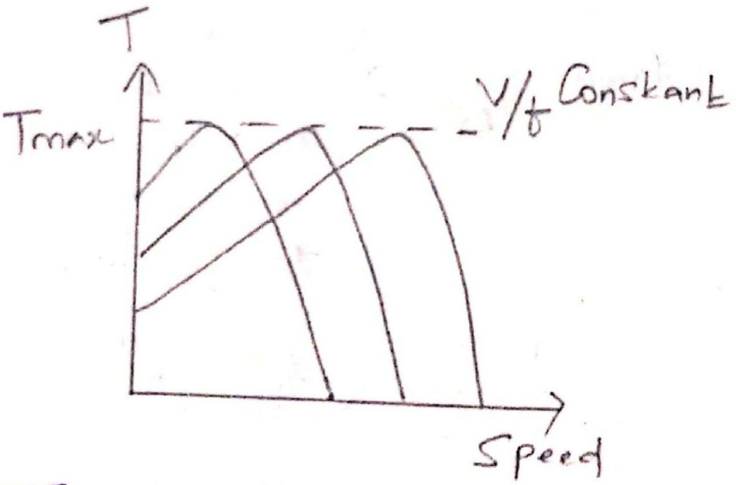


(i) f ↑ (i) V ↑
(ii) N ↑ (ii) T_{max} ↑
(iii) T_{max} ↓

(i) We Consider the reference voltage V_1 and frequency f_1 for Fan type Load (curve 1)

(ii) If we Increase the Frequency of the Supply f_2(new) while keeping the voltage V_1 Unchanged, N ↑, T_{max} ↓ (curve 2)

(iii) f_2 new value, V Increases (V_2 new), T_{max} ↑ (curve 3)



$$T_{max} = k\left(\frac{V}{f}\right)^2$$

Torque Equation

$$T = \frac{3}{\omega_s} \frac{V^2}{\left(R_s + \frac{R_r'}{s}\right)^2 + (X_s + X_r')^2} \cdot \frac{R_r'}{s}$$

$$T = \frac{3}{k\omega_s} \frac{k^2 V^2}{\left(R_s + \frac{R_r'}{s}\right)^2 + k^2 (X_s + X_r')^2} \cdot \frac{R_r'}{s}$$

$$T_{max} = \frac{3}{2kw_s} \frac{k^2V^2}{R_s \pm \sqrt{R_s^2 + k^2(X_s + X_r')^2}}$$

$$I_{st} = \frac{V}{\sqrt{(R_s + R_r')^2 + (X_s + X_r')^2}}$$

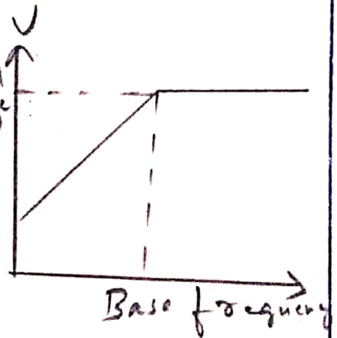
PF for V/f method $= \dfrac{R_s + R_r'/s}{\sqrt{(R_s + R_r'/s)^2 + k^2(X_s + X_r')^2}}$

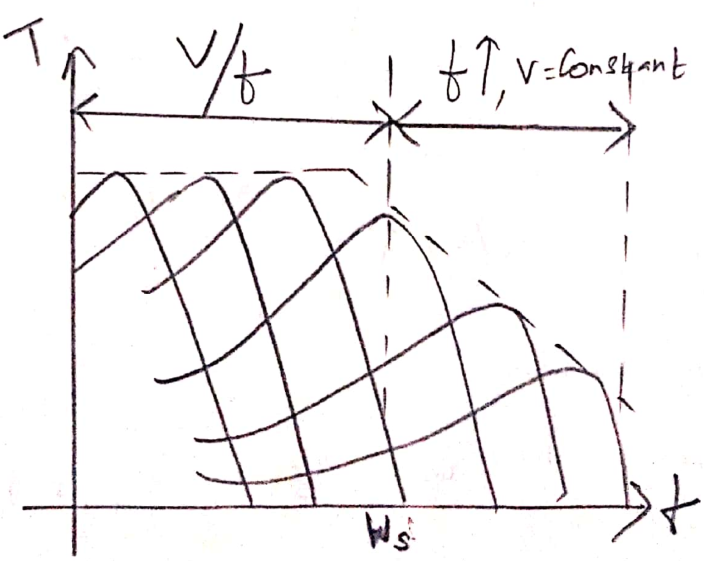
Speed - torque characteristics of V/f method

$$T_{max} = \frac{\left(\frac{k}{f}\right) V^2}{R_s \pm \sqrt{R_s^2 + 4\pi^2 f^2 (L_s + L_r')^2}}$$

$$T_{max} = \pm \frac{k \left(V/f\right)^2}{2\pi (L_s + L_r')}$$

From the Above Equation, Constant V/f ratio, motor develops Constant Maximum torque except at low Speeds ∴ (Motor operates in Constant torque Mode)

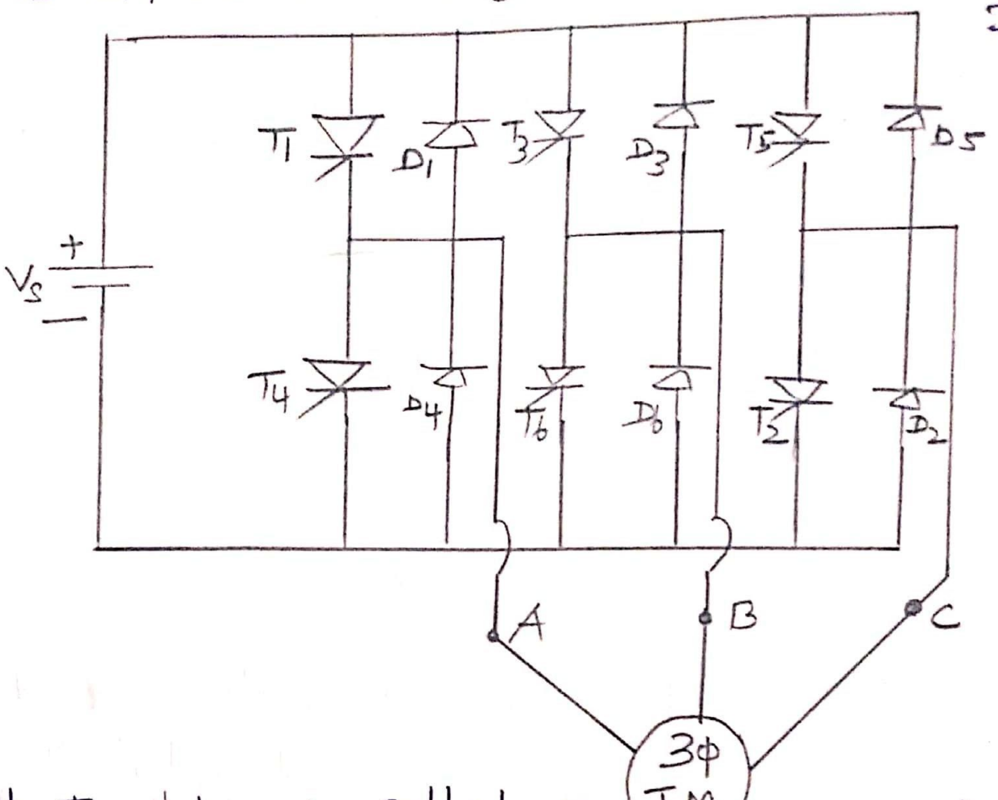




VSI fed 3φ Induction Motor drive:

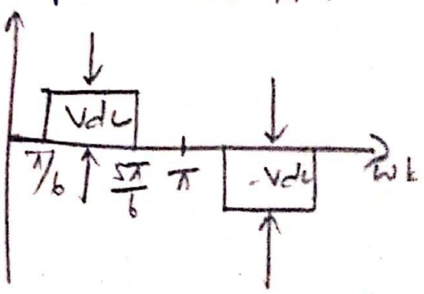
An Inverter is defined as, Converter that Converts DC to AC, If the VSI, viewed from Load side, Input Voltage should be constant (MOSFET is Used low power App)

IGBT, IGCT, GTO Used High power Appl.



3φ Inverter is called Six Step Inverter, A step defined as a change in the firing from one power Semi Conductor Switch (IGBT) To next power SemiConductor IGBT in proper Sequence.

A Stepped wave Inverter (or) Pulse width Modulated Inverter Used.



Interval	Conducting device
I	$T_1 T_6 T_5$
II	$T_1 T_6 T_2$
III	$T_1 T_3 T_2$
IV	$T_4 T_3 T_2$
V	$T_4 T_3 T_5$
VI	$T_4 T_6 T_2$

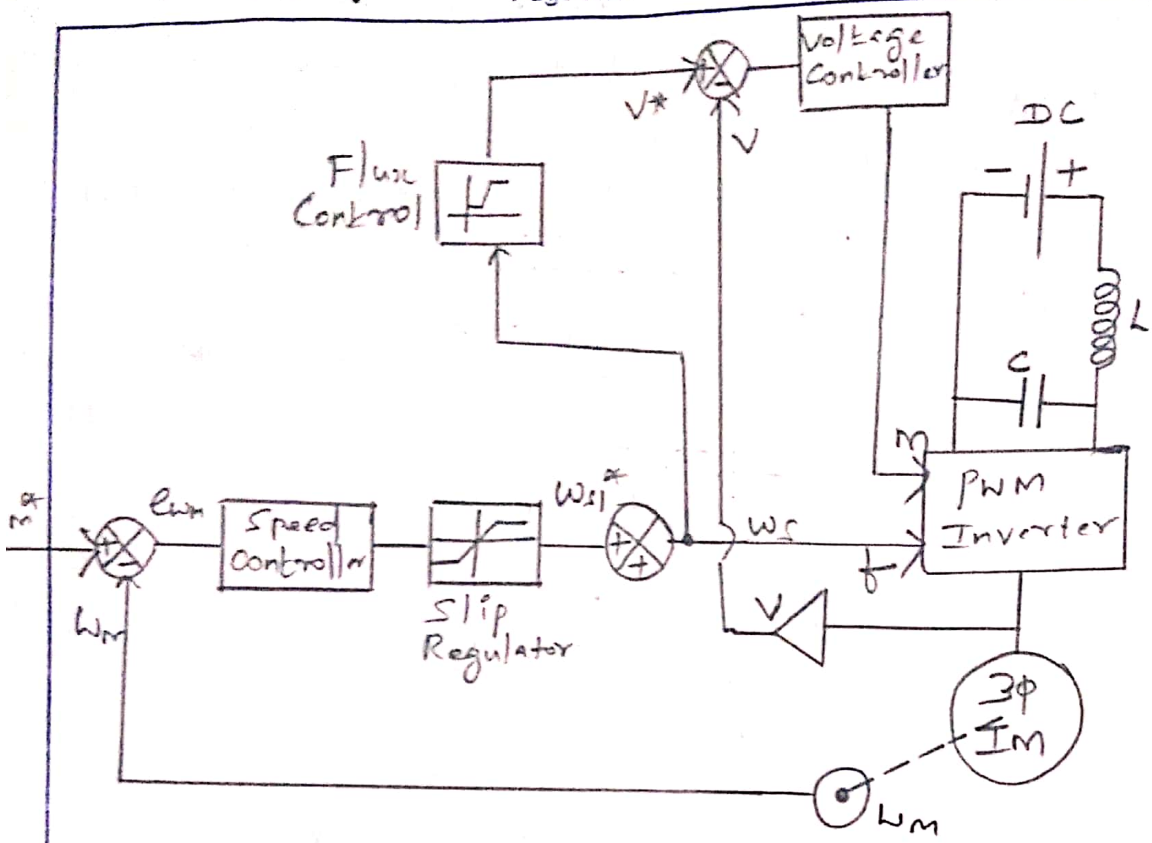
Line voltage : $(V_s, 0, -V_s)$

phase voltage : $V_s/3 \left(\frac{2V_s}{3}\right)$

Multiple PWM → $M = A_r/A_c$, $N_p = \frac{1/2f_r}{1/f_c} = \frac{f_c}{2f_r} = \frac{m_f}{2}$

Sinusoidal PWM → $M = A_r/A_c \left(d_m/_n\right)$

Closed loop Control VSI :-



Actual Speed ω_m Sensed from Speed Sensor. It is Compared with the reference Speed ω_m^*. The Speed Error signal processed through PI Controller & Slip Regulator gives Slip speed Command ω_{sl}^*.

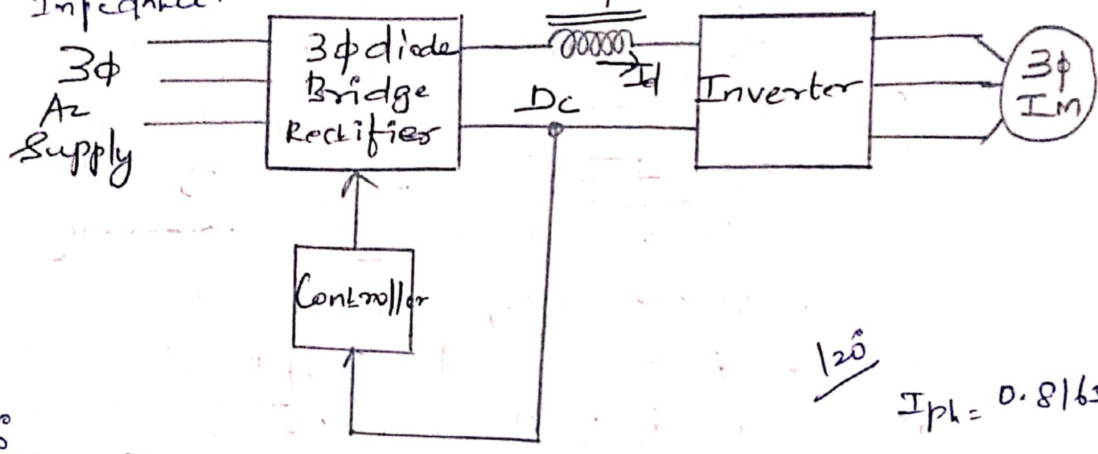
Synchronous Speed ω_s is obtained by Adding ω_m and ω_{sl}^*, PI Controller is mainly used to get Good Steady State Accuracy and a Attenuate Noise. It determines Inverter frequency f and The frequency f is fed to flux Control block. the reference V* Constant flux operation.

PWM Inverter o/p voltage and Frequency Can by Controlled by Modulation Index. m & f.

The drive Accelerates at the Maximum permissible PWM Inverter Current, producing Maximum Available torque, Until the Speed error is reduced a very Small value, Now the drive system Settles at a Slip Speed for which the Motor torque equals to the Load torque.

3ϕ CSI fed Induction Motor drive :

In CSI, the Input Current is maintained Constant, but it can be Adjusted. A large value of Inductor is Connected in Series with voltage source, It acts as a Constant current Source. The o/p voltage waveform depends on the Load Impedance.



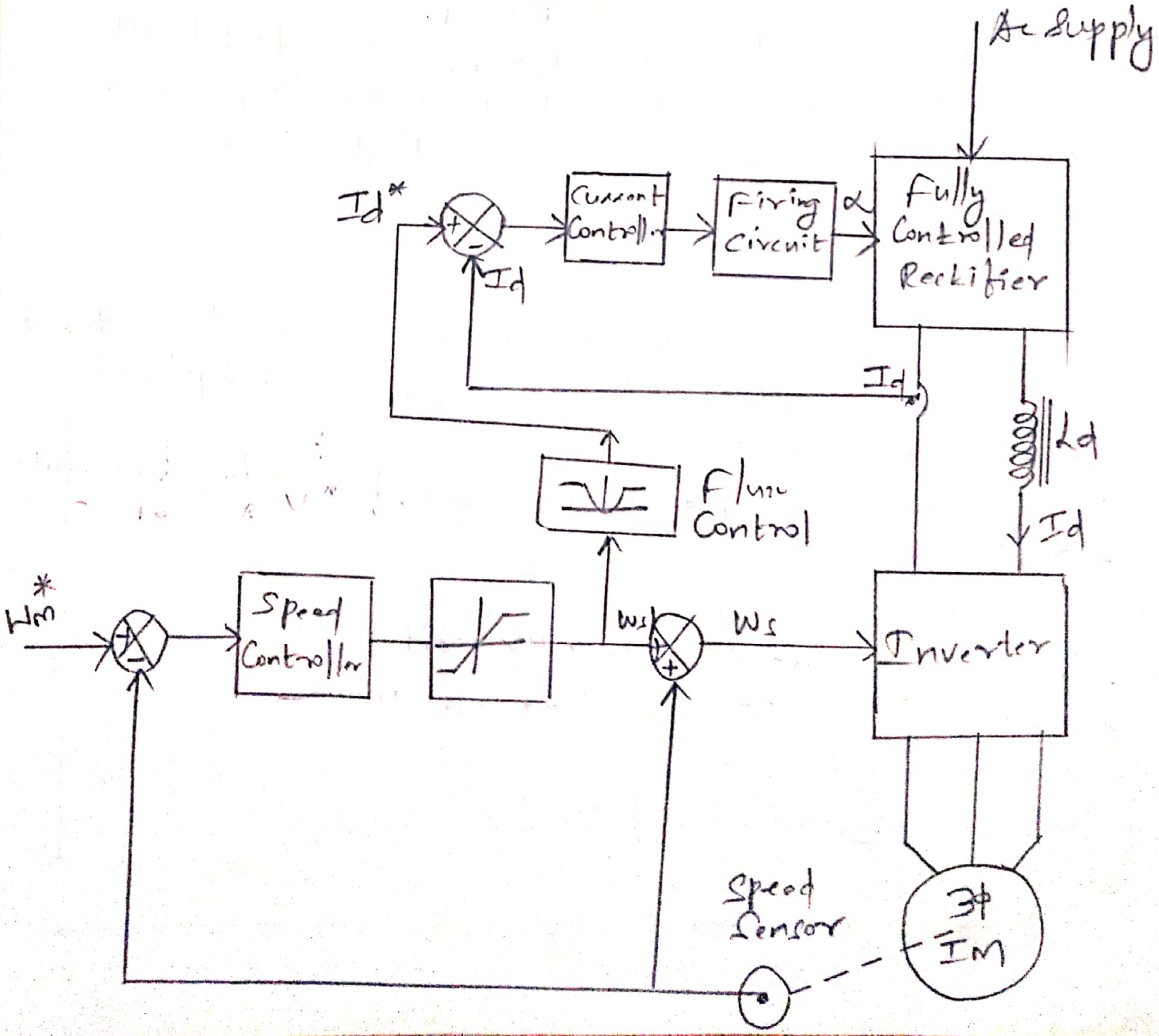
120°

$I_{ph} = 0.8165 I = I_L$

180°

$I_{ph}(rms) = I\sqrt{1/2} = 0.707 I$

$I_L(rms) = I\sqrt{\frac{1}{2}} = 0.707 I \quad \therefore I_L = I_{ph}$



Closed loop Speed Control of CSI fed drive

Actual Speed ω_m is sensed by Speed sensor, It's Compared with the reference Speed ω_m^*.

The Speed error Signal is processed through a PI Controller (Speed Controller) and Slip Regulator. The Slip regulator gives the Slip Speed Command ω_{sl}^*. The Synchronous Speed is obtained by adding ω_m^* and ω_{sl}^*. It determines Inverter frequency. The Slip Speed Command ω_{sl}^* is processed through Flux Control. The Flux Control block produces a reference current I_d^*. The dc link current current I_d is sensed and given to the Comparator.

The Comparator compares two signals, Its given to the current Controller and firing circuit. The o/p determines the Firing angle α. Its fed to the Fully Controlled rectifier. The closed loop Current control Adjusts the DC link current I_d to maintain Constant flux.

Adv:.

(i) Conduction of two devices in the same leg due Commutation failure doesn't lead to sharp rise current through devices.

(ii) It has Inherent protection against a Short circuit across Motor terminals.

D. Adv:.

It has Large Inductors and Capacitors

It has higher cost, weight and volume

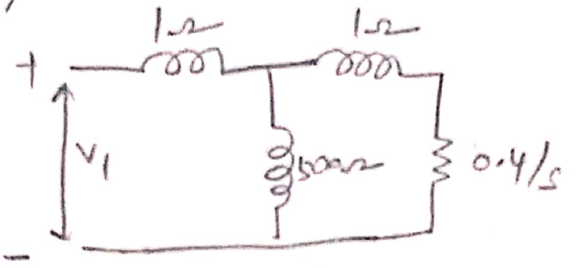
Lower Speed Range

Slower dynamic response.

A 400V, 4 pole, 50Hz, 3φ, Star Connected Induction Motor has $r_1 = 0$, $X_1 = X_2 = 1\Omega$, $r_2 = 0.4\Omega$, $X_m = 500\Omega$, The IM is fed from

(1) Constant voltage Source of 231V per φ

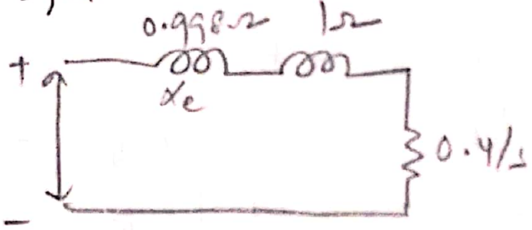
(2) Constant Current Source of 28A. For Both Case calculate the slip at which Maximum torque occurs and the Starting & Maximum Torque.



$$X_e = \frac{(1 \times 500)}{501} = 0.998\Omega$$

$$V_e = \frac{(231 \times 500)}{501} = 230.5V$$

Thevenins Equ:



$$S_m = \frac{r_2}{x_2 + x_e} = \frac{0.4}{1.998}$$

$$S_m = 0.2$$

For Constant operation

$$S_m = \frac{r_2}{X_2 + X_m} = \frac{0.4}{1500} = 0.00079$$

$$\omega_s = 4\pi f/P = 50\pi \text{ rad/sec}$$

$$T_{st} = \frac{3}{\omega_s} \times I_{2f}^2 r_2 = \frac{3}{50\pi} \times \frac{V_e^2 \times r_2}{r_2^2 + (X_e + X_2)^2}$$

$$T_{st} = 99.43 NM$$

$$T_{max} = \frac{3}{\omega_s} \times \frac{V^2}{2(X_e + X_2)} = \frac{3}{50\pi} \times \frac{(230.5)^2}{2 \times 1.9804}$$

$$T_{max} = 256.18 NM$$

For Constant i/p voltage

$T_{st} = 5.965$ Nm / $T_{max} = 3735.8$ Nm

A 440V, 50Hz, 6 pole Y connected slip ring IM has the following parameters:

$V = 440$, $f = 50Hz$, $P = 6$, $R_s = 0.5\Omega$, $R_r' = 0.4\Omega$, $X_s = X_r' = 1.2\Omega$

$X_m = 50\Omega$

Stator to rotor turns ratio = 3.5

Rotor to stator turns ratio = 0.2857

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

$$S_m = \frac{R_e + R_r'}{\sqrt{R_s^2 + (X_s + X_r')^2}} = \frac{R_e + 0.4}{\sqrt{(0.5)^2 + (2.4)^2}}$$

$$R_e = 2.45 S_m - 0.4$$

$$R_e = 0.5R(1-\alpha) \, 1/a^2$$

$$R_e = 6.125(1-\alpha)R$$

$$6.125(1-\alpha)R = 2.45 S_m - 0.4 \quad \text{— (1)}$$

Maximum torque at $S_m = 1$ for $\alpha = 0$

$$6.125R = (2.45 \times 1) - 0.4$$

$$R = 0.3347\Omega$$

$$\therefore S_m = \frac{N_s - N}{N_s} \quad \text{Using equation (1)}$$

$$\alpha = 1.195 \times 10^{-3} N$$