UNIT - IV

CONTROL OF INDUCTION MOTOR

Equivalent Circuit of Induction motor: refer to rotor side:

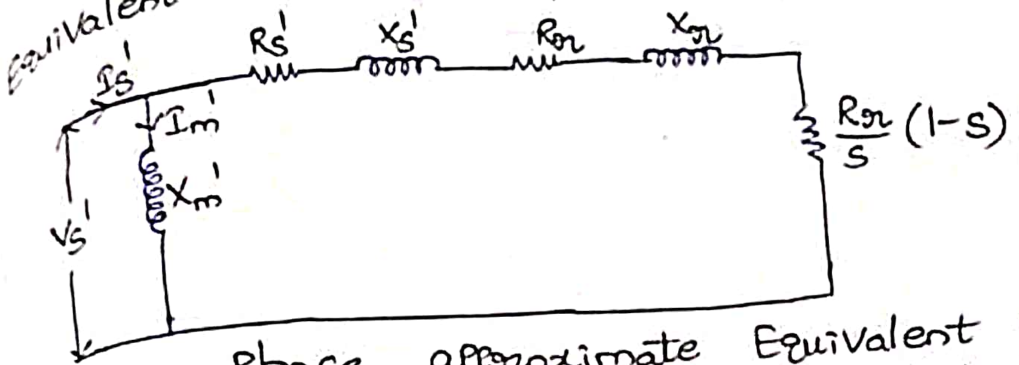


Fig. Per Phase approximate Equivalent circuit of induction motor

In the circuit,

V_s' - Per Phase supply Voltage referred to rotor in 'V'.

X_m' - Per Phase magnetising reactance referred to rotor in ohms

R_s' - Per Phase stator winding resistance referred to rotor in ohms.

X_s' - Per Phase stator winding reactance referred to rotor in ohms.

$R_s' = \left(\frac{N_s}{N_r}\right)^2 R_s$ and $X_s' = \left(\frac{N_s}{N_r}\right)^2 X_s$

N_r = Rotor speed

N_s = Stator speed.

R_r - Per Phase rotor winding resistance in ohms.

X_r - Per Phase rotor winding reactance in ohms.

Equivalent Circuit of Induction motor refer to stator side:

As it is not Possible to do analysis with mechanical components of stator and rotor, we are going to represent these quantities in terms of electrical quantities. i.e., in terms of resistance and reactanc

∴

Steady state representation of equivalent circuit of induction motor refer to stator side is shown below.

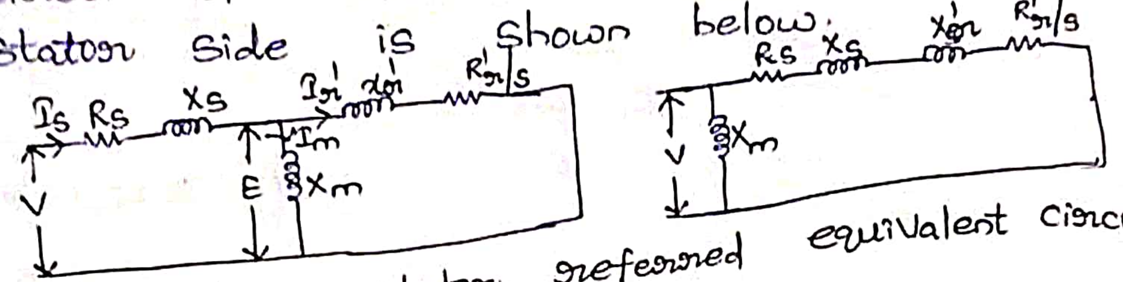


Fig. Per phase stator referred equivalent circuit of an induction motor.

From above circuit,

V = Per phase supply voltage referred to stator in Volts.

X_m - Per phase magnetizing reactance referred to stator in ohms.

R_s - Per phase stator winding resistance in ohms.

X_s - Per phase stator winding reactance in ohms.

X_r' - Per phase rotor winding reactance refer to stator in ohms.

R_r' - Per phase rotor winding resistance refer to stator in ohms.

S - slip

$$S = \frac{N_s - N_r}{N_s} \rightarrow ① \Rightarrow \frac{\omega_s - \omega}{\omega_s} \times 100 = \% S$$

where N_s = synchronous speed = $\frac{120f}{P}$ rpm = $\frac{4\pi f}{P}$ rad/sec → ②

N_r = Rotor speed in rpm.

$$N_r = N_s(1-S) \rightarrow ③$$

From figure,

Rotor current is given by

$$I_r' = \frac{V}{\left(R_s + \frac{R_r'}{s}\right) + j(X_s + X_r')} \rightarrow ④$$

Power transferred to rotor or air-gap Power is given by

$$P_g = 3 I_r'^2 \frac{R_r'}{S} \rightarrow ⑤$$

Rotor copper loss is

$$P_{cu} = 3 I_r'^2 R_r' \rightarrow ⑥$$

Electrical Power converted into mechanical Power

$$P_m = P_g - P_{cu} = 3 I_{2r}'^2 R_{2r}' \left(\frac{1-s}{s}\right) \rightarrow (7)$$

Torque developed by motor $= \frac{P_m}{N_{2r}} \rightarrow (8)$

$$\therefore T = \frac{3}{\omega_s} \cdot I_{2r}'^2 \cdot \frac{R_{2r}'}{s} \rightarrow (9)$$

Substitute eq (7) in eq (4), we get

$$T = \frac{3}{\omega_s} \frac{V^2 \frac{R_{2r}'}{s}}{\left(R_s + \frac{R_{2r}'}{s}\right)^2 + (X_s + X_{2r}')^2} \rightarrow (10)$$

From eq (5) and eq (9), we get

$$T = \frac{P_g}{N_s} \rightarrow (11)$$

motor output torque at shaft is obtained by deducting friction windage and core-loss torques from developed torque.

Developed torque is function of slip only. Differentiate eq (10) w.r.to 's' and equate to zero gives slip for maximum torque.

$$\therefore S_{max} = \pm \frac{R_{2r}'}{\sqrt{R_s^2 + (X_s + X_{2r}')^2}} \rightarrow (12)$$

Substitute eq (12) in eq (10), we get

$$T_{max} = \frac{3}{2\omega_s} \frac{V^2}{\sqrt{R_s \pm (R_s^2 + (X_s + X_{2r}')^2}}$$

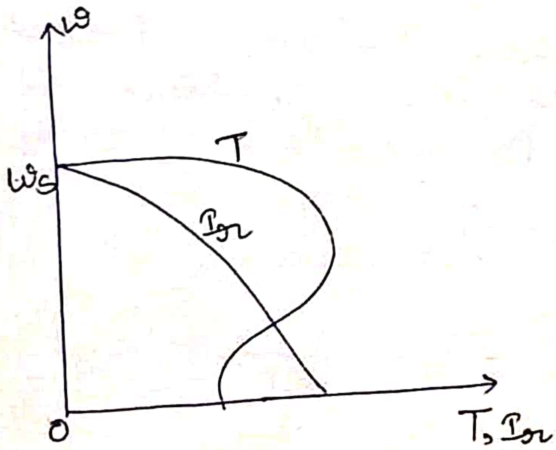


Fig. Speed-torque and speed-current characteristics of an induction motor.

Torque speed characteristics of three phase induction motors.

Since the speed of induction motor is constant irrespective of load fluctuations, it has flat speed-torque characteristics. The most of loads in industry or on power system are three phase induction motors. The expression for torque developed by three phase induction motor is

$$\text{Torque} = K \cdot \frac{sE_{2s}^2 R_{2s}}{R_{2s}^2 + (sX_{2s})^2} \text{ N-m} \rightarrow ①$$

Torque-slip characteristics of three phase induction motor can be explained as follows.

1. when rotor speed is equal to synchronous speed i.e $N_r = N_s$, then slip(s) = 0 and from eq①, torque is zero.

2. when load on motor increases, speed decreases and slip increases. The value of slip is very small compared to R_2 and $s \cdot X_{2s}$ is neglected for constant rotor emf E_2.

$$\text{Torque} = K \cdot \frac{sR_{2s}}{R_{2s}^2}$$

Hence for low value of slip, torque-slip curve represented as straight line.

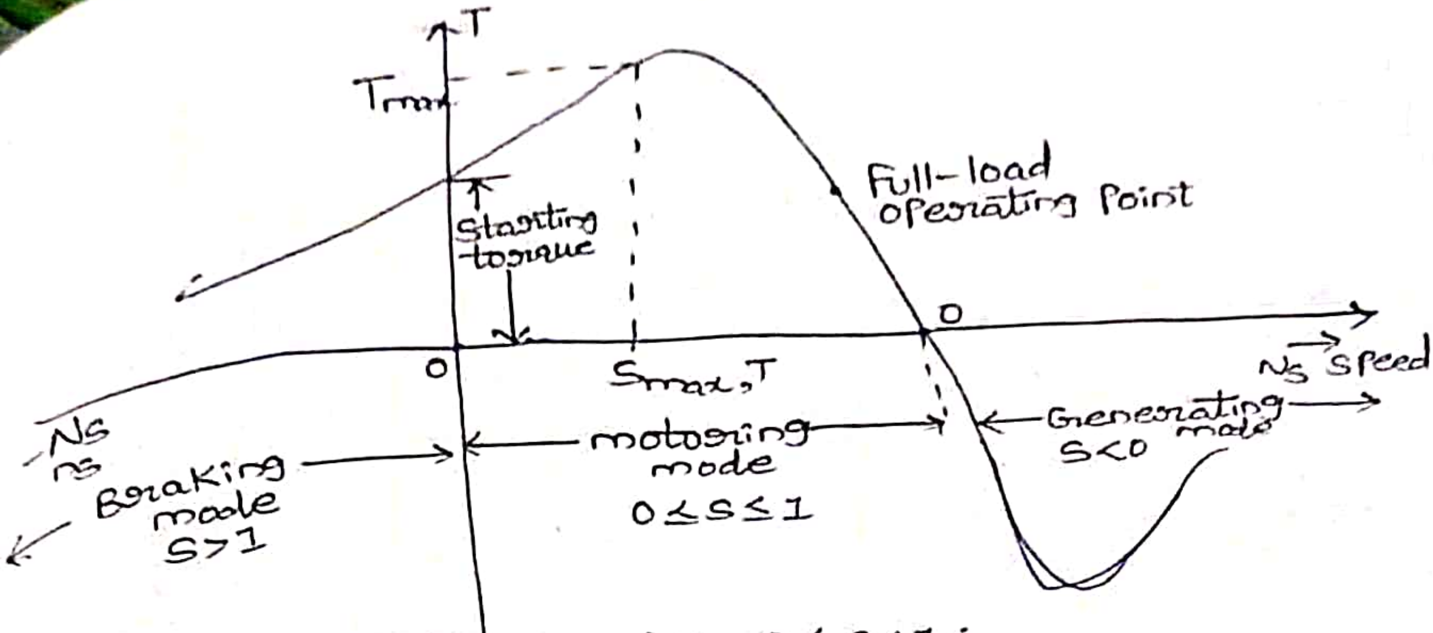
As load increase further, speed decreases and slip increases. This result in increase in torque and reaches to maximum when

$$\text{slip} = \frac{R_{2s}}{X_{2s}}$$

3. with increase in load beyond T_{max}, slip increases further. Now value of sX_2 is more compare to R_2 and R_2 is neglected so

From eq①, $T = K \cdot \frac{s}{s^2 X_{2s}^2}$

$$T \propto \frac{1}{\text{slip}}$$



when s is positive i.e $0 \le s \le 1$: motor speed lies between zero and synchronous speed and direction of rotation of rotor is same as stator field. The power is positive and machine acts as motor.

when s is negative i.e., $s<0$: The rotor rotates in same direction as stator field but at higher speed than synchronous speed. since rotor speed is more than synchronous speed, machine acts as generator.

when s is positive i.e., $s>1$: The rotor rotate in opposite direction to direction of rotation of stator field. This indicate that rotor is decelerating, it is called electorical brake.

$s = 1$ is called starting torque (T_{st})

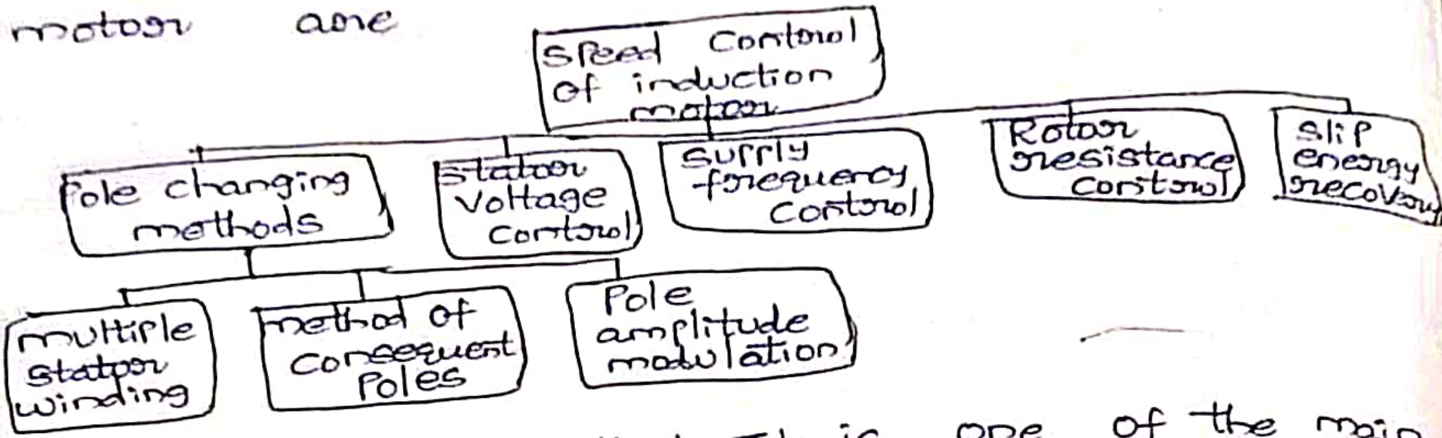
∴ $s<1$, motoring

$s>1$, Braking

$s<0$, Generating

Slip Range	Slip sign	Speed
$s<1$	Positive	Positive
$s>1$	Positive	Negative
$s<0$	Negative	Positive.
$s=1$		

Speed control methods of Induction motor:
Different speed control methods of induction motor are



1. Pole changing method: It is one of the main methods of speed control of induction motor. This method of controlling speed by pole changing is mainly used for squirrel cage motor only because it automatically develops a number of poles which is equal to poles of stator winding. The number of stator poles can be changed by three methods.

They are:

(i) multiple stator windings.
(ii) method of consequent poles.
(iii) Pole amplitude modulation (PAM)

(i) multiple stator windings:

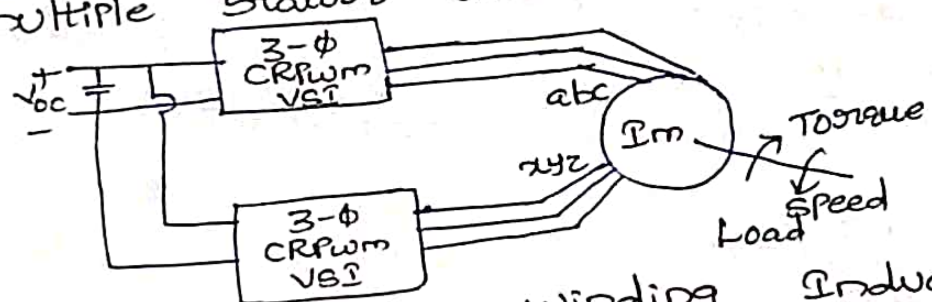


Fig. Dual stator winding Induction motor

In this method, two windings are provided on stator which are wound on two different number of poles. One winding is energized one at a time.

Let us consider that motor has two windings for 6 and 4 poles. For frequency of 50Hz, synchronous speed is given by

$$N_S = \omega_S = \frac{120f}{P} = 1000 \text{ for 6 Poles}$$

$$= 1500 \text{ for 4 Poles.}$$

This method is less efficient and more c

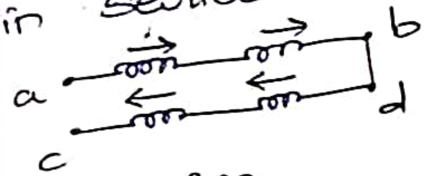
(ii) Method of Consequent Poles: In this method, a single stator winding is divided into few coil groups. The terminals of all these groups are brought out.

By simply changing the coil connections, number of poles can be changed. In practice, stator windings are divided only in two coil groups. The number of poles can be changed in ratio 2:1.

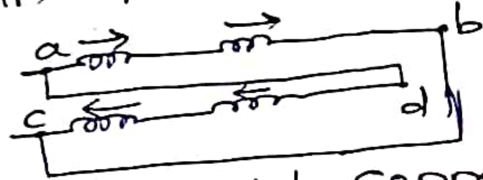
Fig. connection for 4 Poles.

Above figure shows single phase of stator winding which consist of four coils. The coils are divided into two groups named as a-b and c-d.

Group a-b consist of odd number of coils i.e 1,3 whereas group c-d consist of even number of coils i.e., 2,4. Two coils are connected in series. The terminals a, b, c, d are taken out as shown in above figure. The coils are carrying current in given directions by connecting coil groups either in series or in parallel as shown below.



Series



Parallel connection.

There are total four poles. At 50Hz, these poles give $N_s = 1500$ rpm.

If current through coils of group a-b is reversed as shown. All coils will produce north poles as follows.

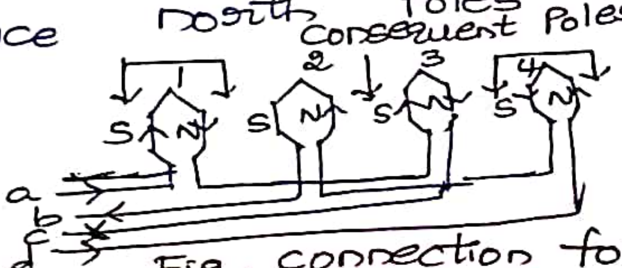


Fig. connection for 8 Poles

The flux of Poles group should be passed through given space between pole group to complete the magnetic path. Thus a magnetic pole of opposite polarity is induced. These induced poles are known as consequent poles. Hence machine has 8 poles which gives $N_S = 750$ rpm at 50Hz i.e half of speed compare to previous case.

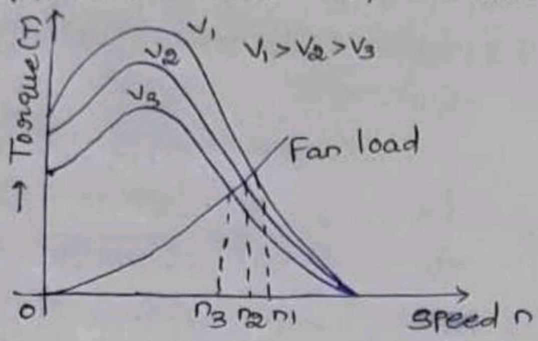
This method can be extended to all three phases of induction motor. By choosing combination of series and parallel connections between coil groups of each phase.

Also star or delta connections between phase speed change can be obtained with constant torque and constant power operation or variable torque operation.

(iii) Pole Amplitude modulation Technique: It is a flexible method of pole changing which can be used in applications where speed ratios other than 2:1 are required.

The motors designed for speed changing based on poled amplitude modulation scheme are known as PAM motors.

2. stator Voltage control method (or) Variable Voltage characteristics of induction motor:



By changing supply voltage, speed of induction motor changes.
stator Voltage control is method used to control the speed of induction motor.
Torque developed in an induction motor is given by

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

From above expression, it is clear that, torque is proportional to square of voltage
i.e., $T \propto V^2$
∴ By varying supply voltage, speed can be controlled $T \propto sV^2$. Voltage is varied until the torque required by load is developed at desired speed.
∵ $T \propto V^2 \propto I^2$
Hence to reduce the speed for same value of current, value of voltage is reduced and as a result torque developed by motor is reduced. This method is suitable for applications where load torque decrease with speed.
Ex: Fan load.
This method gives speed control only below rated speed as operation of voltages higher than rated voltages is not admissible.
It is suitable where intermittent operation of drive is require and also for fan and pump drives, as in fan and pump drives load torque varies square of speed.

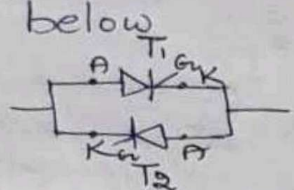
$$T \propto N^2$$

These type of drives require low torque at lower speeds. This condition can be obtained by applying lower voltage without exceeding motor current.

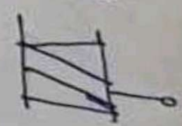
This method is simple and easy but it is rarely used because a large change in voltage required for small change in speed.

Ac voltage controllers: These are thyristor based devices which converts fixed ac to variable ac at constant frequency.

Ac voltage controllers are represented by two thyristors connected in anti parallel as shown below



It is applicable for both single phase and three phase i.e., for low and high power applications.

For single phase we prefer triode ac terminal i.e., TRIAC represented by 

It is preferred in low power applications.

Advantages:
1. High efficiency
2. Fast response
3. Compact in size
4. Flexibility in control.

Dis Advantage:
Harmonics appear at lower voltage due to natural commutation.

Applications:
1. Industrial pumps, lighting control
2. Speed control of AC motors.
3. Fans.
4. Transformer tap changing.

Classification of AC Voltage Controllers: These are classified as two types:

1. Half wave ACVC (Uni-directional)
2. Full wave AC Voltage Controller (Bi-directional)

1. Half wave AC Voltage controller:

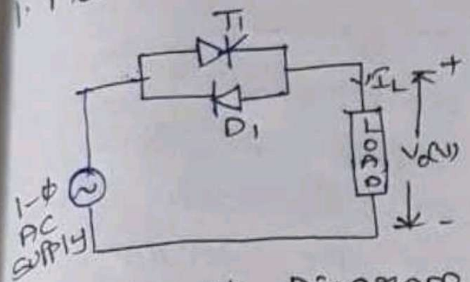


Fig. Circuit Diagram

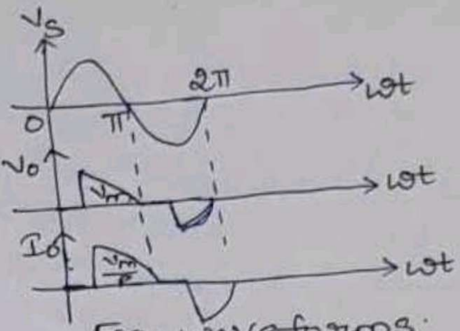


Fig. waveforms.

Total number of thyristors are one and diode is one in this Controller.

Circuit diagram and waveforms of single phase half wave ac Voltage controller is shown in above figures.

During Positive half cycle, T_1 is in forward bias and triggered at an angle of α, then current start flowing through load and Voltage will appear across load. At π, T_1 comes to off state due to natural commutation.

During negative half cycle, D_1 is in forward bias and starts conducting, current start flowing through load and Voltage will appear across load. At 2π, D_1 comes to off state due to reverse bias.

In this manner fixed Voltage is converted to Variable Voltage at constant frequency.

2. Single Phase Full wave AC Voltage Controller

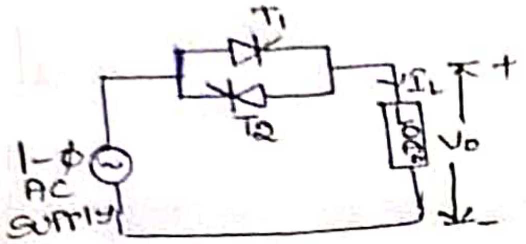


Fig. Circuit Diagram

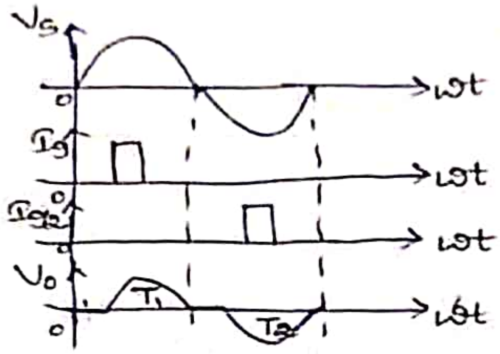


Fig. waveforms

Total number of thyristors in this Controller are two. Circuit diagram and waveforms of 1-ϕ full wave AC Voltage Controller is shown above.

During Positive half cycle, T_1 is in ON state and triggered at an angle α, current start flowing through load and Voltage will appear across load. At π, T_1 Comes to off state due to natural commutation.

During negative half cycle, T_2 is in ON state and triggered at an angle of $\pi+\alpha$, current start flowing through load and Voltage will appear across load. At 2π, T_2 Comes to off state due to natural Commutation.

Here fixed ac Voltage is Converted to Variable ac Voltage at constant frequency.

∴ Average output Voltage, $V_o = \frac{1}{2\pi}\int_{\alpha}^{2\pi} V_m \sin\omega t \cdot d\omega t$

$$= \frac{V_m}{2\pi}\left[-\cos\omega t\right]_{\alpha}^{2\pi}$$

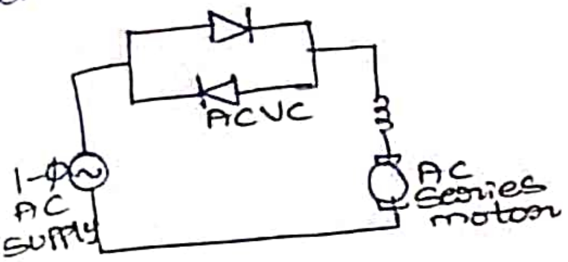
$$= \frac{V_m}{2\pi}\left[-\cos 2\pi + \cos\alpha\right]$$

$$V_o = \frac{V_m}{2\pi}\left[\cos\alpha - 1\right]$$

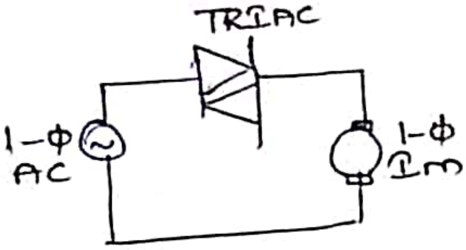
Stator Voltage Control of induction motor by using ACVC:

The stator voltage is controlled in speed control systems by means of power electronic controller. There are two methods of control namely ON-OFF control and phase control.

Now a days thyristor voltage controller method is preferred for varying voltage. For a single phase supply, two thyristors are connected in anti parallel as shown below



(a)



(b)

Domestic fan motors, which are single phase are controlled using TRIAC as shown in fig.(b)

Speed control is obtained by varying firing angle of TRIAC. These controllers are known as solid state fan regulators. As solid state regulators are more compact and efficient compare to conventional over variable regulator, they are mostly preferred.

For Induction motor:

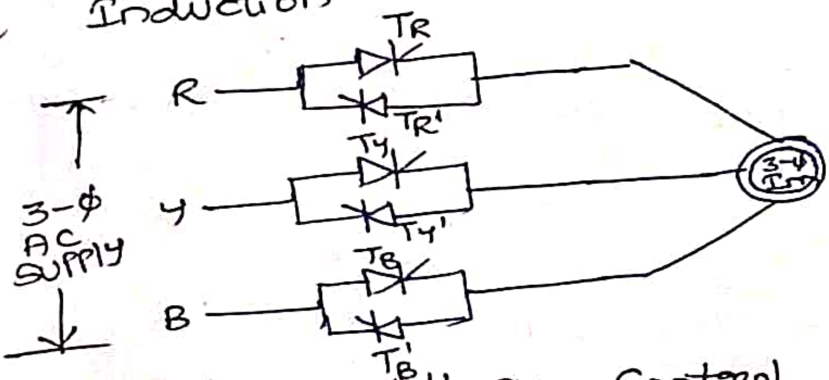


Fig. stator Voltage Control of IM using ACVC.

The above figure shows AC Voltage Controller for star connected stator. It consists of six SCR's. Here pair of thyristor are connected in antiparallel between line and motor in each phase.

Each Pair of thyristors controls the Voltage of Phase to which they are connected.

Speed control is obtained by changing (or) Varying the conduction Period of thyristors and hence Voltage Varies, torque also Varies since $T \propto V^2$.

Due to this reason Voltage Varied then speed at which torque is going to Produce also Varied by Varying the firing angle of thyristors.

Various Configurations (or) Connections of AC Voltage Controllers:

Advantages of ACVC in stator Voltage control in Induction motor:

1. control circuit is Very simple.
2. more compact in size and less weight.
3. Response time is fast.
4. There is considerable savings in energy and hence it is economical method.

Various types of Solid State three Phase AC Voltage controllers are:

1. Half wave AC Voltage controller
2. Full wave AC Voltage controller

Based on stator side winding connection, these are

1. Star connected ACVC to star connected stator
2. Delta connected ACVC to Delta connected stator winding.

1. Star connected ACVC to Star Connected stator winding:

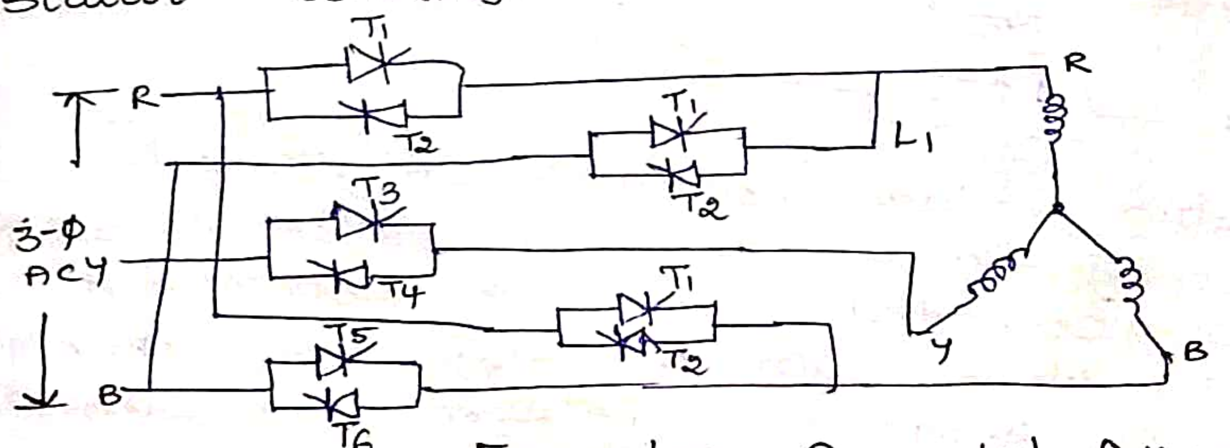


Fig. star connected full wave ACVC

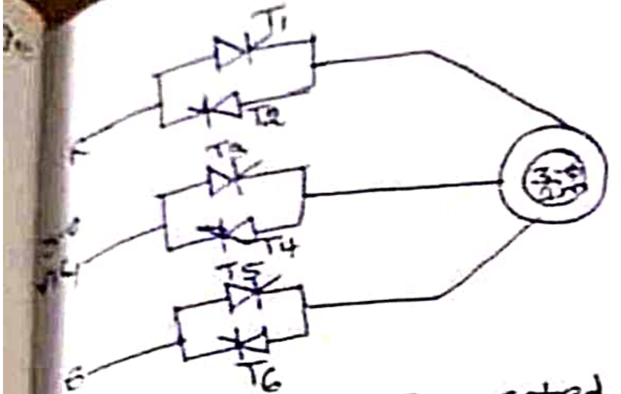


Fig (a) 3-ϕ star connected full wave ACVC to star connected stator.

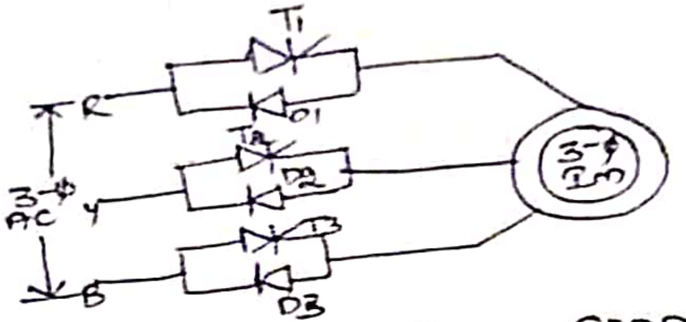


Fig (b) 3-ϕ star connected Half wave ACVC to star connected stator

2. Delta connected ACVC to Delta connected stator winding:

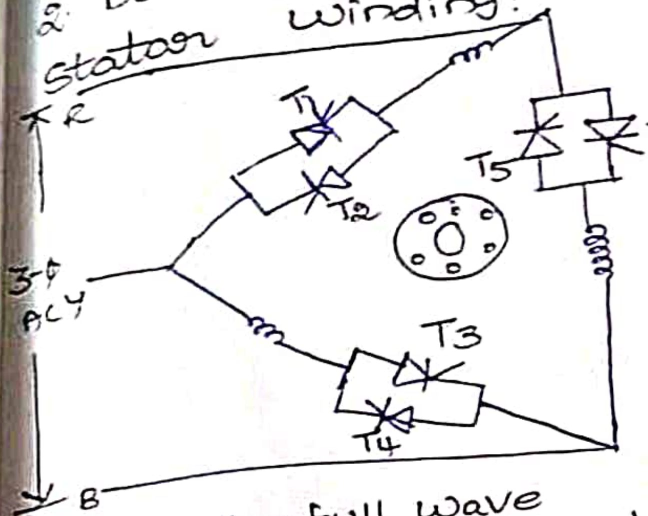


Fig (c) 3-ϕ full wave ACVC to Delta connected stator

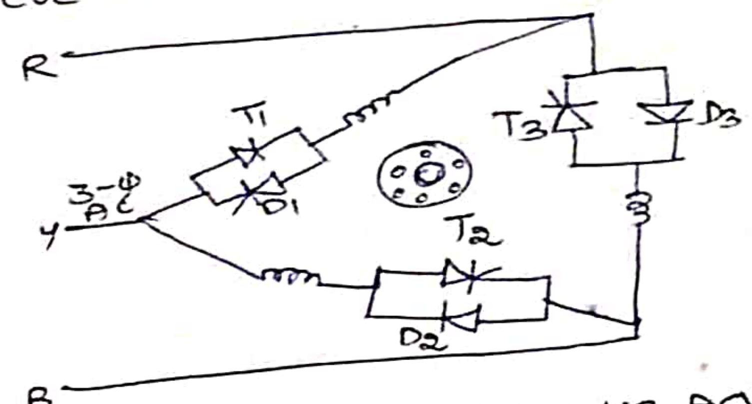


Fig (d). 3-ϕ Half wave ACVC to Delta connected stator.

Connection which can function similar as three groups of 1-ϕ controllers, is shown in fig (c) and fig (d) three single phase converters supply their loads are connected in delta. Each controller supplies its own load.

The advantage of delta connection is that the reduction of current of device.

For low power ratings, TRIAC is preferred.

Problems:

1. A 440V, three phase, 50Hz, 4 pole, 1456 rpm delta connected induction motor has the following parameters referred to stator side. $R_s = 2\Omega$, $R_r = 2\Omega$, $X_s = 3\Omega$, $X_r = 4\Omega$. When driving a fan load at rated voltage, it runs at rated speed. The motor speed is controlled by stator voltage control.

Determine motor terminal Voltage, V[illegible] and torque at 1300 rpm.

<u>Sol</u> Given data,

$V_L = V_{ph} = 400V$ since delta connected.

Frequency, $F = 50Hz$.

No. of Poles, $P = 4$.

Speed $N_1 = 1456$ rpm

$R_s = 2\Omega$

$R_r = 2\Omega$

$X_s = 3\Omega$

$X_r = 4\Omega$

$N_2 = 1300$ rpm.

we know that,

$T \propto V^2 \Rightarrow T = KV^2$

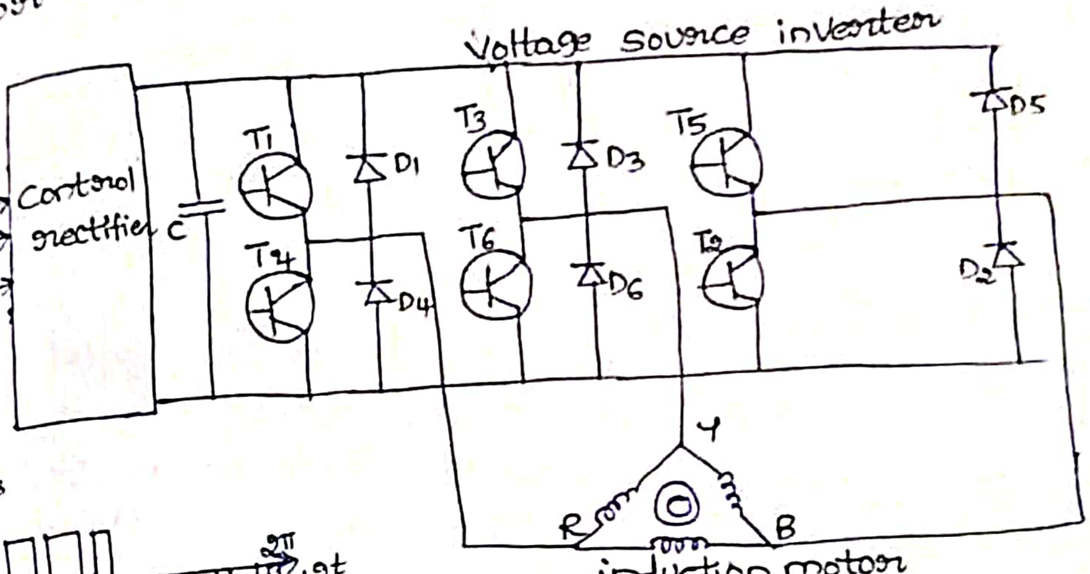
For fan load, $V \propto N \Rightarrow V = N$

$N = N_s (1-S)$

$T = K(1-S)^2$

$S =$

Variable frequency control of induction motor by Voltage source inverter:



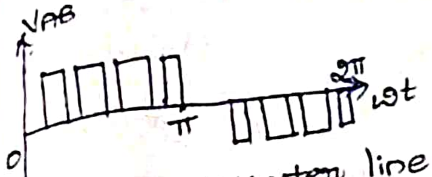
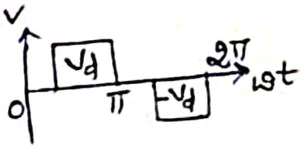


Fig. PWM inverter line Voltage waveform



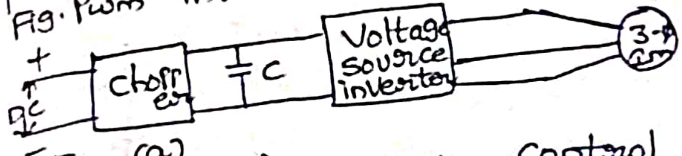


Fig. (a)

Variable frequency control is a method which is used to control speed of induction motor. The synchronous speed and therefore, the speed of motor can be controlled by varying the supply frequency. The synchronous speed of an induction motor is given by

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

The emf induced in stator of induction motor is given by

$$E = 4.44\,\phi_m f\, T_{ph} \cdot K_c \cdot K_d.$$

i.e. $E \propto f$.

Hence if supply frequency is change, the induced emf will also change to maintain same air gap flux. The terminal Voltage is equal to induced emf if stator Voltage drop is neglected.

In order to minimize the losses and to avoid saturation, the motor is operated at rated air gap flux. This condition is obtained by Varying terminal Voltage with frequency so as to maintain $\frac{V}{f}$ ratio Constant. This type of control is known as Constant Volts Per Hertz $\therefore \frac{V}{f} = K\phi$

Thus the speed control of an induction motor using variable frequency supply requires a variable voltage power source.

Variable frequency supply is obtained by following converters.

(i) Voltage source inverter

(ii) Current source inverter

(iii) cyclo converter

Inverter converts fixed DC to fixed or variable AC with variable frequency.

Cyclo converter converts fixed AC voltage at variable frequency to variable AC voltage.

Variable frequency control allows good running and transient performance to be obtained from cage induction motor.

Cyclo converter controlled induction motor drive is suitable only for large power drives and to get lower speeds.

$\frac{V}{F}$ method of speed control:

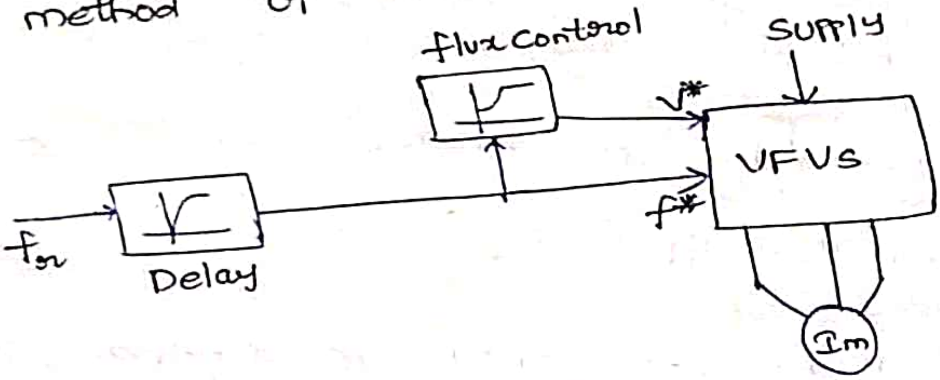


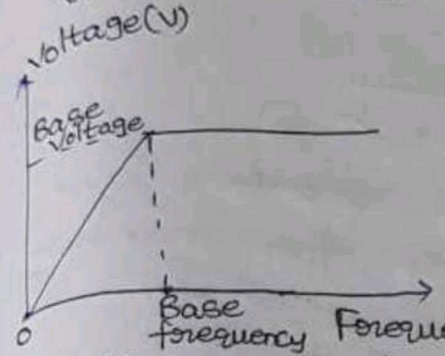
Fig. Variable frequency control

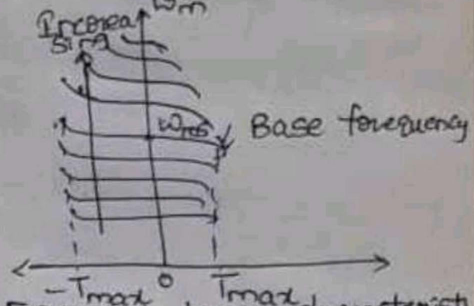
Above figure shows block diagram of variable frequency control of induction motor drive scheme. motor is fed from variable frequency variable voltage source VFVS. V* and f* are voltage and frequency commands for VFVS.

Flux control block produces a voltage command V* for VFVS in order maintain relationship between V* and f*.

Reference frequency f is changed to control speed. A delay circuit is introduced between f_s and f_r so that even when f_t is changed by large amount, f_r will change only slowly so that motor speed can track changes.

VFVS can be a VSI or cyclo converter





Fig(b) Speed - torque characteristics

Fig. Voltage and frequency variation in VSI fed induction motor

Variation in terminal Voltage with frequency is shown in above figure.

Voltage is kept constant above base speed. Below base speed $\frac{V}{f}$ is kept constant, except at lower frequencies where $\frac{V}{f}$ ratio is increased to keep maximum torque constant.

Conclusions:

Constant Voltage - Above rated frequency

Variable Voltage and constant $\frac{V}{f}$ - Below rated frequency.

Fig (b) shows speed torque curves for both motoring and braking operations. The curves shows that speed control and braking operation are available from nearly zero speed to above synchronous speed.

A given torque is obtained with lower current when the operation at any frequency is restricted between synchronous speed and maximum torque point, both for motoring and braking operations.

Therefore motor operation for each frequency is restricted between synchronous speed and maximum torque point as shown in fig(b).

Torque expression of Induction motor is given by

$$T = \frac{3}{\omega_s} \frac{V^2 \frac{R'_r}{s}}{\left(R_s+\frac{R'_r}{s}\right)^2+(X_s+X'_r)^2} \rightarrow ①$$

when $s=1$, starting torque is given by

$$T_{st} = \frac{3}{\omega_s} \cdot \frac{V^2 R'_r}{(R_s+R'_r)^2+(X_s+X'_r)^2}$$

Differentiate above equation w.r.to 's' and equate to zero gives slip for maximum torque.

$$S_{max} = \pm \frac{R'_r}{\sqrt{R_s^2+(X_s+X'_r)^2}} \rightarrow ②$$

Substitute eq② in eq①, we get maximum torque, $T_{max} = \frac{3}{2\omega_s}\left[\frac{V^2}{R_s \pm \sqrt{R_s^2+(X_s+X'_r)^2}}\right]$ → ③

where ω_s = speed in rad/sec

T_{max} = maximum torque.

Let us consider, $a = \frac{f}{f_{rated}}$

where f = actual (or) operating frequency

f_{rated} = rated frequency

a = per unit frequency

Case I: when $a<1$: Operation below rated frequency:

when actual frequency is less than rated frequency then per unit frequency is less than 1.

Ex: $f = 40Hz$, $f_{rated} = 50Hz$ then $a = \frac{40}{50} = 0.8 < 1$

In this case, parameters become

$V = a \cdot V$

$\omega_s = a \cdot \omega_s$

$X_s = a \cdot X_s$

$X_r = a \cdot X_r$, substitute these values in eq③,① we get

$$T = \frac{3}{a \cdot \omega_s} \cdot \frac{V^2 \frac{R'_r}{s}}{\left(R_s + \frac{R'_r}{s}\right)^2 + (aX_s + aX'_r)^2}$$

$$T_{st} = \frac{3}{a \cdot \omega_s} \cdot \frac{V^2 \cdot R'_r}{(R_s + R'_r)^2 + (aX_s + aX'_r)^2}$$

$$T_{max} = \frac{3}{2a \cdot \omega_s} \frac{V^2}{R_s \pm \sqrt{R_s^2 + (a \cdot X_s + a X'_r)^2}}$$

+ for motoring
− for braking

Case II: $a > 1$ − operation above rated frequency:

when actual frequency is greater than rated frequency then per unit frequency is greater than 1.

$f > f_{rated} \Rightarrow a > 1$.

Ex: $f = 60Hz$, $f_{rated} = 50Hz$ then $a = \frac{60}{50} = 1.2 > 1$

Problems:

1. A three phase, star connected, 50Hz, four pole induction motor has following parameters refer to stator side ; $R_s = R'_r = 0.024\Omega$, $X_s = X'_r = 0.12\Omega$. motor is controlled by $\frac{V}{f}$ for an operating frequency of 12Hz. Calculate Breakdown torque as ratio of its value at rated frequency for both motoring and braking.

Sol Given data,

$f_{rated} = 50Hz$

No. of Poles, $P = 4$.

$R_s = R'_r = 0.024\Omega$

$X_s = X'_r = 0.12\Omega$

$f = 12Hz$

Now per unit frequency is given by

$$a = \frac{f}{f_{rated}} = \frac{12}{50} = 0.24$$

$a < 1$, then

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

Variable frequency control of Induction motor using VSI:

The circuit diagram, waveform for the Variable frequency control of induction motor using VSI was shown in fig (a) in the previous page.

Total number of transistor and diodes in this arrangement were six

[Note: we can also draw thyristors in place of transistors]

Here Diodes will acts as switches for the purpose of commutation.

Thyristors are triggered in sequence according to their numbering.

Voltage source inverter control of induction motor allows variable frequency supply to be obtained from dc supply.

It consists of voltage source inverter i.e. the combination of transistors and diodes which provide variable frequency control to induction motor.

The terminal voltage is kept constant when the load is varying. Output voltage is square wave, hence this inverter is also named as variable frequency or square wave inverter.

Transistors are switched in sequence with time difference of $\frac{T}{6}$ and each transistor is kept ON for duration $\frac{T}{2}$ where

T- Time period for one cycle.

Frequency of inverter is varied by varying time period and output voltage is varied by varying dc input voltage.

When supply is dc, variable input is obtained by chopper between dc supply and inverter and for ac supply, rectifier is connected.

Capacitor is used to filter out the harmonics in dc link voltage.

Different configurations using dc and ac supply to provide input to inverter is as shown below:

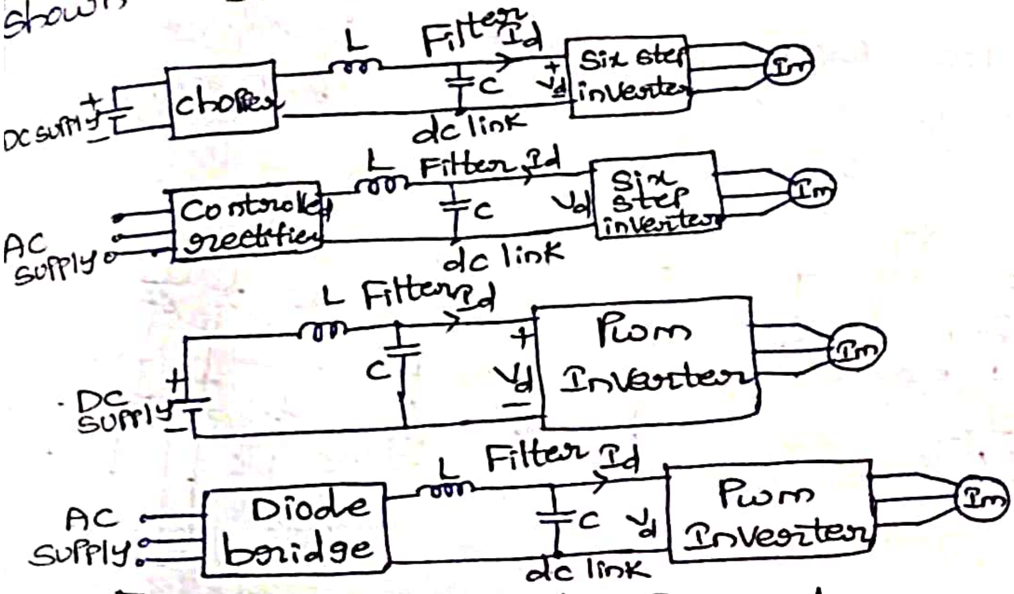


Fig. VSI controlled Im drives

Inverter output Voltage in both line and Phase are given by fouries series as shown below

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

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

Rms Value of fundamental Phase Voltage

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

Torque for given speed can be calculated by Considering only fundamental component

The main drawback of stepped wave inverter is larger harmonics of low frequency in output voltage, ripples, DC ripples and harmonics.

Harmonics, losses are reduced and smooth motion is obtained when inverter is operated as PWM inverter.

output waveforms is shown in figure.

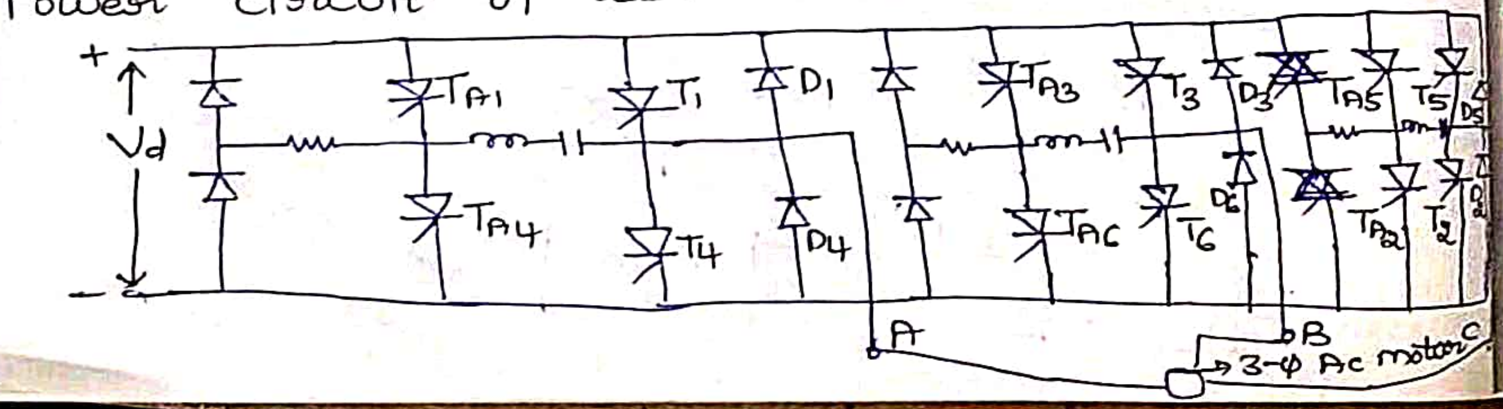
Fundamental component in output Phase Voltage of PWM inverter operating with Sinusoidal PWM is given by

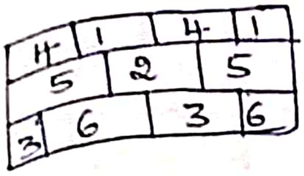
$$V = m \cdot \frac{V_d}{2\sqrt{2}}$$

where m = modulation index $= \frac{f_r}{f_c} = \frac{V_r}{V_c}$.

Current harmonics which Produce Pulsating torque are reduced by connecting higher leakage reactance.

Power circuit of VSI:





At any instant three thyristors are in conduction i.e two from upper and one from lower side or vice-versa.

Each thyristor is triggered at angle of 60°. Period of conduction of each thyristor is 180°.

Voltage source inverter is used for high and medium power applications, PWM used for low and medium power applications.

Closed loop operation of Induction motor drives:

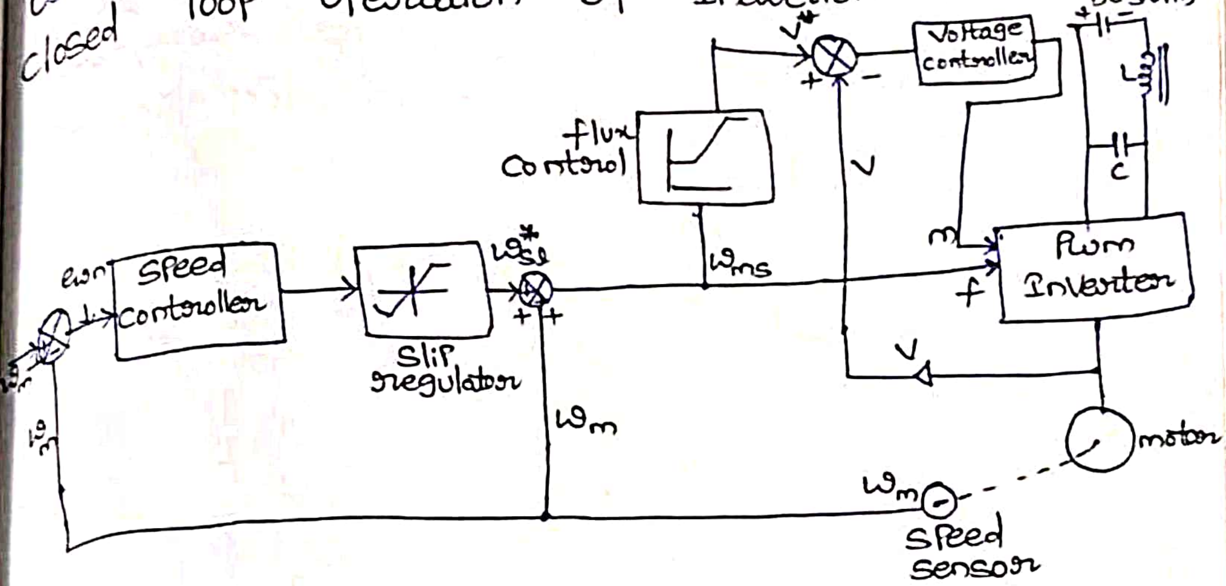


fig. closed loop slip controlled PWM inverter drive

Above figure shows closed loop slip controlled PWM inverter drive.

It employs inner slip-speed loop with a slip regulator and outer speed loop.

Since for a given current, slip speed has a fixed value, the slip speed loop also functions as inner current loop. Further it also ensures that motor operation always occurs on portion of speed torque curve between synchronous speed and the speed at maximum torque for all frequencies, thus ensuring high torque to current ratio. The drive uses a PWM inverter fed from dc source, which has capability for regenerative braking and four quadrant operation.

The drive scheme is however applicable to VSI or cyclo converter drive having regenerative or dynamic braking capability. The drive operation is explained below.

The speed error is processed through a PI controller and slip regulator. PI controller is used to get good steady state accuracy, to attenuate noise. The slip regulator sets the slip speed command ω_{sl}^*, whose maximum value is limited to limit inverter current to permissible value. The synchronous speed, obtained by adding actual speed ω_m and slip speed ω_{sl}, whose maximum value determines inverter frequency. The reference signal for closed loop control