whose maximum value deter

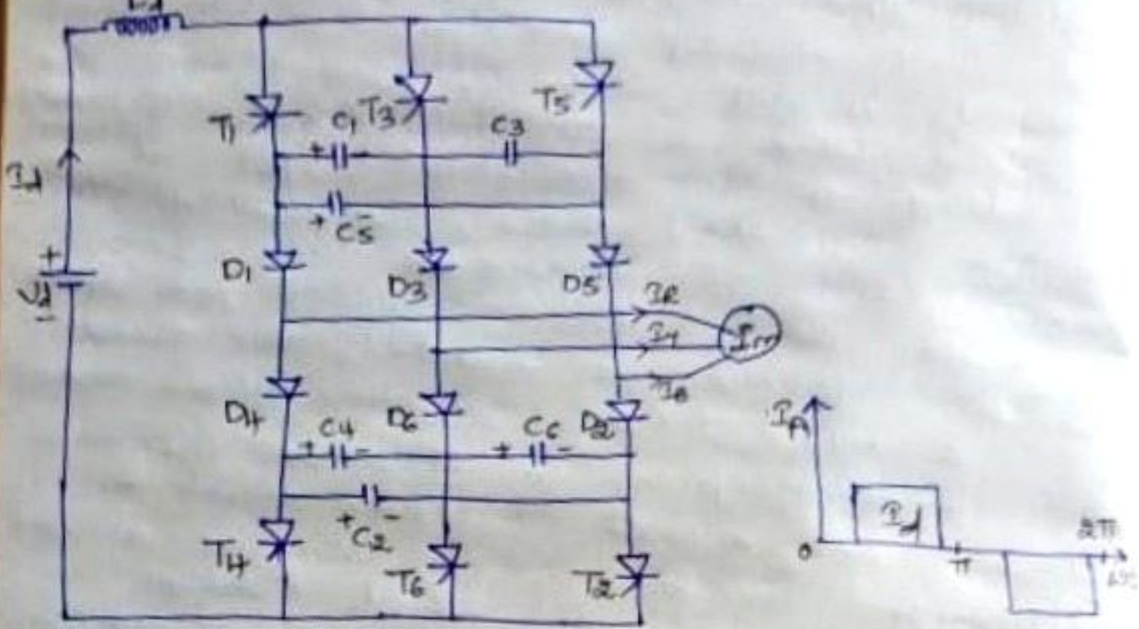
The reference signal for closed loop control of induction motor drives of machine terminal voltage V* is generated from frequency f using function generator. It ensures nearly constant flux operation upto base speed and operation at constant terminal voltage above base speed.

A step increase in speed command ω_m produces positive speed error, then drive accelerates at permissible inverter current producing maximum available torque, until speed error is reduced to small value. The drive finally settles at slip speed for which motor torque balances load torque.

A step decrease in speed command produces negative speed error, then slip speed command is set at maximum negative value. The drive decelerates under regenerative braking torque until speed error reduce to small value. Now the operation shifts to motoring and drive settles at slip speed for which motor torque equals to load torque.

The drive has fast response because speed error is corrected at maxi

Circuit diagram for Variable frequency Control of induction motor using CSI is shown below.



Fig(a) CSI Fed induction motor drive

The current source inverter converts input direct current to alternating current. In CSI, input current remains constant but this input current is adjustable. Current source is also called current fed inverter. Output Voltage of inverter is independent of load. The magnitude and nature of load current depends on nature of load impedance.

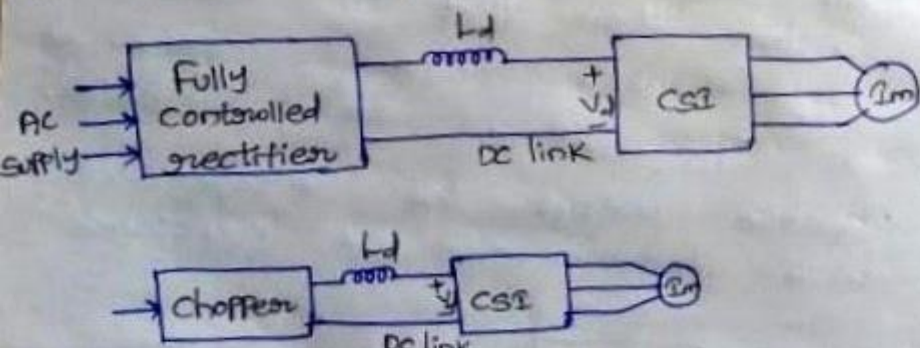


Fig. CSI Fed induction motor drives.

Current expression is given by

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

available torque. Direct control of slip assures stable operation under all operating conditions.

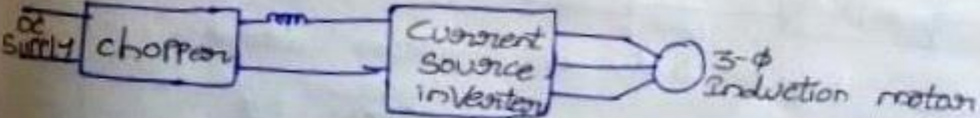
For operation beyond base speed, the slip speed limit of slip regulator must be increased linearly with frequency until the breakdown value is reached. This is achieved by adding to slip regulator output an additional slip speed signal, proportional to frequency and of appropriate sign. For frequencies higher than frequency for which breakdown torque is reached, slip speed limit is kept fixed near breakdown value.

When fast response is required maximum slip can be allowed to be equal to S_m, because induction motors can be allowed to carry several times rated current during transient operations of short duration. The inverter and its front end converter are built using semiconductor devices whose transient and steady-state current rating are same. Then ratings of inverter and front end converter will have to be chosen several time the motor current rating. This will substantially increase drive cost.

When fast transient response is not required, current ratings of inverter and front end converter can be chosen to be marginally higher than that of motor.

Speed control of variable frequency control of induction motor using current source inverter:

Current source means the voltage source in series with large value of inductance.



A thyristor current source inverter fed induction motor is shown in fig(a)

Total numbers of thyristors, diodes and capacitors in this arrangement are six.

Thyristors are triggered in sequence according to their numbering.

Diodes $D_1 - D_6$, Capacitor $C_1 - C_6$ provide commutation of thyristors $T_1 - T_6$, which are fixed with phase difference of 60°. It also shows nature of output current waveform.

Inverter behaves as current source due to presence of large value of inductance L_d in dc link.

(or)

Variable frequency of induction motor obtained using CSI. Inductor is connected in series with input.

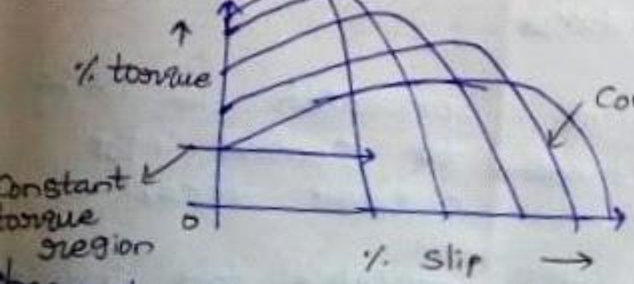
By varying thyristors conduction periods and inverter, DC current is converted to three phase current source.

Stator current is function of rotor frequency, by keeping flux as constant, the magnitude of stator is controlled by rotor frequency.

When supply is AC, controlled rectifier converts it into variable DC, if supply is DC, chopper manages circuit.

Thyristors are triggered at an angle of 180°. Diodes are used for preventing discharge of capacitors through load.

Characteristics



Characteristics are drawn by taking percentage slip on X-axis and % torque on Y-axis

From characteristics,
For below rated speed, motor operates at constant flux mode
For above rated speed, motor operates at field weakening mode
For speed equal to rated speed, the voltage reaches its rated value and there is no further increase of speed.

Differences between voltage source inverter and current source inverter

S.No.	Voltage source Inverter	Current Source Inverter
1.	In VSI, input voltage is maintained constant	In CSI, Input Currents constant but adjustable
2.	output voltages does not depend on load	Amplitude of output current is constant but adjustable.
3.	magnitude of output current and its waveform depends upon nature of load impedance.	magnitude of output voltage and its waveform depends upon nature of load impedance
4.	It requires feed back diodes.	It does not requires feedback diodes.
5.	Commutation circuit is complex.	Commutation circuit is simple.
6.	A large capacitor is connected at input side of VSI.	Large inductor is connected at input side of CSI
7.	Input voltage source should be short circuited due to misfiring of switching semi conductor device.	There is no such effects in CSI.
8.	~~Free~~ There is not necessary any converter in VSI.	Converter is necessary to control input current in CSI.
9.	suitable for multi-motor drives.	Suitable for individual motor drives.

Closed Loop slip controlled current source inverter drive with Regenerative Braking:

The block diagram for closed loop slip controlled current source inverter drive with Regenerative braking is shown below

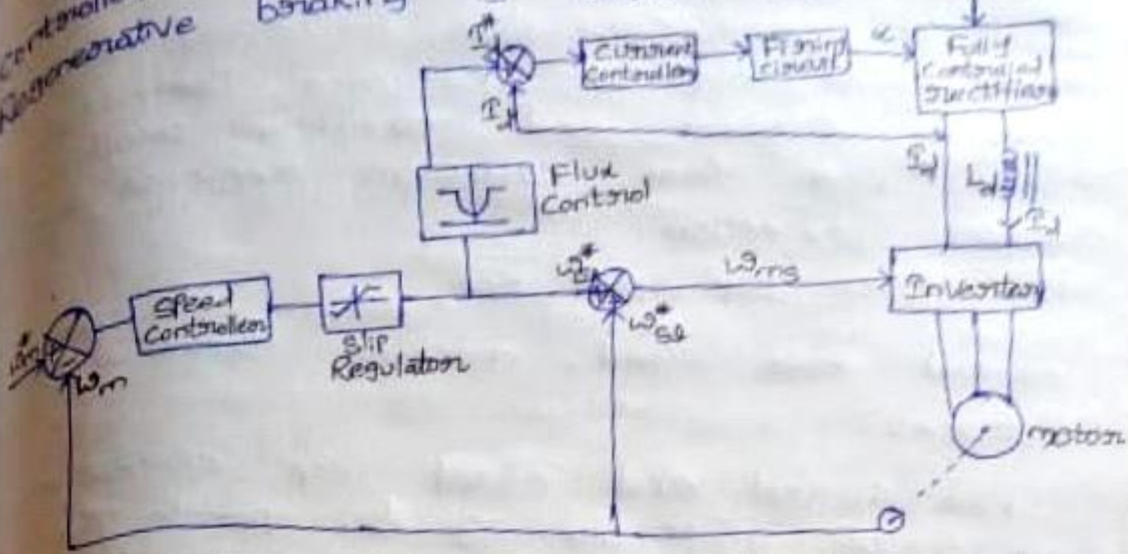
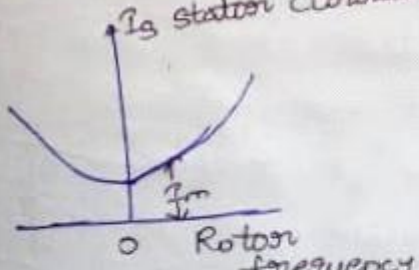


Fig. closed loop slip controlled CSI drive with Regenerative Braking

From Block diagram,

actual speed ω_m is compared with reference speed ω_m^*. The speed error is processed through a PI controller and slip regulator. The slip regulator sets the slip speed command ω_{sl}^*. synchronous speed is obtained by adding ω_m & ω_{sl}^* which determines the inverter frequency. constant flux operation is obtained when slip speed ω_{sl} and I_s having relationship as shown in figure below



Since $I_d \propto I_s$, a relation similar exists between ω_{sl} and I_d for constant flux operation.

Based on value of ω_{sl}^*, the flux control block produces reference current I_{sl} which

Passes through closed loop current control and it adjusts the dc link current I_d to maintain a constant flux. The limit imposed on output of slip regulator, limits I_d at inverter rating.

Therefore any correction in speed error is carried out at maximum permissible inverter current and maximum available torque, giving fast transient response and current protection.

For given slip speed, K_{sf},

Beyond base speed, machine terminal voltage saturates.

Flux control and closed loop control of I_d are made ineffective. To ~~do~~ operate the drive upto rated inverter current, the slip speed limit of slip regulator must increase linearly with frequency.

This is realized by adding to the slip regulator output a signal proportional to the frequency.

Variable frequency control of Induction motor using cyclo-converter:

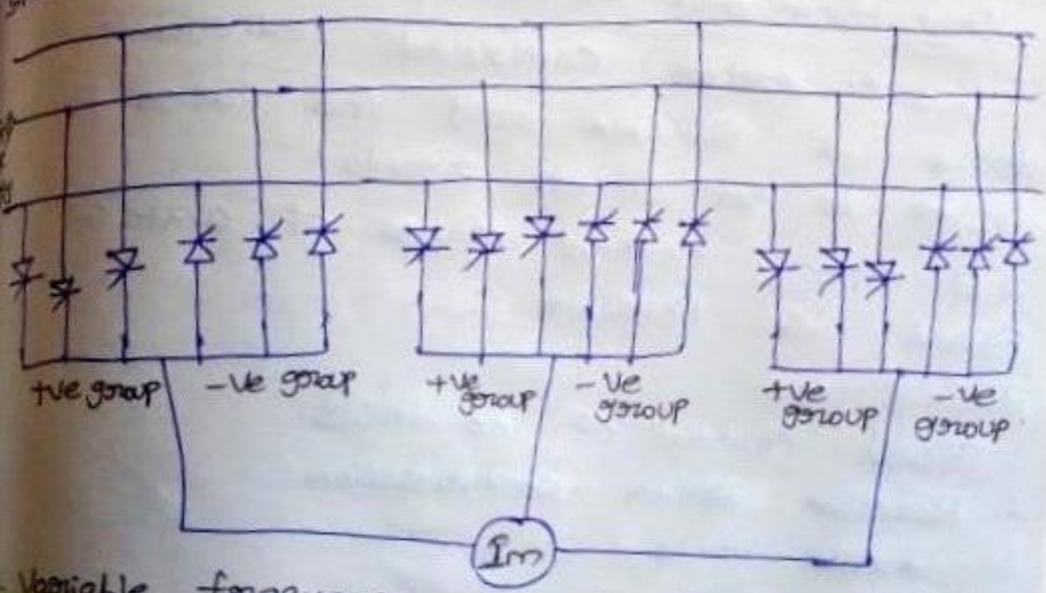
Speed control of induction motor is necessary in industrial applications. There are several method for speed control of induction motor cyclo converters are used in very large variable frequency drives with ratings from few megawatts upto tens of megawatts.

A cyclo converter is a device which converts input voltage at one frequency to output voltage at another frequency without DC link ;. in among all method V/F method is simple, reliable and economical.

The various cycloconverter provides variable voltage supply to be obtain from fixed voltage and frequency ac supply. It was always preferred for high power rating devices which operates at low frequencies and low speed.

It was always operated at $\frac{1}{3}$rd of input frequency in order to overcome as problem of harmonic content in load the current waveform.

The circuit for variable frequency control of Induction motor using cyclo-converter is shown below.



Variable frequency control of Induction motor using cyclo converter

Total number of thyristors are 18 in this Converter i.e., six thyristors Per Phase

Total number of thyristor are divided into Positive and negative groups.

Positive group of thyristors are triggered in order to trace the Path of Positive envelope and negative group are thyristors are triggered in order to trace the Path of negative envelope.

Here $f_0 = \frac{1}{3} f_s$ since to reduce the harmonic Content otherwise the harmonic content in Current waveform is increased which requires filter and increases the cost which is uneconomical.

Hence it is Known as step down cyclo converter.

Ex: If input frequency is $f_s = 50Hz$, then Converter operates at $f_0 = \frac{50}{3} = 16.33Hz$.

These are Preferred for

High Power and

low frequency applications.

cyclo converter Controlled induction motor drive is suitable only for large Power drives to get lower speeds.

A speed control range of 0.33% of base speed is Possible.

Applications:

1. Speed control of AC drives.
2. Reactive Power compensation
3. Textile mills
4. Paper mills
5. Cement and Rolling mills.

Speed control of Induction motor from Rotor side:

There are two types of speed control methods of induction motor from rotor side.

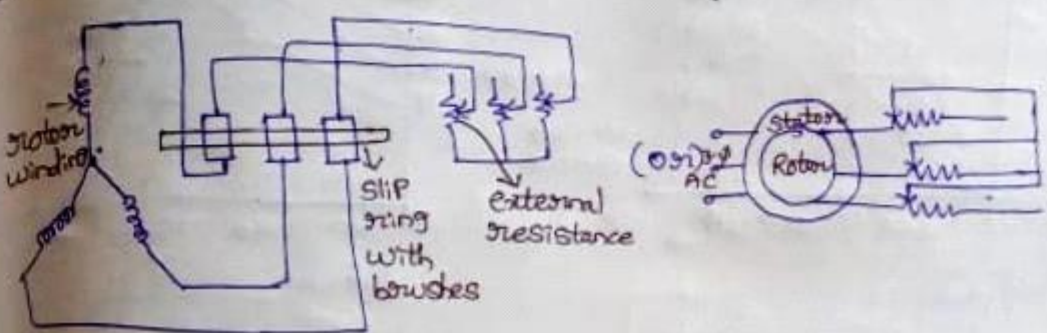
1. Rotor resistance control
   (i) Conventional rotor resistance control
   (ii) static rotor resistance control
2. slip Energy recovery method

static rotor resistance control is achieved by preferring choppers as switches.

Conventional Rotor resistance control method:

It is also simply known as rotor resistance control method.

It is one of the method by which we can control the speed of induction motor. The speed of wound rotor (or) slip ring induction motor can be controlled by connecting an external resistance in rotor circuit through slip rings as shown below.



This method cannot be applicable to squirrel cage Induction motors.

We know that,

Torque expression of 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 equation, it is clear that torque depends on rotor circuit resistance. Maximum torque expression is given by

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

and slip at maximum torque is

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

From above two equations, it is clear that maximum torque is independent of rotor resistance but slip at which maximum torque is directly proportional to rotor circuit resistance.

Therefore if we change the rotor resistance, maximum torque will remain constant but slip will increase.

Figure below shows the torque speed characteristics for three different rotor resistances R_1, R_2 and R_3.

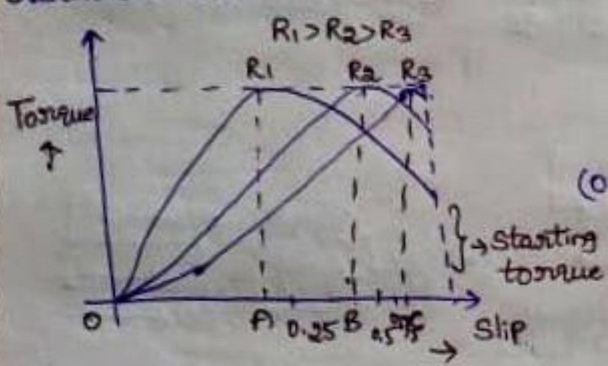


Fig (a)

(or)

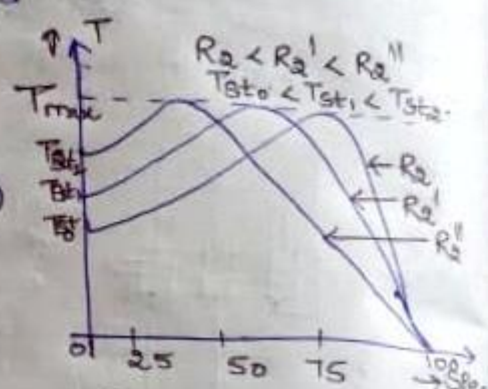


Fig (b)

In figure (a), maximum torque is same for rotor resistances R_1, R_2 and R_3 but slip increase from points A to B and C. This means increase in slip which in turn reduction in motor speed.

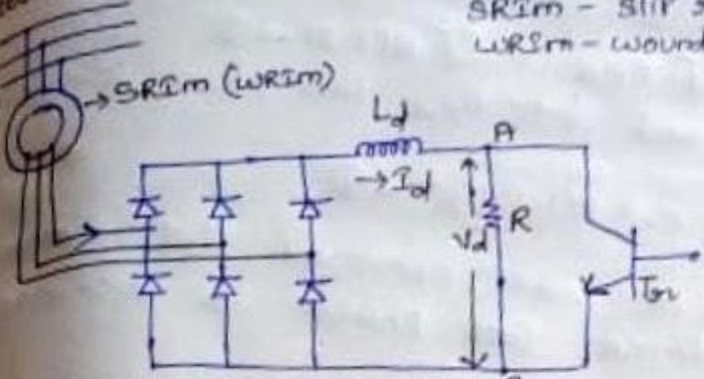
Hence we can achieve variable speed at constant torque. This method is suitable for constant torque drive.

It may be also noted from fig(a), starting torque increases with increase in rotor resistance.

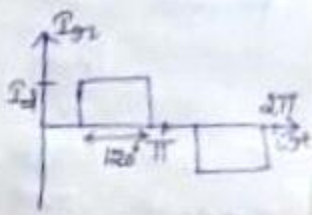
Therefore this method is advantageous where we require high starting torque Ex: cranes.

Static rotor resistance control of Induction motor (Dynamic braking of Induction motor):

SRIm - slip ring induction motor
WRIm - wound rotor " "



Fig(a) Circuit Diagram



Fig(b) Rotor current waveform

Fig: Rotor resistance control employing semi conductor converters.

Rotor resistance control of Induction motor scheme is shown in above figure. Here devices like MOSFET, IGBT, chopper and transistors can be preferred. The ac output voltage from rotor of induction motor is rectified by a diode bridge. The dc voltage is fed to parallel combination of fixed resistance 'R' and semi conductor switch realized by transistor T_r.

Effective value of 'R' can be varied by adjusting duty ratio of transistor which in turn varies circuit resistance.

'L_d' which is smoothing reactor used to reduce ripples and discontinuity in dc link current I_d. Rotor current waveform is shown fig(b) when ripples are neglected.

Rms value of rotor current is given by

$$I_r = \sqrt{\frac{2}{3}}\, I_d \rightarrow (1)$$

Resistance between terminals A and B will be 0 when transistor is in ON state

$R_{AB} = 0$ when transistor is in ON state

$R_{AB} = R$ when T_r is in OFF state.

∴ Average value of resistance between terminals is given by

$$R_{AB} = (1-\delta) R \rightarrow ②$$

where δ = Duty ratio of transistor T_r

'δ' varies from 0 to 1 and should not cross beyond '1'

From ① & ②
Power consumed by R_{AB} is given by

$$P_{AB} = I_d^2 \cdot R_{AB} = I_d^2 R(1-\delta) \rightarrow ③$$

Power consumed by R_{AB} per phase is given by

$$\frac{P_{AB}}{3} = 0.5 R(1-\delta) I_r^2 \rightarrow ④$$

From eq ④, it was observed that rotor circuit resistance per phase is increased by $0.5R(1-\delta)$

∴ Rotor circuit resistance per phase is given by

$$R_{rT} = R_r + 0.5R(1-\delta)$$

R_{rT} can vary from R_r to $R_r + 0.5R$

Closed loop speed control with static rotor resistance control:

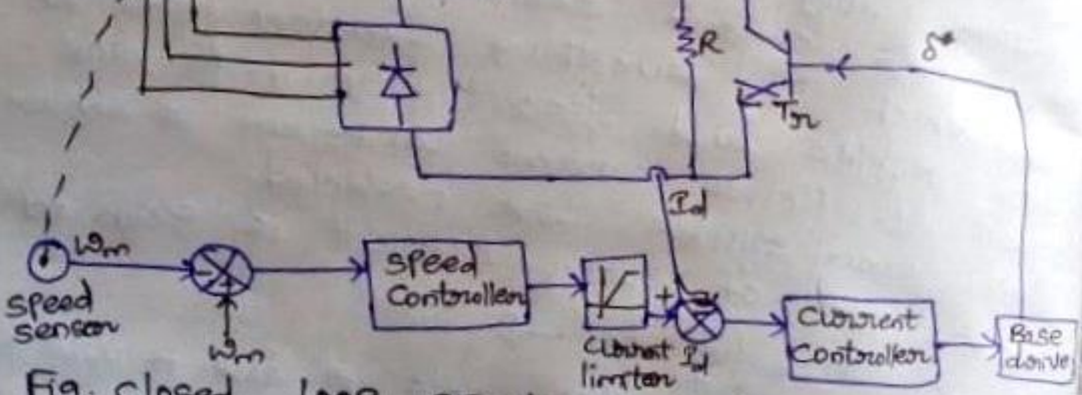


Fig. Closed loop speed control with static rotor resistance control.

In this scheme, rotor current I_r and I_d h... constant value at maximum torque point both during motoring and plugging. If current limit is made to saturate at this current I_d, drive will accelerate and decelerate at maxim[um] torque, giving very fast transient response.

For plugging to occur, arrangement will have t[o] be made for reversal of phase sequence.

Compared to conventional rotor resistance control, this method has several advantages such as

1. smooth and stepless control
2. Fast response
3. less maintenance
4. compact size
5. simple closed loop control.
6. Rotor resistance remains balanced between three phases for all operating points.

Slip power Recovery method:

This method is applicable for only slip ring induction motor (SRIm or WRIm → wound rotor Im)

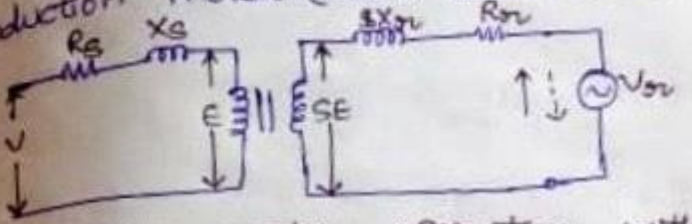


Fig. Induction motor operation with an injected voltage in rotor.

we know that,

$$P_m = P_g - P_r$$

where

P_r = Power absorbed by source V_r.

The equivalent circuit of wound rotor [in]duction motor with voltage V_r injected to [i]ts rotor, assuming stator to rotor turns [u]nity. when rotor copper loss is neglected

$$P_m = P_g - P_r$$

A part of air gap power which is not [c]onverted into mechanical power is called [sli]p power which is represented by SP_g.

The air gap power which is getting wasted [in] rotor is fed back to supply mains. This is called slip recovery.

This system is mainly used for Induction motor speed control. The speed control in Induction motor has poor efficiency due to wasting of slip power in rotor circuit.

By using recovery schemes the induction motor is controlled to avoid slip power loss.

The slip power recovery is classified into two types:

1. static scherbius system
2. static Kramer system.

Static scherbius system:

Static scherbius system:

Static Scherbius system is applicable to wound rotor or slip ring induction motor.

This drive is used to control the speed of induction motor both below and above base speeds. In this induction motor is started by using resistance switch.

The schematic representation for controlling speed of motor by using scherbius drive is shown below.

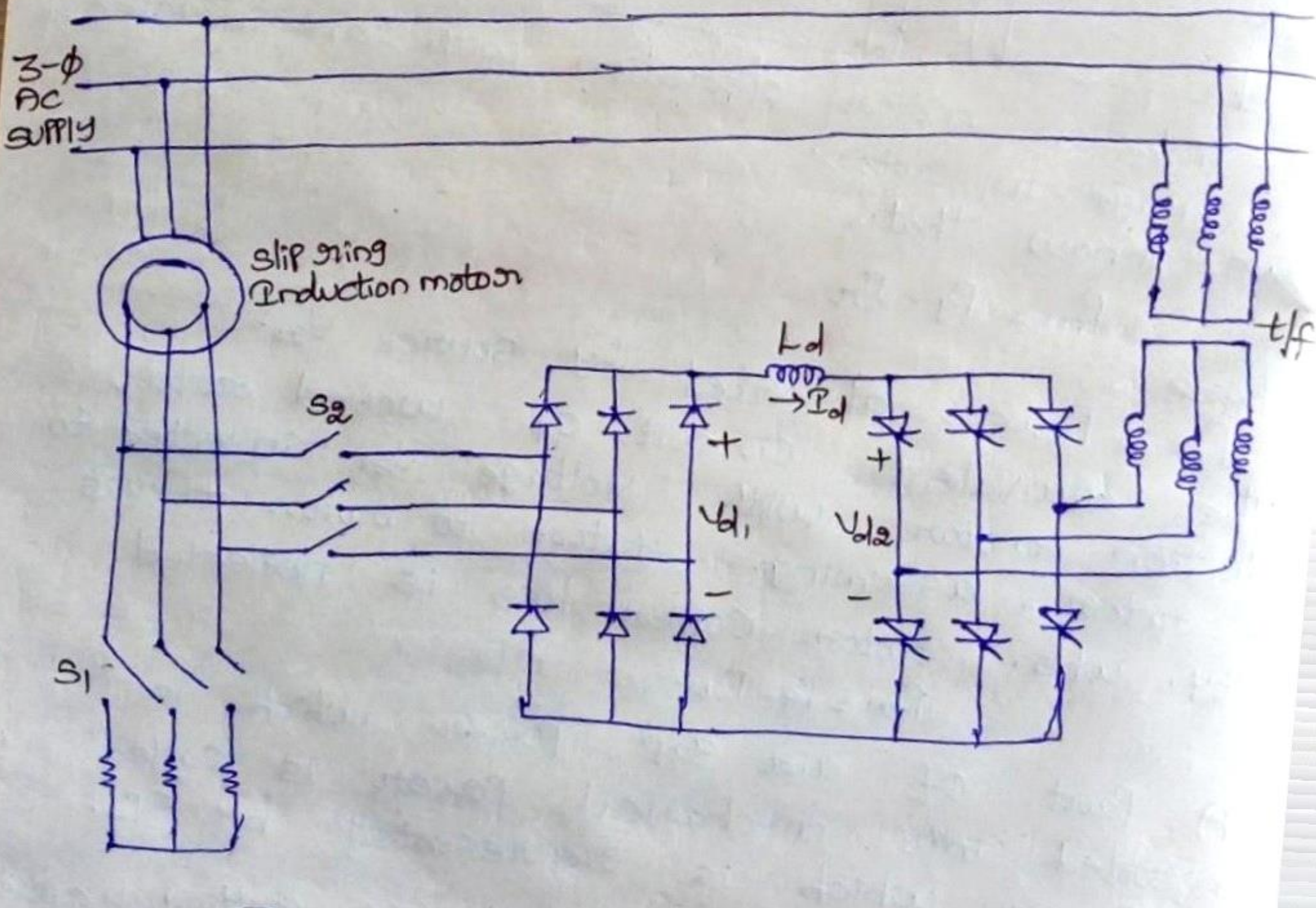


Fig. Static scherbius Drive

once induction motor attains speed, resistance inserted into circuit.

In this drive wasted ac power is collected by means of slip rings, ac is converted into dc by using diode bridge. Ripples in dc components can be eliminated by using smoothing reactor L_d, then dc is converted into ac by using inverter. This converted ac power is collected by using transformer which is connected to three phase ac supply.

we know that,

For full bridge rectifier, output voltage is given by $V_0 = \frac{3\sqrt{3} V_m}{\pi} \cos\alpha$

where $V_m = \sqrt{2} V_s$

By varying firing angle, output voltage can be varied

since $T \propto V^2$, torque also varied by varying voltage.

Hence we can achive speed control below and above rated speeds.

since for diode bridge, 'α' is absent then

$$V_{d1} = \frac{3\sqrt{3} \cdot \sqrt{2} V}{\pi} = \frac{3\sqrt{6} V}{\pi n} = \frac{3\sqrt{6} S}{\pi} \cdot \frac{V}{n}$$

where

n = stator to rotor turns ratio.

V = Voltage Per Phase

S = slip

From receiver side, voltage is given by

$$V_{d2} = \frac{3\sqrt{6}}{\pi} \frac{V}{m} \cos\alpha$$

where

V = Voltage Per Phase

m = source side to converter side transformer ratio.

α = Firing angle

Since voltage of rectifier is positive, voltage of inverter is negative i.e

$$V_{d1} = -V_{d2}$$

$$\Rightarrow V_{d1} + V_{d2} = 0$$

$$\Rightarrow \frac{3\sqrt{6}s}{\pi}\frac{V}{n} + \frac{3\sqrt{6}V}{\pi m}\cos\alpha = 0$$

$$\Rightarrow \frac{3\sqrt{6}V}{\pi}\left(\frac{s}{n} + \frac{\cos\alpha}{m}\right) = 0$$

$$\Rightarrow \frac{s}{n} = -\frac{\cos\alpha}{m}$$

$$\Rightarrow s = \frac{n}{m}\cos\alpha$$

$$s = -a\cos\alpha$$

where $a = \frac{n}{m}$

maximum value of firing angle is restricted to 165° for safe commutation of inverter thyristor.

Transformer is used to match voltages. At lowest speed required from drive, V_{d1} will have maximum value given by

$$V_{d1} = nVs_{max}$$

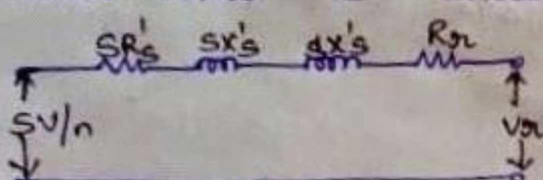
s_{max} is slip at lower speeds.

$\alpha = 165°$, 'm' is given by

$$mV\cos 165° + nVs_{max} = 0$$

$$m = \frac{-ns_{max}}{\cos 165} = 1.035\, ns_{max}$$

Equivalent circuit of motor referred to rotor side is shown below



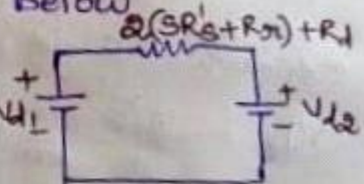


Fig (a) motor equ. circuit

(b) Drive equivalent circuit

From above circuit,

R'_s = Stator resistance refer to rotor side = $\frac{R_s}{n^2}$

R_r = Rotor resistance = $\frac{R'_r}{n^2}$

R_d = DC link resistance.

current is given by

$$I_d = \frac{V_{d1} + V_{d2}}{2s(R_s' + R_r) + R_d}$$

Torque is given by,

$$T = \frac{P_g}{\omega_s}$$

where ω_s = speed in rad/sec.

In this, we can change power from receiving end only and hence

power $P = \frac{|V_{d2}| \cdot I_d}{s \cdot \omega_m}$

where s = slip