UNIT IV

INDUCTION MOTOR DRIVES

4.1 INTRODUCTION

Induction motors, particularly squirrel cage IM, have many advantages when compared to DC motors. They are,

- ❖ Ruggedness
- ❖ Lower maintenance requirements
- ❖ Better reliability
- ❖ Low cost, less weight and volume
- ❖ Higher efficiency
- ❖ Also induction motors are able to operate in dirty and explosive environments.

Because of the above said advantages, induction motors are predominantly used in many industrial applications. But induction motors were used only for applications requiring constant speed.

DC motors were used for variable speed applications as their speed control is cheap and efficient when compared to induction motors.

After the advent of power electronic converters, it was able to design variable speed drives for induction motors. Because speed control of IM using power electronic converters have become cheap and less costly when compared to dc drives.

4.2 SPEED CONTROL

The conventional methods of speed control of induction motors are,

Stator Side

- ❖ Stator voltage control
- ❖ Variable frequency control
- ❖ Stator current control
- ❖ V/f control
- ❖ Changing the number of poles on stator

Rotor Side

- ❖ Rotor resistance control
- ❖ Injecting emf in the rotor

4.2.1 STATOR VOLTAGE CONTROL

- ❖ Speed of induction motor can be varied in a narrow range by varying the voltage applied to the stator winding.
- ❖ Torque developed by 3 phase induction motor is directly proportional to the square of the stator voltage as given by the equation,

$$T_m = \frac{3}{2\pi N_s} \times \frac{S.E_2^2.R_2}{R_2^2 + (S.X_2)^2} - - - - - - 1$$

Or

1

$$N_s = \frac{3}{2\pi T_m} \times \frac{S.E_2^2.R_2}{R_2^2 + (S.X_2)^2} - - - - - 2$$

❖ In low slip region $(S.X_2)^2$ is very small as compared to R_2. So, it can be neglected. So equation 1 becomes,

$$T_m \propto \frac{S.E_2^2}{R_2}$$

❖ Since rotor resistance R_2 is constant, the torque equation becomes,

$$T_m \propto S.E_2^2$$

Here E_2 is proportional to the supply voltage V_1. Hence,

$$T_m \propto S.V_1^2 - - - - - -3$$

2/22

❖ From equation 2, it is clear that any reduction in supply voltage will reduce the motor speed. But from equation 3, it is seen that any reduction in supply voltage v⁇   ⁇e torque also.
❖ So in this method of speed control, torque reduces when supply voltage redu⁇ method is used in applications where torque demand reduces with reduction in voltage.
❖ In general, this method can be used for small range of speed variation.
❖ In this method of speed control, the slip increases at low speeds. Hence the efficiency of the drive reduces.
❖ Examples: Fans and pump drives.

Stator voltage control using AC voltage controllers

❖ The variation of motor voltage is obtained by ac voltage controllers. AC voltage controllers convert fixed ac to variable ac with same frequency.
❖ But this method produces harmonics in the output and the power factor is low.
❖ The harmonic content increases and power factor decreases with decrease in output voltage.
❖ Hence the torque produced by the motor reduces.
❖ This method is used in applications like fans, pumps and crane drives.
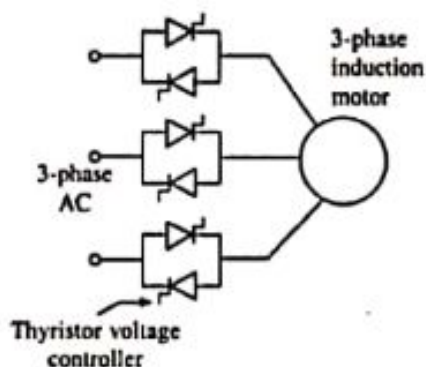❖ The circuit for star connected ac voltage controller feeding a 3 phase induction motor is shown in Fig. 4.1
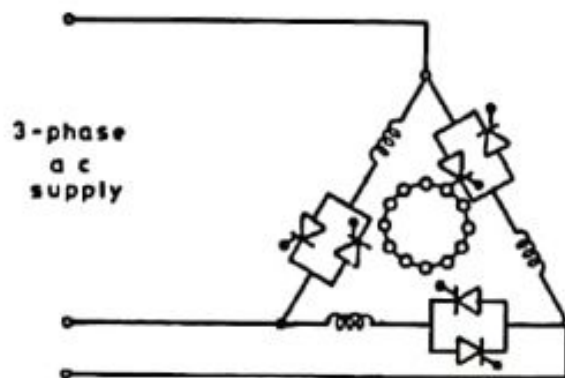

Fig. 4.1 Star connected controller   Fig. 4.2 Delta connected controller

2

- By controlling the firing angle of the thyristors connected in each phase, the rms value of stator voltage can be varied.
- As a result of this, the motor torque and the speed of the motor are varied.
- In star connected controller, all the thyristors carry line currents. But in delta controller shown in Fig. 4.2, all the thyristors carry phase current only. Hence low rating thyristors may be employed in delta controller.
- But delta controller produces circulating currents due to third harmonic voltages. This may increase power loss across each device.
- The speed range is limited in this method of speed control.
- This method is used for applications where load torque requirement reduces with reduction in speed as shown in Fig. 4.3. When a voltage of V_1 is applied, the load load torque required is high and when a voltage V_3 is applied. The load torque is low.
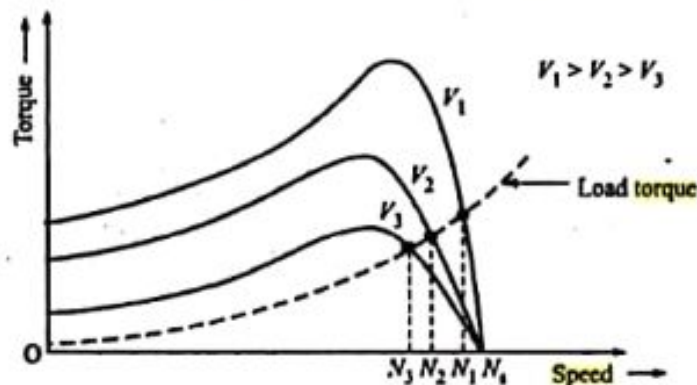
Fig. 4.3 Speed – Torque characteristics with stator voltage control

- These ac voltage controllers are also used as starters for soft start of motors.
- The power factor of ac voltage circuit is low.
- It can be used for fans and pump drives.

4.2.2 STATOR FREQUENCY CONTROL (OR) FIELD WEAKENING METHOD OF SPEED CONTROL

- In an induction motor, we know that,

$$N_s = \frac{120.f}{P} ------4$$

- From the above equation 4, it is clear that changing the supply frequency will change the synchronous speed and hence the rotor speed.
- Emf equation in ac machines is given by,

$$V_1 = 4.44. f. \varphi. K_w. N_1$$

$$\therefore \varphi = \frac{V_1}{4.44. f. K_w. N_1} -----5$$

- The above equation 5 states that the flux φ will be constant if V_1 and f are kept constant.

3

* If frequency is reduced with constant V_1, then the flux φ increases. Hence the core gets saturated.
* This will increase the magnetizing current of the motor. Hence power losses increased and efficiency decreases. It also produces noise.
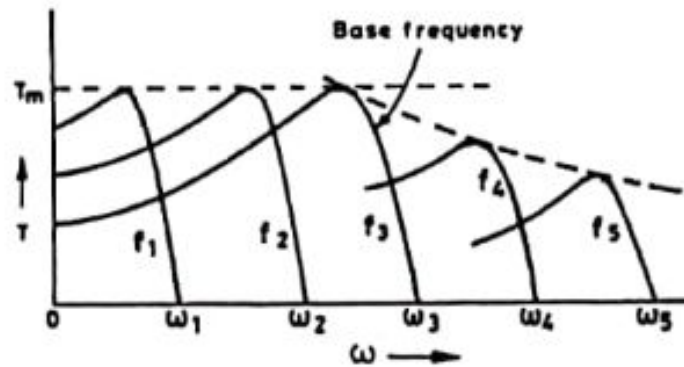

Fig. 4.4 Speed – Torque characteristics with stator frequency control

* If the frequency is increased by keeping the V_1 constant, then flux decreases. This will reduce the maximum torque produced by the motor as shown in Fig. 4.4.
* So this method is rarely used in practice.
* With constant voltage, if the frequency is increased, the air-gap flux reduced also called as field weakening mode of speed control.

4/22

4.2.3 VOLTAGE / FREQUENCY CONTROL (OR) VOLTS / HERTZ CONTROL

* Varying the voltage alone or frequency alone has some disadvantages with regards to the operation of induction motor.
* The maximum torque in an induction motor is given by,

$$T_{max} = \frac{K(V/f)^2}{\frac{R_s}{f} \pm \sqrt{\left[\left(\frac{R_s}{f}\right)^2 + 4\pi^2(L_s + L_r')^2\right]}} ----- 6$$

* Here K is a constant and Ls & Lr' are the stator and stator referred rotor inductances.
* At high frequencies, the value of (R_s/f) will be very much less than 2π (Ls+ Lr'). So (R_s/f) can be neglected and hence the torque equation becomes,

$$T_{max} = \pm \frac{K(V/f)^2}{\sqrt{[4\pi^2(L_s + L_r')^2]}}$$

$$T_{max} = \pm \frac{K(V/f)^2}{2\pi(L_s + L_r')} ----- 7$$

* From equation 7, it is clear that if the ratio (V / f) is kept constant, the motor can produce a constant maximum torque, T_{max}. i.e constant torque operation.

4

- At low frequencies (when speed is reduced), the term (R_s / f) will be high and it cannot be neglected in equation 6. Hence the motor torque reduces.
- This is because of the fact that the flux reduces as the frequency is decreased as per equation 5.
- Hence if maximum torque needs to be maintained constant at low speeds, then (V / f) ratio must be increased.
- Near to base speed (or rated speed), the supply voltage will be maximum and it cannot be increased further. Therefore, above base speed, the frequency is changed by keeping supply voltage constant.
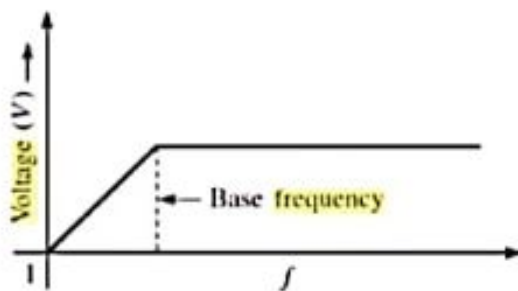- But this will decrease the maximum torque produced by the motor as per the equation 7.
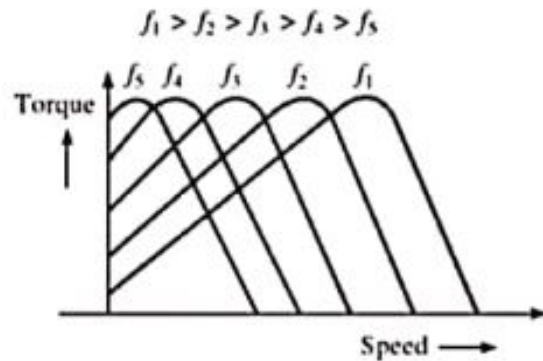

Fig. 4.5. V – f relationship

Fig. 4.6. Speed – Torque characteristics

- From the graph of Fig. 4.5, it is clear that
  - (V/f) ratio is increased at low frequency to keep maximum torque constant.
  - (V/f) ratio is kept constant at high frequencies up to base frequency
  - V is kept constant and frequency is varied above base frequency.
- From Fig. 4.6, it is clear that the maximum torque is same at all different speeds.
- This volts / Hertz control offers speed control from standstill up to rated speed of IM.
- This (V/f) control is achieved by using VSI and CSI fed induction motor drives.
- If a six step inverter is used, the frequency alone can be varied at the inverter output and the output voltage is controlled by varying the input dc voltage.
- If a PWM inverter is used, both voltage and frequency can be varied inside the inverter itself by changing the turn on and off periods of the devices.

4.3 VOLTAGE SOURCE INVERTER (VSI) FED INDUCTION MOTOR DRIVES

- In voltage source inverters, the input voltage is kept constant.
- The magnitude of output voltage of VSI is independent of the load.
- But the magnitude of output current depends on the type of load.
- A VSI converts the input dc voltage into an ac voltage with variable frequency at its output terminals.

❖ VSI using normal transistors is shown in Fig. 4.7. Any other self commutated device can be used in place of transistors.
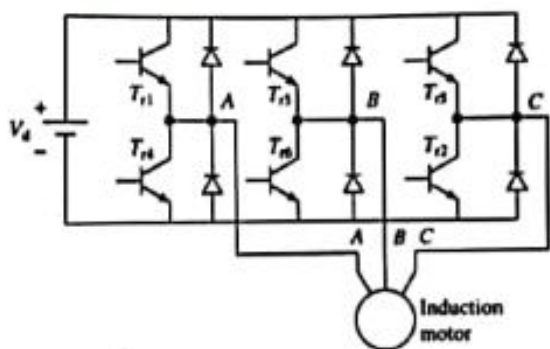

Fig. 4.7 VSI fed Induction Motor

❖ MOSFET is used in low voltage and low power inverters.

❖ IGBTs and power transistors are used up to medium power levels.

❖ GTO and IGCT are used for high power levels.

❖ VSI may be a six step inverter or a PWM inverter.

❖ When VSI is operated as a six step inverter, the transistors are turned ON in the sequence of their numbers with a time interval of T/6 seconds if T is the total time period of one output cycle.

❖ Frequency of the inverter output is varied by varying the time period (T) of one cycle.

❖ If the supply is dc, then a variable dc voltage is obtained by connecting a chopper between input dc and the inverter as shown in Fig. 4.8
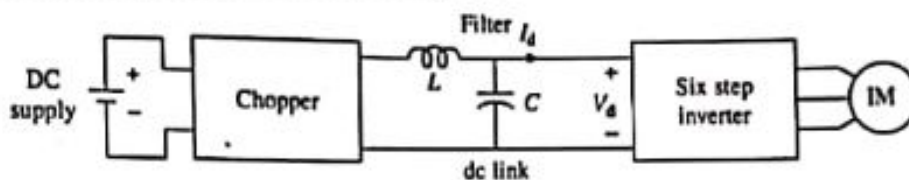

Fig. 4.8

❖ If the input supply is ac, then a variable dc is obtained by connecting a con' between the input ac and the inverter as shown in Fig. 4.9. The output voltag a six step inverter is shown in Fig. 4.10
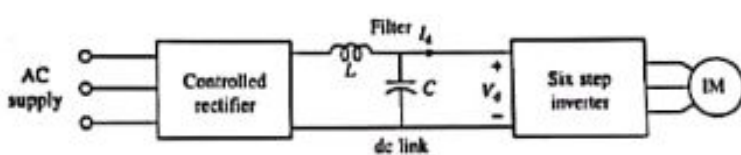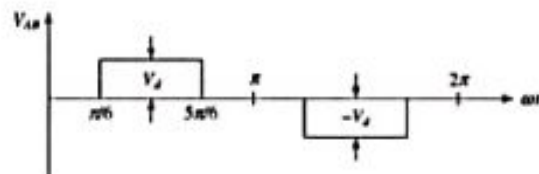
Fig. 4.9

Fig. 4.10

Disadvantages of six step inverter

❖ Low frequency harmonics are more and hence the motor losses are increased at all speeds.

❖ Motor develops pulsating torques due to 5th, 7th, 11th and 13th harmonics.

❖ Harmonic content increases further when the motor rotates at low speeds. This will overheat the machine.

The above said problems are rectified when a PWM inverter is used.

6

- If a PWM inverter is used as VSI as shown in Fig 4.11, then the input voltage may be a constant dc which is obtained from a simple diode rectifier. The output of a PWM inverter is a variable voltage and variable frequency.
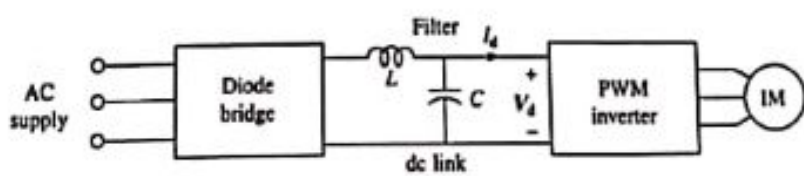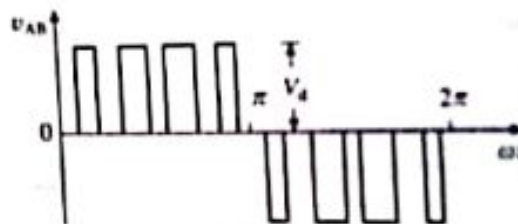

Fig. 4.11

Fig. 4.12

- In a PWM inverter, it is possible to control the output voltage and frequency as well as the harmonic content can be minimized.
- The output voltage waveform of a PWM inverter is shown in Fig. 4.12
- The motors having high leakage inductance are used when a VSI is used to feed the induction motors.

4.4 CLOSED LOOP SPEED CONTROL OF INDUCTION MOTOR FED FROM VOLTAGE SOURCE INVERTER

- It employs an inner slip speed loop and an outer speed loop as shown in Fig. 4.13.
- The slip speed loop acts as inner current control loop. It also ensures the motor to operate between synchronous speed and the speed at which maximum torque occurs for all frequencies.
- Thus a high torque will be produced for a small current drawn from supply.
- The drive uses a PWM inverter fed from a dc source. Regenerative braking and four quadrant operation of drive is possible because of the use of PWM inverter.
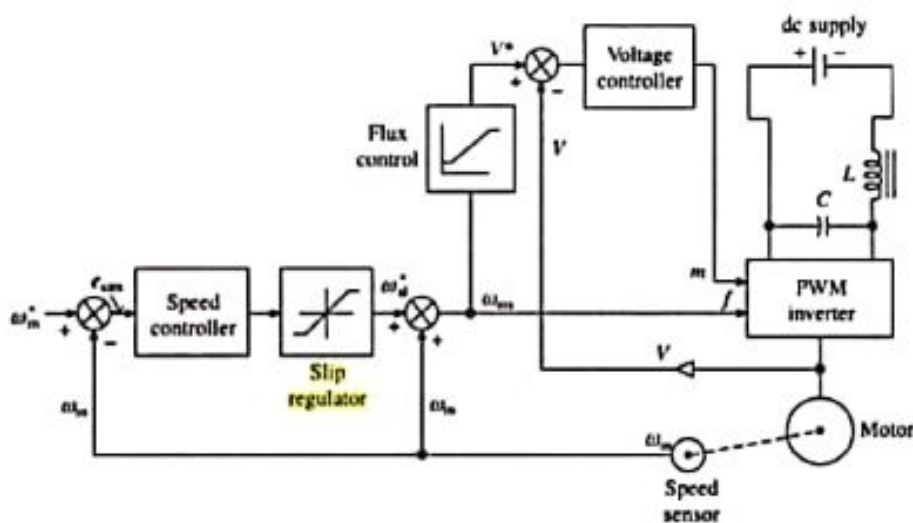- The speed error is processed through a speed controller, usually a PI controller, and a slip regulator.

Fig. 4.13 Closed Loop Speed Control of Induction Motor fed from VSI

7

- *P* controller reduces the steady state error and *I* controller reduces the peak overshoot and settling time so that the response will be faster.
- PI controller gives good steady state accuracy and reduces the noise.
- Slip regulator set the slip speed command ω_{sl}^*. This command controls the inverter current to its maximum allowable value.
- The synchronous speed obtained by adding actual speed ω_m and slip speed ω_{sl}^* determines the frequency of inverter output voltage.
- Reference signal **V*** for controlling the output voltage of inverter is generated using a flux control block.
- This reference signal ensures a constant flux operation below base speed and constant voltage operation above base speed.

- **If the motor speed is to be increased**, then the reference speed ω_m^* will be set to the required speed.
- Now the comparator compares the actual speed and reference speed and produces a positive error.
- This will set the slip speed command ω_{sl}^* at its maximum value.
- Hence the motor starts accelerating (i.e speed increases) at the maximum inverter current and hence the speed error decreases.
- When the actual motor speed reaches the reference value, the drive finally settles at that speed. At this speed, the motor torque equals the load torque.

- **If the motor speed is to be decreased**, then the reference speed ω_m^* will be set to the required speed.
- Now the comparator compares the actual speed and reference speed and produces a negative error.
- This will set the slip speed command ω_{sl}^* at its maximum negative value.

- Hence the motor starts decelerating (i.e speed decreases) at the maximum in and hence the speed error decreases. Here regenerative braking is applied.
- When the actual motor speed reaches the reference value, the drive finally settles at that speed. At this speed, the motor torque equals the load torque.

- For operation below base speed, the ratio (V/f) is kept constant.
- For operation above base speed, the terminal voltage is kept constant and frequency is increased.
- For low frequency operation, the ratio (V/f) is increased to maintain constant flux operation.

8

- **When a fast response is required**, the drive can be made to accelerate at a current more than the rated current of induction motor.

- But the power electronic switches present in the inverter must be selected such that they can withstand for those high currents. Any device with increased current rating will be more costly. This will increase the cost of total drive system.

- When fast response is not required, current ratings of inverter and rectifier can be chosen to be marginally higher than that of the motor.

4.5 CURRENT SOURCE INVERTER (CSI) FED INDUCTION MOTOR DRIVES

- In current source inverters, the input current is constant but adjustable.
- The magnitude of output current of CSI is independent of the load.
- But the magnitude of output voltage depends on the type of load.
- A CSI converts the input dc current into an ac current at its output terminals.
- The output frequency of ac current depends upon the triggering of SCRs.
- Magnitude of output current can be adjusted by controlling the magnitude of dc input current.
- Out of the force commutated CSIs, Auto Sequential Commutated Inverter (ASCI) is the most popular CSI.
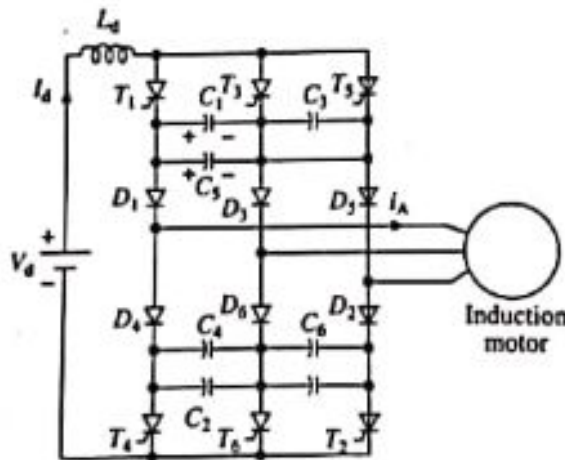- A single phase ASCI is shown in Fig. 4.14

Fig. 4.14   CSI fed Induction Motor Drive   Fig. 4.15

- A large inductance is connected to make this inverter as current source inverter.
- Capacitors C_1 to C_6 are used for commutating the thyristors. These thyristors are fired in sequence with 60^0 intervals.
- Diodes D_1 to D_6 are connected in series with thyristors to prevent the capacitors through load.

- The inverter output frequency is controlled by adjusting the period T through triggering circuits of thyristors.

- The fundamental component of motor phase current shown in Fig. 4.15 is,

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

- For any given speed, the motor torque is controlled by varying the dc current I_d. This I_d can be varied by varying V_d.
- Different types of circuit configurations are shown in Fig. 4.16 and 4.17.
- When the available supply is AC, then a controlled rectifier is connected between the input supply and the inverter as shown in Fig. 4.16
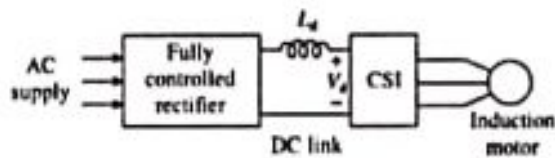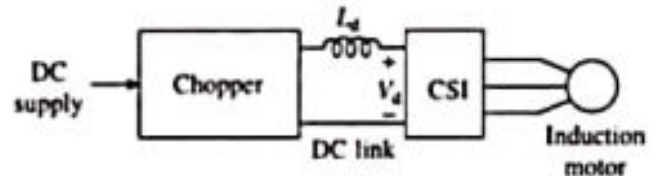

Fig. 4.16   Fig. 4.17

- The output of fully controlled rectifier will be a variable DC which will vary I_d. This DC current is converted into AC using a CSI and it is given to the induction motor.
- If the available supply is a fixed DC, then a chopper may be added between the supply and the inverter as shown in Fig. 4.17.
- Chopper will give a variable DC voltage V_d which further varies I_d. This DC current is converted into AC using a CSI and it is given to the induction motor.
- In VSI, in case of commutation failure, two SCRs in the same leg may conduct. This will short circuit the input supply and hence the current through SCRs will rise to a high value.
- Hence high speed semiconductor fuses are needed to protect the devices and thus making the system costly.
- In case of CSI, no such problem arises even if two devices in same leg conduct. Because the current is controlled by the large inductance connected in series with the source.
- Hence CSI is more reliable than VSI.
- The output current of CSI shown in Fig. 4.15 rises and falls very rapidly. This creates a huge voltage across the leakage inductance of the motor windings. Hence a motor with less leakage inductance is used.
- Using large values of commutation capacitors can reduce these voltage spikes. But because of large values of capacitors and inductors, the CSI drive becomes expensive and bulky.
- These types of auto sequentially commutated inverters are used widely in medium and large power current source inverter drives.

4.6 CLOSED LOOP CONTROL OF CURRENT SOURCE INVERTER (CSI) FED INDUCTION MOTOR DRIVES

❖ The closed loop CSI shown in Fig. 4.18 consists of an inner slip speed loop and outer speed loop as in the case of VSI.

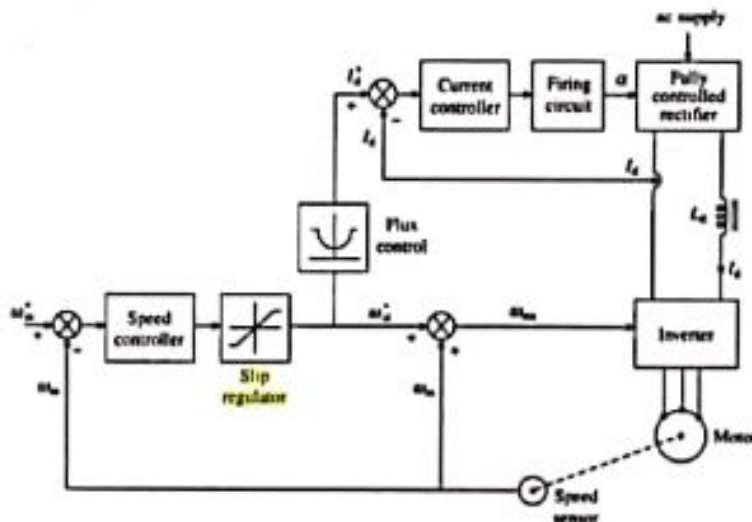❖ This drive operates at constant flux up to base speed. Hence it gives constant torque operation.

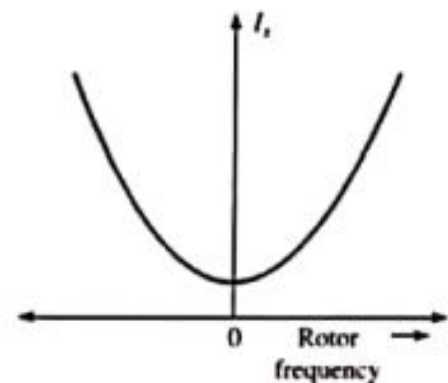Fig. 4.18 Closed loop CSI fed IM drive   Fig. 4.19 Is Vs sf curve

❖ Terminal voltage is kept constant above base speed which gives constant power operation.

❖ The actual speed ω_m is compared with the reference speed ω_m^*.

❖ The speed error is processed through a speed controller (normally a PI controller) and a slip regulator.

❖ Slip regulator controls the slip speed (Ns – Nr). The sum of rotor speed ω_m and slip speed ω_{sl} gives the synchronous speed. This determines the frequency of the inverter output.

❖ Constant flux operation below base speed is obtained when the slip speed (or rotor frequency) and inverter current Is have the relationship as shown in Fig. 4.19

❖ This relationship is maintained by flux control block. Flux control block produces a reference signal I_d^* based on the value of ω_{sl}^*.

❖ This I_d^* will adjust the dc link current I_d through a closed loop to maintain constant flux.

❖ Both speed and current controllers use PI controllers to get good steady state accuracy.

❖ **If the speed of the drive is to be increased**, then the required speed is set as reference speed ω_m^*. Now the speed error is positive and slip speed (Ns – Nr) also positive.

❖ The drive now accelerates at maximum current in motoring mode. When the motor speed equals the reference speed, the motor continues to rotate at that speed where the motor torque equals load torque.

❖ **If the speed of the drive is to be decreased**, then the required speed is set as reference speed ω_m^*. Now the speed error and slip speed (Ns - Nr) are negative.

11

- ❖ The drive now decelerates at maximum current in braking mode. When the motor speed equals the reference speed, the motor continues to rotate at that speed where the motor torque equals load torque.
- ❖ Above base speed, the terminal voltage is kept constant to get constant power operation.
- ❖ Now flux control block and closed loop control of I_d become ineffective. Hence I_d may increase to high value which is not appreciable.
- ❖ To control I_d, the slip speed limit of slip regulator must increase proportional to inverter frequency.
- ❖ This achieved by adding a signal proportional to frequency with the slip regulator output.

4.7 Comparison of Current Source Inverter (CSI) & Voltage Source Inverter (VSI) drives

Current Source Inverter (CSI) drives	Voltage Source Inverter (VSI) drives
CSI is more reliable because conduction of two devices in the same leg does not short circuit the input supply.	Conduction of two devices in the same leg due to commutation failure causes short circuit of the input supply. This may raise the current through the devices and damage them.
Raise of current is prevented because of the presence of large inductance in the current source.	It requires expensive high speed semiconductor fuses for controlling the current due to short circuit.
Motor current rise and fall are very fast and that creates high voltage across windings.	No such problem arises here in case of VSI.
These high voltage spikes are controlled by having large values of commutating capacitors which may increase the cost and size of the inverter.	Less costly than CSI.
Slow response due to large value of input inductance.	Fast dynamic response is possible if VSI uses PWM inverter. If a six step inverter is used, then response becomes slower like CSI drives.
Frequency range of CSI is lower than VSI. Hence CSI drive has lower speed range.	Frequency range is wide and hence the speed range is also wide.
CSI requires a separate rectifier and inverter combination. Hence it is not suitable for multi motor drives.	A single rectifier can be used to feed many VSIs. Hence VSI is suitable for multi motor drives.
Regenerative braking is naturally possible in CSI.	An additional full converter is required to achieve regenerative braking.
If input AC supply fails, electric braking is not possible in CSI.	But VSI can use dynamic braking in case input AC supply fails.

4.8 SPEED CONTROL OF INDUCTION MOTOR ON ROTOR SIDE

❖ This method of speed control is applicable only to wound round or slip ring induction motors.

❖ The portion of air-gap power which is not converted to mechanical energy is called slip power.

❖ Hence the mechanical power developed is controlled by varying the slip power by some methods. This further controls the speed of the motor.

❖ Controlling the slip power is done by three different methods.

- Static rotor resistance control
- Emf injection into rotor circuit
  - Static Scherbius drive
  - Static Kramer drive

4.8.1 Rotor resistance control

❖ In this method of speed control, an external resistance is added with rotor circuit and it is varied to control the speed of the induction motor. This method is applicable only to slip ring induction motor.

❖ We know that

$$T \propto \frac{S}{R_2} \quad \text{and hence} \quad R_2 \propto \frac{S}{T}$$

❖ From the above equation, it is clear that any increase in R_2 will increase slip S. Increase in slip means reduction in speed. Hence rotor resistance varies the speed.

❖ Rotor resistance does not affect the value of maximum torque produced by the motor. But it changes the speed at which the maximum torque is produced. It is shown in Fig. 4.20.

❖ It is clear from Fig. 4.20 that for the same value of motor torque, the speed reduces with an increase in rotor resistance.
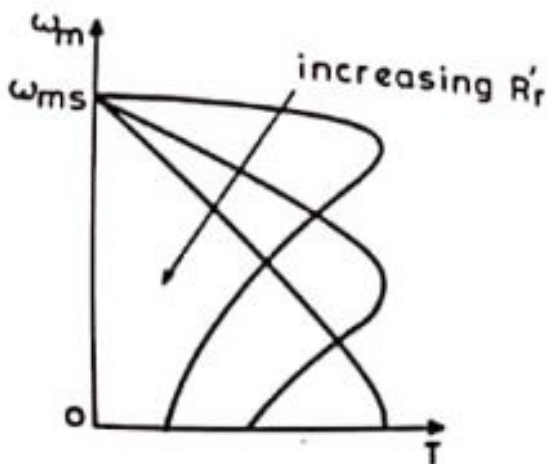
❖ In this method of speed control, the motor torque does not change even at low speeds. Also this method is less costly when compared to variable frequency operations.

❖ Because of its low cost and high torque producing capabilities, this method is used in cranes.

❖ But major disadvantage of this method is its low efficiency due to additional power losses in the external resistance connected to the rotor.

❖ These losses occur in the external resistor. So the heat produced around the external resistor does not increase the heat of the motor.

Fig. 4.20 Speed – Torque char.

13

4.8.2 Static Rotor resistance control

❖ In a three phase slip ring induction motor, a three phase diode rectifier, a chopper and a single resistor is connected as shown in Fig. 4.21.
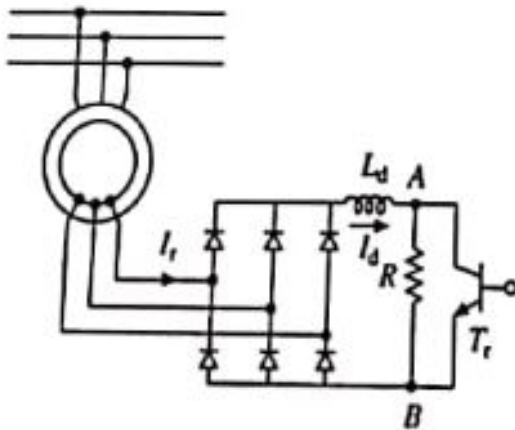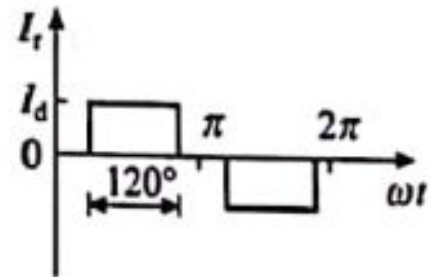

Fig. 4.21   Fig. 4.22

❖ An inductor L_d is connected to reduce the ripple present in the dc link current.

❖ The rotor current waveform is shown in Fig. 4.22

❖ The rms value of rotor current is given by,

$$I_r = \sqrt{\frac{2}{3}} I_d -------1$$

❖ The ac output voltage from rotor windings is rectified using diode bridge and it is fed to the parallel combination of fixed resistor and a transistor.

❖ The effective value of this resistance connected between the terminals A & B is varied by varying the duty cycle of the transistor.

❖ The resistance between A & B is zero when transistor is ON. Resistance between A & B is maximum (i.e R) when transistor is off.

❖ The effective resistance connected between A & B is given by,

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

Where α is the duty cycle.

❖ Power consumed by R_{AB} is,

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

❖ Power consumed by R_{AB} per phase is,

$$\frac{P_{AB}}{3} = \frac{I_d^2(1 - \alpha)R}{3} -----3$$

❖ From eqn. 1,

$$I_d = \sqrt{\frac{3}{2}} I_r -----4$$

14

- ❖ Substituting eqn 4 in eqn 3, we get,

$$\frac{P_{AB}}{3} = \frac{I_d^2(1-\alpha)R}{3} = \frac{\frac{3}{2}I_r^2(1-\alpha)R}{3}$$

- ❖ Therefore power consumed by R_{AB} per phase is,

$$= 0.5. I_r^2(1-\alpha). R ----5$$

- ❖ From the above equation 5, it is clear that the rotor resistance is increased by 0.5 R(1-α)
- ❖ Thus the total resistance in the rotor circuit is,

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

- ❖ From the above equation, it is clear that rotor resistance is varied from R_r to $(R_r+0.5R)$ when α is varied from 1 to 0.

Advantages of rotor resistance control method

- ❖ Smooth and stepless control is possible.
- ❖ Quick response
- ❖ Less maintenance
- ❖ Compact size.

Disadvantages of rotor resistance control method

- ❖ Increase in rotor resistance leads to increase of power loss in the rotor resistance. This will reduce the system efficiency.

4.8.3 Energy efficient drive (Or) Slip Power Recovery Schemes

- ❖ In rotor resistance control method of speed control, the slip power is wasted in the external resistance and hence the efficiency reduces.
- ❖ However instead of wasting the slip power in external resistor, it can be recovered and supplied back in order to improve the overall efficiency.
- ❖ This scheme of recovering the power is called slip power recovery scheme and this is done by connecting an external source of emf of slip frequency to the rotor circuit.
- ❖ The injected emf can either oppose the rotor induced emf or aids the rotor induced emf.
- ❖ If it opposes the rotor induced emf, the total rotor resistance increases and hence speed decreases
- ❖ If the injected emf aids the main rotor emf the total resistance decreases and hence speed increases.
- ❖ Therefore by injecting induced emf in rotor circuit the speed can be easily controlled.