Section-B

INDUCTION MOTOR:

An induction motor (also known as an asynchronous motor) is a commonly used AC electric motor. In an induction motor, the electric current in the rotor needed to produce torque is obtained via electromagnetic induction from the rotating magnetic field of the stator winding. The rotor of an induction motor can be a squirrel cage rotor or wound type rotor.

Induction motors are referred to as 'asynchronous motors' because they operate at a speed less than their synchronous speed.

Synchronous speed is the speed of rotation of the magnetic field in a rotary machine, and it depends upon the frequency and number poles of the machine. The induction motor always runs at speed less than its synchronous speed.

The types of induction motors can be classified depending on whether they are a single phase or three phase induction motor.

1. **Single Phase Induction Motor**

The types of single phase induction motors include:

- Split Phase Induction Motor
- Capacitor Start Induction Motor
- Capacitor Start and Capacitor Run Induction Motor
- Shaded Pole Induction Motor

2. **Three Phase Induction Motor**

The types of three phase induction motors include:

- Squirrel Cage Induction Motor
- Slip Ring Induction Motor

VOLTAGE / FREQUENCY CONTROL (OR) VOLTS / HERTZ CONTROL (V/F):

- 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.

- At low frequencies (when speed is reduced), the term (Rs / 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.

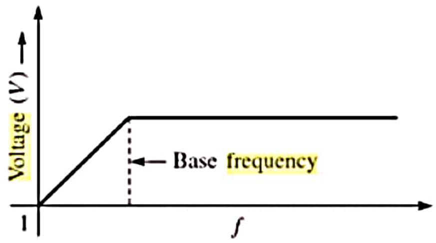


Fig. 4.5. V – f relationship

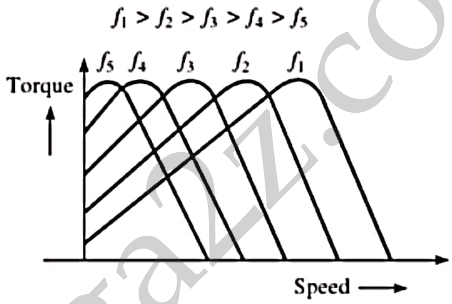


Fig. 4.6. Speed – Torque characteristics

- 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.

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.

VECTOR CONTROL OF INDUCTION MOTOR

The control of inverter fed induction motor has given good steady state response. But it gives poor dynamic response.

- The reason for this is that the air-gap flux keeps changing in magnitude and direction.
- This variation needs to be controlled by controlling the magnitude and angle of the stator and rotor currents.
- The variation in angle of the currents results in torque variations which is not good. Also it increases the current drawn by the motor and hence higher rating inverters are needed.
- Separately excited DC motor drives are simpler in control because they separately control the flux.
- Separate control in dc motors is possible because armature current and field current can be independently controlled.
- But in an induction motor, a coordinated control of the magnitude, phase and frequency of the stator current is required. This type of control is much complicated when compared to dc motor control.

Vector control schemes are classified into two types based on how the field angle is calculated. They are,

1. Direct vector control: If the field angle is calculated by using terminal voltages and currents or hall sensors, then it is called direct vector control.

2. Indirect vector control: If the field angle is calculated by using rotor position measurement, then it is called indirect vector control.

REFEREBCE FRAME THEORY FOR INDUCTION MOTOR:

- A change of variables which formulates a transformation of the 3-phase variables of stationary circuit elements to the arbitrary reference frame may be expressed

$$f_{qdos} = K_s f_{abcs}$$

$$(f_{qdos})^T = [f_{qs} \; f_{ds} \; f_{os}]$$

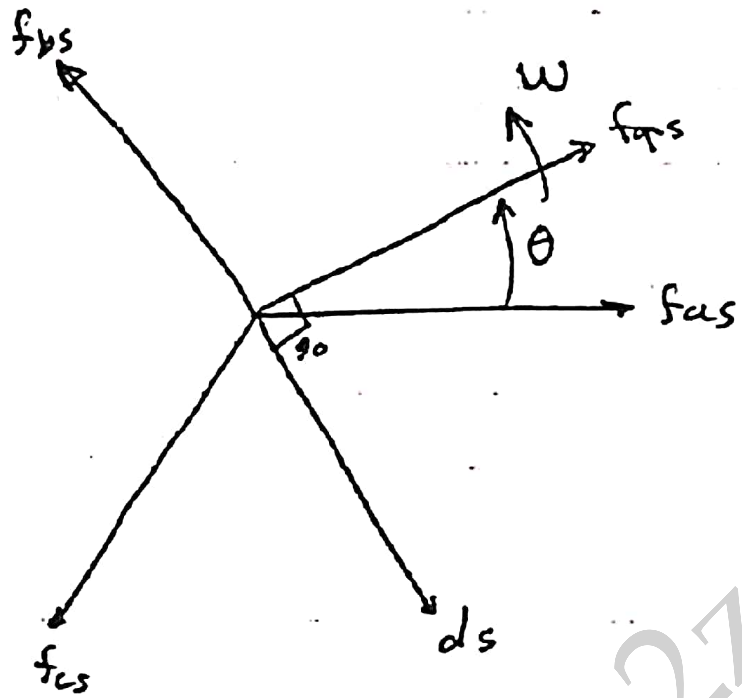
$$(f_{abcs})^T = [f_{as} \; f_{bs} \; f_{cs}]$$

$$K_s = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin\theta & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

$$\theta = \int_0^t \omega(t)dt + \theta(0)$$

$$(K_s)^{-1} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{2\pi}{3}) & 1 \\ \cos(\theta + \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) & 1 \end{bmatrix}$$

- "f" can represent either voltage, current, or flux linkage.
- 's' indicates the variables, parameters and transformation associated with stationary circuits.
- 'w' represent the speed of reference frame.



$\omega = 0$ stationary reference frame

$\omega = \omega_e$ synchronously rotating reference frame

$\omega = \omega_r$ rotor ~~refe~~rence frame (i.e the reference frame is fixed on the rotor)

For the three-phase circuit shown, L_s is a diagonal matrix, and

$$\lambda_{abcs} = L_s i_{abcs}$$

$$\lambda_{qdos} = \underbrace{K_s L_s K_s^{-1}}\, i_{qdos}$$

$$\lambda_{qdos} = L_s\, i_{qdos}$$

- For three-phase induction or synchronous machines, L_s matrix is expressed as

$$L_s = \begin{bmatrix} L_{ls}+L_{ms} & -\frac{1}{2}L_{ms} & -\frac{1}{2}L_{ms} \\ -\frac{1}{2}L_{ms} & L_{ls}+L_{ms} & -\frac{1}{2}L_{ms} \\ -\frac{1}{2}L_{ms} & -\frac{1}{2}L_{ms} & L_{ls}+L_{ms} \end{bmatrix}$$

L_{ls} : leakage inductance , L_{ms} : magnetising inductance.

$$K_s L_s (K_s)^{-1} = \begin{bmatrix} L_{ls}+\frac{3}{2}L_{ms} & 0 & 0 \\ 0 & L_{ls}+\frac{3}{2}L_{ms} & 0 \\ 0 & 0 & L_{ls} \end{bmatrix}$$

DIRECT TORQUE CONTROL OF INDUCTION MOTOR:

In Direct Torque Control it is possible to control directly the stator flux and the torque by selecting the appropriate inverter state.

Its main features are as follows [LUD 1] [VAS 2]:

- Direct torque control and direct stator flux control.
- Indirect control of stator currents and voltages.
- Approximately sinusoidal stator fluxes and stator currents.
- High dynamic performance even at locked rotor.

In figure 2.2 a possible schematic of Direct Torque Control is shown. As it can be seen, there are two different loops corresponding to the magnitudes of the stator flux and torque. The reference values for the flux stator modulus and the torque are compared with the actual values, and the resulting error values are fed into the two-level and three-level hysteresis blocks respectively. The outputs of the stator flux error and torque error hysteresis blocks, together with the position of the stator flux are used as inputs of the look up table (see table II.II). The position of the stator flux is divided into six different sectors. In accordance with the figure 2.2, the stator flux modulus and torque errors tend to be restricted within its respective hysteresis bands. It can be proved that the flux hysteresis band affects basically to the stator-current distortion in terms of low order harmonics and the torque hysteresis band affects the switching frequency [VAS 2].

The DTC requires the flux and torque estimations, which can be performed as it is proposed in figure 2.2 schematic, by means of two different phase currents and the state of the inverter.

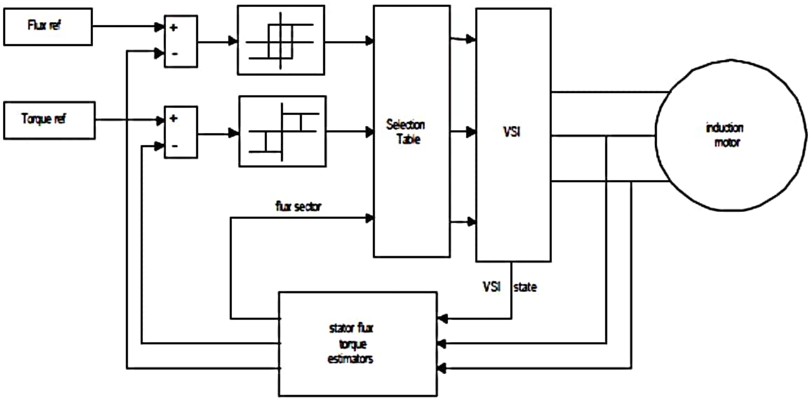


Figure 2.2. Direct Torque Control schematic.

However, flux and torque estimations can be performed using other magnitudes such as two stator currents and the mechanical speed, or two stator currents again and the shaft position

This method presents the following advantages:

- Absence of co-ordinate transform.
- Absence of voltage modulator block, as well as other controllers such as PID for flux and torque.
- Minimal torque response time, even better than the vector controllers.

Although, some disadvantages are present:

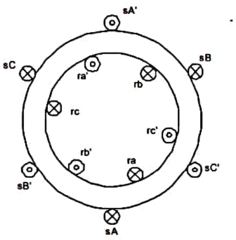
- Possible problems during starting.
- Requirement of torque and flux estimators, implying the consequent parameters identification.
- Inherent torque and flux ripples.

Modelling of Induction Motor:

A dynamic model of the machine subjected to control must be known in order to understand and design vector controlled drives. Due to the fact that every good control has to face any possible change of the plant, it could be said that the dynamic model of the machine could be just a good approximation of the real plant. Nevertheless, the model should incorporate all the important dynamic effects occurring during both steady-state and transient operations.

For simplicity, the induction motor considered will have the following assumptions:

- Symmetrical two-pole, three phases windings.
- The slotting effects are neglected.
- The permeability of the iron parts is infinite.
- The flux density is radial in the air gap.
- Iron losses are neglected.
- The stator and the rotor windings are simplified as a single, multi-turn full pitch coil situated on the two sides of the air gap.



In the stationary reference frame, the equations can be expressed as follows:

$$u_{sA}(t) = R_s i_{sA}(t) + \frac{d\psi_{sA}(t)}{dt} \quad (1.1)$$

$$u_{sB}(t) = R_s i_{sB}(t) + \frac{d\psi_{sB}(t)}{dt} \quad (1.2)$$

$$u_{sC}(t) = R_s i_{sC}(t) + \frac{d\psi_{sC}(t)}{dt} \quad (1.3)$$

Similar expressions can be obtained for the rotor:

$$u_{ra}(t) = R_r i_{ra}(t) + \frac{d\psi_{ra}(t)}{dt} \quad (1.4)$$

$$u_{rb}(t) = R_r i_{rb}(t) + \frac{d\psi_{rb}(t)}{dt} \quad (1.5)$$

$$u_{rc}(t) = R_r i_{rc}(t) + \frac{d\psi_{rc}(t)}{dt} \quad (1.6)$$

The instantaneous stator flux linkage values per phase can be expressed as:

$$\psi_{sA} = \overline{L}_s i_{sA} + \overline{M}_s i_{sB} + \overline{M}_s i_{sC} + \overline{M}_{sr}\cos\theta_m i_{ra} + \overline{M}_{sr}\cos(\theta_m + 2\pi/3) i_{rb} + \overline{M}_{sr}\cos(\theta_m + 4\pi/3) i_{rc} \quad (1.7)$$

$$\psi_{sB} = \overline{M}_s i_{sA} + \overline{L}_s i_{sB} + \overline{M}_s i_{sC} + \overline{M}_{sr}\cos(\theta_m + 4\pi/3) i_{ra} + \overline{M}_{sr}\cos\theta_m i_{rb} + \overline{M}_{sr}\cos(\theta_m + 2\pi/3) i_{rc} \quad (1.8)$$

$$\psi_{sC} = \overline{M}_s i_{sA} + \overline{M}_s i_{sB} + \overline{L}_s i_{sC} + \overline{M}_{sr}\cos(\theta_m + 2\pi/3) i_{ra} + \overline{M}_{sr}\cos(\theta_m + 4\pi/3) i_{rb} + \overline{M}_{sr}\cos\theta_m i_{rc} \quad (1.9)$$

In a similar way, the rotor flux linkages can be expressed as follows:

$$\psi_{ra} = \overline{M}_{sr}\cos(-\theta_m) i_{sA} + \overline{M}_{sr}\cos(-\theta_m + 2\pi/3) i_{sB} + \overline{M}_{sr}\cos(-\theta_m + 4\pi/3) i_{sC} + \overline{L}_r i_{ra} + \overline{M}_r i_{rb} + \overline{M}_r i_{rc} \quad (1.10)$$

$$\psi_{rb} = \overline{M}_{sr}\cos(-\theta_m + 4\pi/3) i_{sA} + \overline{M}_{sr}\cos(-\theta_m) i_{sB} + \overline{M}_{sr}\cos(-\theta_m + 2\pi/3) i_{sC} + \overline{M}_r i_{ra} + \overline{L}_r i_{rb} + \overline{M}_r i_{rc} \quad (1.11)$$

$$\psi_{rc} = \overline{M}_{sr}\cos(-\theta_m + 2\pi/3) i_{sA} + \overline{M}_{sr}\cos(-\theta_m + 4\pi/3) i_{sB} + \overline{M}_{sr}\cos(-\theta_m) i_{sC} + \overline{M}_r i_{ra} + \overline{L}_r i_{rb} + \overline{M}_r i_{rc} \quad (1.12)$$

Taking into account all the previous equations, and using the matrix notation in order to compact all the expressions, the following expression is obtained:

$$\begin{bmatrix} u_{sA} \\ u_{sB} \\ u_{sC} \\ u_{ra} \\ u_{rb} \\ u_{rc} \end{bmatrix} = \begin{bmatrix} R_s + p\overline{L}_s & p\overline{M}_s & p\overline{M}_s & p\overline{M}_{sr}\cos\theta_m & p\overline{M}_{sr}\cos\theta_{m1} & p\overline{M}_{sr}\cos\theta_{m2} \\ p\overline{M}_s & R_s + p\overline{L}_s & p\overline{M}_s & p\overline{M}_{sr}\cos\theta_{m2} & p\overline{M}_{sr}\cos\theta_m & p\overline{M}_{sr}\cos\theta_{m1} \\ p\overline{M}_s & p\overline{M}_s & R_s + p\overline{L}_s & p\overline{M}_{sr}\cos\theta_{m1} & p\overline{M}_{sr}\cos\theta_{m2} & p\overline{M}_{sr}\cos\theta_m \\ p\overline{M}_{sr}\cos\theta_m & p\overline{M}_{sr}\cos\theta_{m1} & p\overline{M}_{sr}\cos\theta_{m2} & R_r + p\overline{L}_r & p\overline{M}_r & p\overline{M}_r \\ p\overline{M}_{sr}\cos\theta_{m2} & p\overline{M}_{sr}\cos\theta_m & p\overline{M}_{sr}\cos\theta_{m1} & p\overline{M}_r & R_r + p\overline{L}_r & p\overline{M}_r \\ p\overline{M}_{sr}\cos\theta_{m1} & p\overline{M}_{sr}\cos\theta_{m2} & p\overline{M}_{sr}\cos\theta_m & p\overline{M}_r & p\overline{M}_r & R_r + p\overline{L}_r \end{bmatrix} \cdot \begin{bmatrix} i_{sA} \\ i_{sB} \\ i_{sC} \\ i_{ra} \\ i_{rb} \\ i_{rc} \end{bmatrix}$$

(1.13)