Lecture-14

AC DRIVES -Speed Control of Induction Motors

14.1 INTRODUCTION

The three- phase induction motor runs at a speed slightly less than synchronous speed and is load dependents. Therefore, it is an inherently a constant speed motor and its output mechanical power depends on the slip s , that is :

$$P_o = T_L\omega = T_L(1 - s)\omega_s$$

So it is difficult to control its speed and if it is done ,it will be at the cost of decrease in efficiency and low electrical power factor.
The synchronous speed is given by the equation

$$n_s = \frac{120f}{p} \qquad (14.1)$$

where f = frequency and p is the number of pole .

The speed of induction motor is given by,

$$\mathrm{n} = n_s(1 - s) \qquad (14,2)$$

Hence, the speed of the induction motor can be changed either from the **<u>stator</u>** or from the **<u>rotor</u>** sides. Therefore, from Eq. (14.1), the speed control of the motor from **stator** side are classified as:

1. Changing the number of stator poles (p).
2. Stator voltage control (controlling the supply voltage (V_1)).
3. Supply frequency changing:
   (i) Variable-voltage, variable-frequency (V/ f) control.
   (ii) Variable-current, variable-frequency (I / f) control.
4. Adding rheostat in the stator circuit (rotor resistance control).

The speed controls of induction motor from **rotor** side are further classified as:

1. Adding external resistance on rotor side.
2. Rotor injected voltage / slip energy recovery.
3. Cascade control method.

These methods are sometimes called scalar controls to distinguish them from vector controls. The torque–speed characteristics of the motor differ significantly under different types of control.

14.2 SPEED CONTROL FROM STATOR SIDE

(1) Changing the number of stator poles (p)

The stator poles can be changed by two methods

(i) Multiple stator winding method.
(ii) Pole amplitude modulation method (PAM)

- Multiple - stator winding method: In this method of speed control of three - phase induction motor , the stator is provided by two separate winding. These two stator windings are electrically isolated from each other and are wound for two different pole numbers.

Using switching arrangement, at a time, supply is given to one winding only and hence speed control is possible.

Disadvantage:

This method will enable speed changes in terms of 2:1 ratio steps, hence to obtained variations in speed, multiple stator windings has to be applied. Multiple stator windings have extra sets of windings that may be switched in or out to obtain the required number of poles. Unfortunately this would an expensive alternative.

This method is not in use now a days.

- Pole amplitude modulation method (PAM) – In this method of speed control of three-phase induction motor the original sinusoidal mmf wave is modulated by another sinusoidal mmf wave having different number of poles.

Disadvantage : This method gives limited speed range , since the resultant mmf wave will have two different numbers of poles only.

(2) Controlling supply voltage (Variation of stator voltage)

It is seen from Lecture -13 that at any fixed speed ,if we neglect the mechanical losses, the developed torque T_L (=T_d) is proportional to the square of the applied stator voltage V_1^2 . As the stator voltage is reduced the rotor speed decreases and the maximum torque available from the motor also decreases. If the stator voltage is varied to control the speed then the speed range of this method is limited with a constant – torque load. This can be proved as follows:

The torque produced by running 3- phase induction motor was given in lecture-13 as

$$T_L \propto \frac{s\, E_2^{\,2}\, R_2}{R_2^{\,2}+(sX_2\,)^2}$$

In low slip region $(sX_2)^2$ is very small as compared to $(R_2)^2$, hence it can be neglected. Therefore the torque becomes,

$$T_L \propto \frac{s\, E_2^{\,2}}{R_2} \qquad (14.3)$$

Since rotor resistance, R_2 is constant so the equation of torque further reduces to

$$T_L \propto s\, E_2^{\,2}$$

We know that rotor induced *emf* $E_2 \propto V_1$, the supply voltage. So,

$$T_L \propto s\, V_1^2 \qquad (14.4)$$

From the equation above it is clear that if we decrease supply voltage by one half the torque reduces to one quarter. Therefore, the low speed performance of the motor with this method is poor because motor current at a given slip is also proportional to the applied voltage whereas the torque varies as the square of the voltage.

Methods of reducing stator voltage V_1 :

1- Rheostatic control

This is done by connecting variable resistance or impedance between stator terminals and the a.c. supply as shown in Fig.14.1. The ohmic losses of this method of speed control are excessive and particularly at low speeds. Since the torque produced in an induction motor is proportional to the square of the supply voltage ($T \propto s\, E_2^{2}$), then if we decrease E_1, by reducing the supply voltage, torque will also decrease. However, this method is not efficient from energy saving point of view and it is rarely used nowadays.

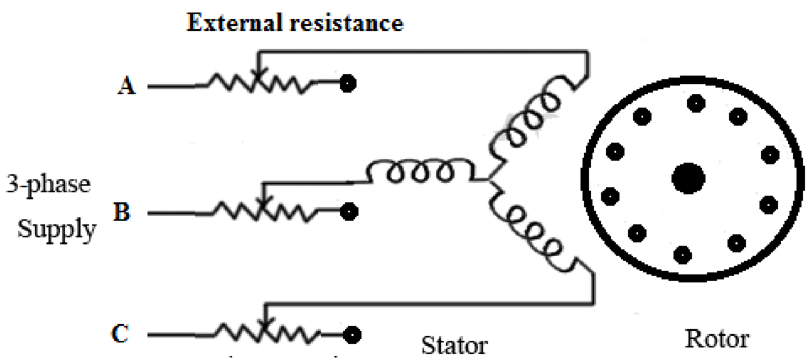


Fig.14.1 Speed control of three-phase induction motor by adding rheostat in the stator circuit.

2. Electronic control

Nowadays, reduction of stator voltage is performed by using thyristors (and tiacs) that offers several advantages. With thyristors different techniques can be used to control the *rms* voltage applied to the motor. Thyristor can be used as:

- AC regulators (see Fig.14.2)
- Transformer adjustable tap changers
- Controllers for multi – winding transformer secondary

The torque – speed characteristics of a 3-phase induction motor with stator voltage variation method is shown in Fig.14.3. The operating point of an induction motor can be located on the torque speed characteristics diagram and it is defined by the point of intersection between the motor characteristics and the load characteristic.

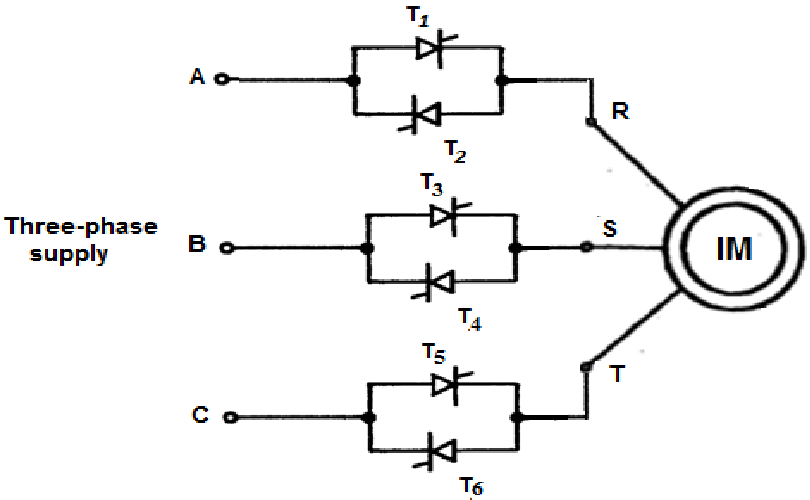


Fig.14.2 Reduction of stator voltage of induction motor using three-phase thyristor a.c. regulator.

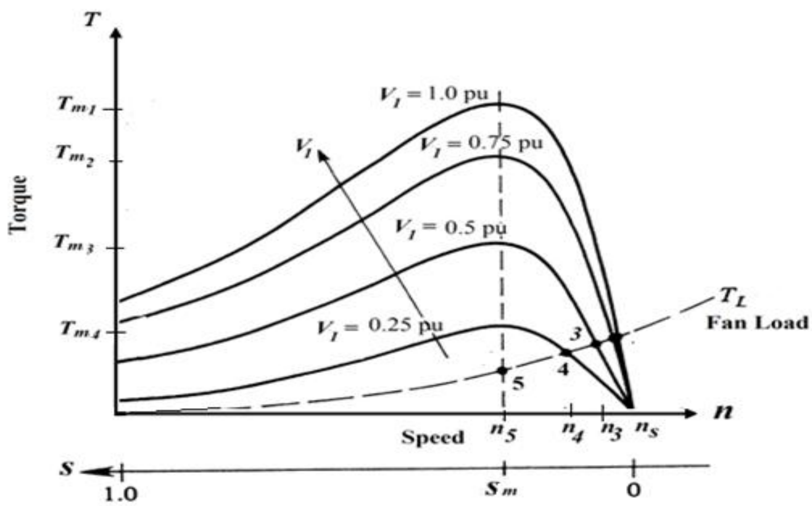


Fig .14.3 Speed- torque characteristic of induction motor for voltage control with fan load.

For small reduction in supply voltage the speed variation will be very small, so that, for example, point 2 in Fig.14.3 is not shown.

The performance analysis of the motor with its thyristor controller would be very complex due to the interaction between the motor and its controller.

The accurate analysis would require solution of several nonlinear differential equations for the voltage, speed and electromagnetic torque. The general solution is only possible using computer simulation techniques such as Matlab and other computer programmes. However, for steady – state solution using the approximate equivalent circuit given in lecture-13 one can find the performance of the three-phase induction motor when speed controlled by voltage variation technique as illustrated in the following example.

Example 14.1

A 3.5 hp, 415V, 50Hz, 4-pole, 1370 rpm, star - connected induction motor has the following parameters referred to the stator side:

$R_1 = 2\ \Omega$, $R_2 = 5\ \Omega$, $X_1 = 5.25\ \Omega$, $X_2 = 4.75\ \Omega$, X_m = Very high.

The speed of the motor is controlled by voltage variation method using two back to back connected thyristors in each line with symmetrical phase angle triggering mode. The delay angles of the thyristors are set to give a line to line voltage of 300V across the motor windings. Calculate the motor speed, current and torque when driving a fan load its characteristic is given by:

$$T_L = 57.8\,(1-s)^2$$

Solusion

The torque of the three-phase induction motor for the three phases is

$$T = \frac{3{V_1}^2}{s\,\omega_s} \times \frac{R_2}{(R_1 + \frac{R_2}{s})^2 + (X_1 + X_2)^2}$$

n_s =Synchronous speed in rpm = $120f$ / p = 120x50 /4 =1500.

$$\omega_s = \frac{2\pi n_s}{60} = \frac{2\pi x 1500}{60} = 50\pi \text{ rad/s}$$

$$T = \frac{3}{50\pi s} x \frac{300^2 x5}{(2+\frac{5}{s})^2 + (5.25+4.75)^2} = \frac{8600\ s}{(104s^2+20s+25)}$$

At steady-state, $T = T_L$, hence

$$\frac{8600\ s}{(104s^2+20s+25)} = 57.8\ (1-s)^2$$

From which ;

$$\therefore \quad 104s^4 + 188s^3 + 89s^2 + 179s + 25 = 0$$

From which; s = 0.1468

The torque produced by the motor is

$$T = 57.8\ (1-0.1468)^2 = 41.9\ Nm$$

The speed of the motor at 300V is

$$n = n_s\ (1-s)^2 = 1500(1-0.1468)^2 = 1280 \text{ rpm}$$

The line current is calculated as , and since X_m is very high , thus I_1=I_2 ,

$$I_1 = I_2 = \frac{V_1}{\sqrt{\left(R_1 + \frac{R_2}{s}\right)^2 + (X_1 + X_2)^2}}$$

$$\therefore \quad I_1 = \frac{300}{\sqrt{\left(5 + \frac{5}{0.1468}\right)^2 + (10)^2}} = 8.1\ \angle 15.48°\ \text{A}$$

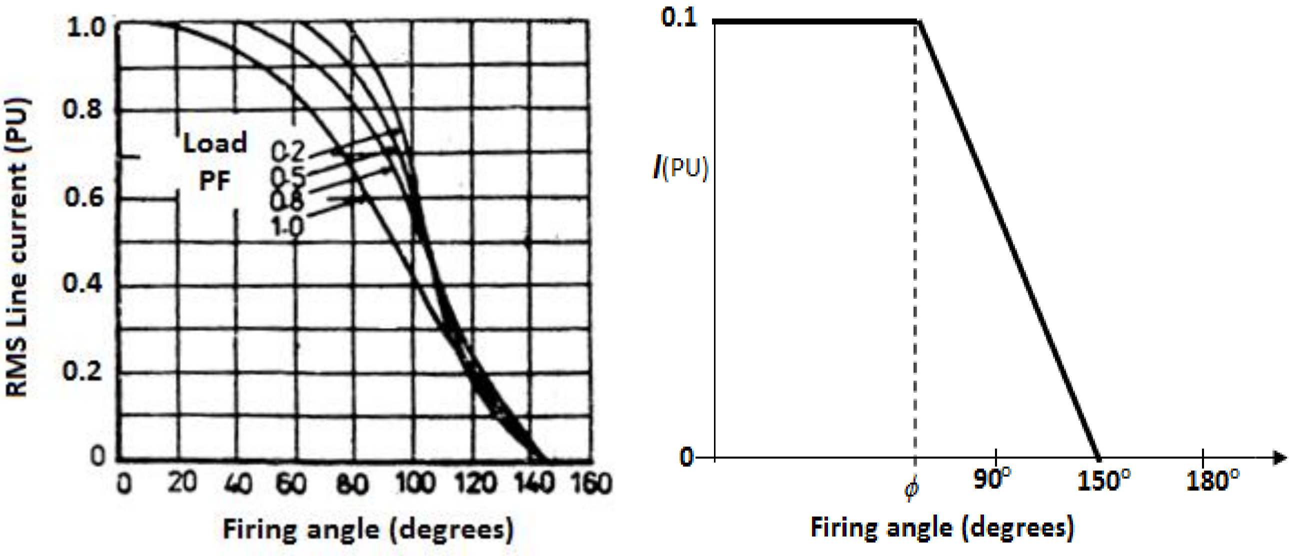
Approximate method of solution

It is seen from the above example that the equation of the slip s obtain is of high order that is mathematically difficult to solve. However, an approximate method of solution for steady-state operation can be used over a range of average speeds to determine the corresponding range of thyristor firing angles.

This approximate method uses the motor fundamental equivalent circuit together with the curves giving the relation between the per unit current and the firing angles for both particular speed and load angles. These curves are shown in Fig.14.4 (a) and can be approximated by straight line as depicted in Fig. 14.4(b).

For star- connected motors with large phase angle ϕ , the approximated straight line relationship between the current and firing angle α can be represented mathematically as

$$I(pu) = \frac{150 - \alpha}{150 - \emptyset} \tag{14.5}$$



(a) (b)

Fig. 14.4 Current and the firing angles relationship for three-phase star connected R-L load : (a) RMS line current versus α ,(b) Straight line approximation of current (pu) for three-wire star-connected induction motor.

For branch-delta connected motor, the approximate relation is found to be roughly as

$$I(pu) = \frac{180 - \alpha}{180 - \emptyset} \tag{15.22}$$

Example 14.2

A variable speed drive is used to drive a water pump which has a torque-speed curves described by the equation $T_L = 0.005\ \omega^2$ SI units, where ω is the speed of the pump motor. The drive employs a three-phase, 240V, six-pole, 50 Hz, star-connected induction motor controlled by pairs of inverse-parallel connected thyristors in each supply line. The per-phase equivalent circuit parameters of the motor, referred to primary turns are $R_1 = 0.3\ \Omega, R_2 = 0.2\ \Omega, X_1 = X_2 = 0.6\ \Omega$,

X_m = infinity. The required speed range is 975-600 r.p.m. Use performance curves of current versus firing-angle to calculate, approximately. The necessary ranges of thyristor firing-angles.

Solution

The synchronous speed of the motor n_s

$$n_s = \frac{120\, f_1}{p} = \frac{120x50}{6} = 1000\, rpm$$

The slip s is given as

$$s = \frac{n_s - n}{n_s}$$

Hence

$$s_1 = \frac{1000 - 975}{1000} = 0.025$$

$$s_2 = \frac{1000 - 600}{1000} = 0.4$$

From lecture - 13 , the output power for the three phases of the motor is

$$P_o = \omega T_L = 3 I_2^2 R_2 \left(\frac{1 - s}{s}\right)$$

$$\frac{R_2}{s_1} = \frac{0.2}{0.025} = 8\,\Omega$$

$$\frac{R_2}{s_2} = \frac{0.2}{0.4} = 0.5\,\Omega$$

From the approximate equivalent circuit, neglecting the magnetising branch,

$$Z_{in1} = (0.3 + 8) + j1.2 = 8.4\,\angle 8.25°\Omega$$

$$Z_{in2} = (0.3 + 0.5) + j1.2 = 1.44\,\angle 56.12°\Omega$$

$$T_{L975} = \omega^2/200 = \frac{(975x\frac{2\pi}{60})^2}{200} = 52.124\, Nm$$

$$I = I_2 = \sqrt{\frac{\omega T_{L975} s}{3R_2(1 - s_1)}} = \sqrt{\frac{975x\frac{2\pi}{60}x52.124x0.025}{3x0.2x(1 - 0.025)}} = 15.1\, A$$

$$I_{base} = \frac{240}{\sqrt{3}} x \frac{1}{8.4} = 16.5\ A$$

$$I_{pu} = \frac{15.1}{16.5} = 0.989$$

From Fig,14.3 (a),

$$PF_1 = \cos 8.25° = 0.989 \qquad \rightarrow \qquad \alpha_1 = 50°.$$

$$T_{L600} = \omega^2/200 = \frac{(600x\frac{2\pi}{60})^2}{200} = 19.74\ Nm$$

$$I = \sqrt{\frac{\omega T_{L600}\, s}{3R_2(1-s_2)}} = \sqrt{\frac{600x\frac{2\pi}{60}x19.74x0.4}{3x0.2x(1-0.4)}} = 37.12\ A$$

$$I_{base} = \frac{240}{\sqrt{3}} x \frac{1}{1.44} = 96.23\ A$$

$$I_{pu} = \frac{37.122}{96.23} = 0.386$$

From Fig,14.3 (a),

$$PF_2 = \cos 56.12° = 0.557 \qquad \rightarrow \qquad \alpha_2 = 110°.$$

Therefore the range of the delay angles is

$$50° \leq \alpha \leq 110°.$$

It is obvious that, with this method of speed control, the variation of speed is not great (if the voltage reduced to ½) . It generates harmonics and electromagnetic interferences. However, the method for obtaining speed change is simple and energy saving is possible.