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EEE 327.2

ELECTRICAL MACHINES II

3.0. STARTING, SPEED CONTROL AND BREAKING OF POLYPHASE INDUCTION MOTOR

27-09-22

3.1. Starting of Squirrel Cage Motors

In general a motor experiences an extremely high current during its starting and accelerating, unless steps are taken to keep starting current down to a reasonable value. In the case of the induction motor for example, the squirrel cage rotor ressembles a short circuited secondary. Therefore the current in the rotor will be very high and consequently the stator will draw a very high current from the supply

The magnitude of the starting current depends on the electrical design of the motor and is independent of the mechanical load. However, the duration of the starting current depends on the time required to accelerate which in turn depends on the nature of the mechanical load. It is important to reduce the starting current to such an extent that the line voltage drop does not affect the operation of other equipment on the same distribution line.

There are several methods of starting the squirrel cage induction motor. The following section describes the more common methods. The common methods include;

i. Derect-on-line or full voltage starting
ii. Primary resistor or reactor starting
iii. Auto transformer starting
iv. Star-Delta starting.

Direct-on-line or full voltage starting

This is the most economical method of starting an induction motor and as the name implies it involves direct switching the squirrel cage induction motor to the supply mains as shown in figure 3.1.

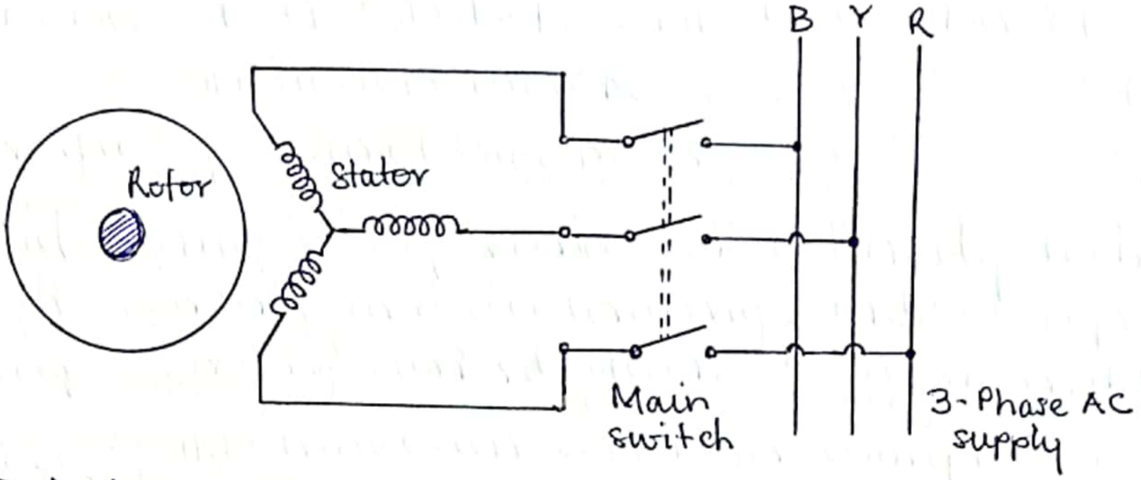

Fig. 3.1. Direct-on-line starting of squirrel cage induction motors

Although there is no limit on the size of motor to be started by this method it may result in unwanted line voltage drop. Therefore its use would depend on the following;

(a) Size and design of the motor.
(b) the kind of application
(c) location of the motor in the distribution line
(d) the capacity of the power system and rules governing such installations.

This method works best for large capacity motors with large rotor resistance.

Primary resistor or reactor starting

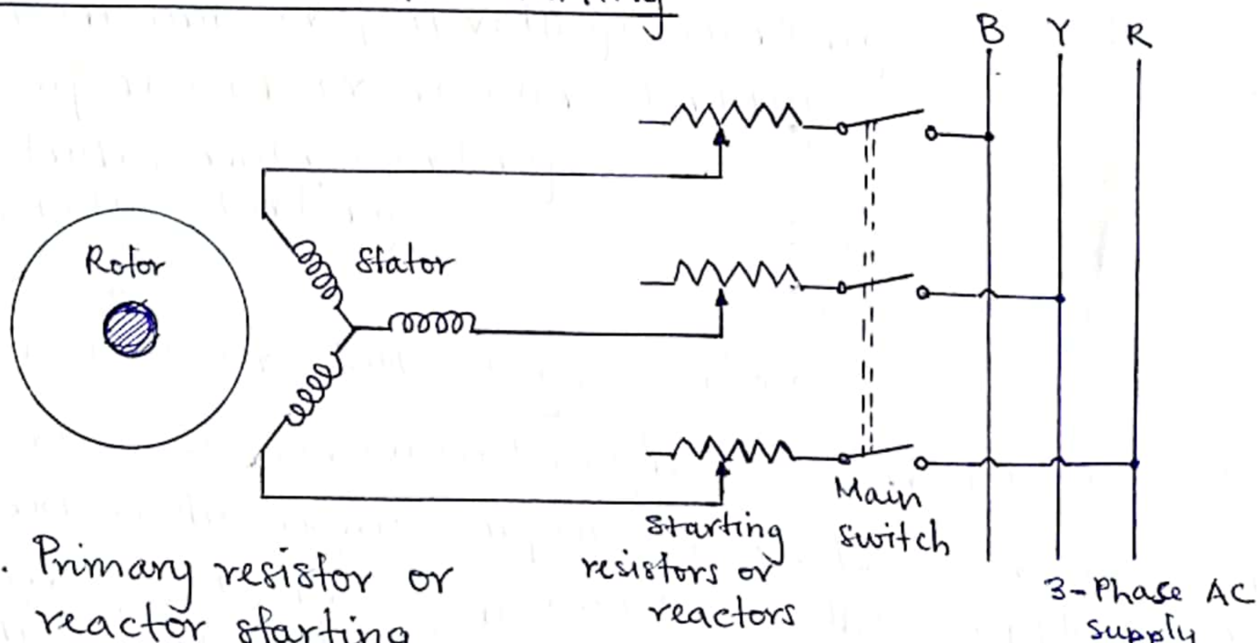

Fig. 3.2. Primary resistor or reactor starting

As dipicted by figure 3.2, in this method of starting a 3-phase induction motor reduced voltage at starting is obtained by connecting resistors (or reactors) in series with each lead of the stator. The voltage drop across each resistor causes a reduced voltage across the stator terminals. As the motor picks up speed the resistors are gradually cut out and finally short circuited when the motor attains operating speed.

The advantages and disadvantages of this method include;

Advantages	Disadvantages
1. Smooth acceleration	1. Resistors give off heat
2. High power factor at starting	2. Low torque efficiency
3. Less expensive than auto-transformer starting	3. It requires expensive resistors since starting time exceeds 5 seconds.
4. Closed transition starting	
5. Available in as many as 7 accelerating points	

Auto transformer starting

In this method the reduced starting voltage is achieved by taking suitable tappings from a 3-phase auto transformer as illustrated in figure 3.3. For proper starting torque requirements the auto transformers are generally tapped at the 50, 60 and 80 percent points.

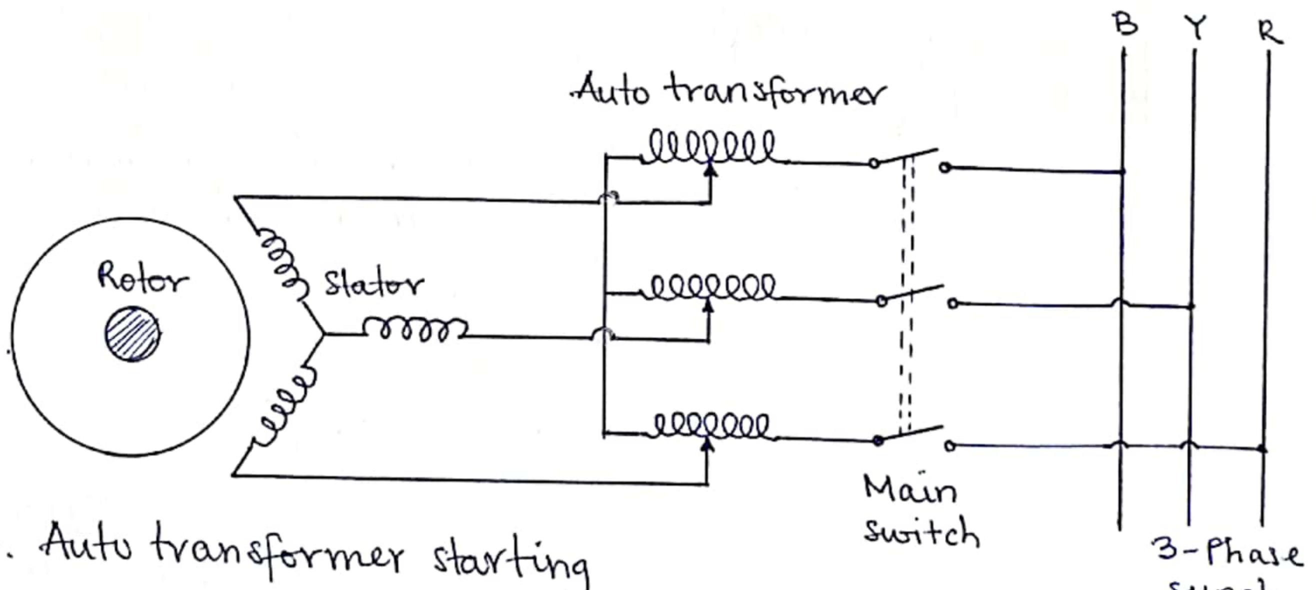

Fig. 3.3. Auto transformer starting

Since the auto transformer contacts frequently break large values of current they are assembled to operate in oil bath to prevent arcing. Auto transformer starters may be manually or magnetically operated.

Star-delta starting

The star-delta starting functions in such a way that at starting the three stator windings are connected in star across the rated supply voltage while after the motor attains speed the same stator windings are connected in delta across the same supply voltage, by means of a change over switch.

This method is based on principle that in star connection the voltage across each winding is $1/\sqrt{3}$ or 57.7 % of the line voltage whereas the same winding connected in delta will have full line-to-line voltage across each. Therefore by this principle the starting voltage is effectively reduced.

3.2. Starting of Slip-ring Induction Motors

In general, though the methods described in the preceding section for the squirrel cage induction motor can be used for a slip ring motor they are not used because the advantages of wound rotor cannot be fully realized. Instead a rotor resistance starter is deployed. Slip-ring induction motors are usually started with full line voltage across the stator terminals made possible by introducing a variable resistance in each phase of the rotor circuit.

The external resistance introduced into each phase of the rotor circuit not only reduces the rotor current but also increases the starting torque due to improved power factor. As the motor accelerates the external resistance is gradually cut out and the rotor windings are eventually short circuited when the rotor attains rated speed.

3.3. Speed Control of Induction Motors

For the purpose of industrial operations motors must satisfy very strict speed requirements both in terms of the range and smoothness of control and also with respect to economic operation. The problem of speed control of electrical motors is therefore of great importance.

It must be noted that in terms of speed control induction motors are inferior to DC motors. This is because the speed of an induction motor cannot be adjusted without loosing efficiency and good speed regulation.

Recall that the synchronous speed N_s is given as

$$N_s = \frac{120f}{P}$$

But percent slip, s is given as

$$S = \frac{N_s - N}{N_s}$$

$$\therefore N_s = N/(1-S)$$

Therefore,

$$\frac{N}{1-S} = \frac{120f}{P}$$

$$\therefore N = \frac{120f(1-S)}{P}$$

Where,

N = Speed of motor in rpm
f = supply frequency in Hz
P = No. of poles

From the above we deduce that the speed of an induction motor depends on;

i. Supply frequency, f
ii. Number of poles, P
iii. slip, s

Hence to change the speed of an induction motor it is essential to change at least one of the above factors. The speed of an induction motor can be controlled from either the stator side or the rotor side.

Methods of speed control from the stator side include;

(a) Variation of supply frequency
(b) Variation of applied voltage
(c) Changing the number of poles

Methods of speed control from the rotor side include;

(a) By changing the resistance of the rotor circuit
(b) By introducing an additional emf into the rotor circuit

Speed Control by Variation of Supply Frequency

As the name suggests in this method speed control is achieved by varying the supply frequency. If an induction motor is to be operated at different frequencies it is essential that the supply voltage V be varied with the change in frequency according to the following equation;

$$\frac{V'}{V} = \frac{f'}{f}\sqrt{\frac{T'}{T}}$$

Where V' and T' are the voltage and torque corresponding to frequency f' while V and T are voltage and torque corresponding to frequency, f.

For constant torque operation ie $T = T'$ we have that

$$\frac{V'}{V} = \frac{f'}{f}$$

Therefore the voltage applied to the stator must vary in direct proportion to the frequency

Variable frequency supply can be achieved from various types of frequency conversion equipment such as adjustable frequency generators and rotating frequency changers. With rapid development in power electronics, combined with ruggedness of an induction motor, motors with this type of drive are gradually replacing DC motors.

Speed Control by Variation of Supply Voltage

As the name suggests speed control is achieved by variation of voltage applied to the stator. This is a slip control method. Recall the torque equation given as;

$$T = \frac{K s R_2 E_2^2}{R_2^2 + s^2 X_2^2}$$

From the above torque equation it is seen that for a given slip s and constant internal motor parameters the torque developed by an induction motor is directly proportional to the square of induced emf in the rotor, E_2

This method of speed control is simple, low in installation cost, low in operations/maintenance cost but has limited use because;

i. A large change in voltage is needed for small change in

Speed
ii. The developed torque reduces greatly with reduction in supply voltage
iii. The range of speed control is very limited in the downward direction

The variable voltage may be achieved by means of either saturable reactors, variac or tap-changing transformers.

Speed Control by Changing the Number of Poles.

While this method is easily adaptable to squirrel cage motors it is not applicable to wound rotor motors as in such machines this method would lead to complications of design and switching. This method controls speed by changing the number of poles and this can be achieved in three ways;

(a) by using multiple stator windings - by having two or more independent windings on the stator, each producing a different number of poles.
(b) by using consequent pole technique.
(c) by using pole amplitude modulation technique.

Speed Control by Variation of Rotor Resistance

As the name suggests, speed control is achieved by varying the resistance of the rotor circuit and as such is only applicable to wound rotor motors. As described earlier wound rotor motors are started by connecting starting resistances in the secondary (rotor) circuit, which are shorted out as the motor picks up speed. By properly choosing the value of external resistors they can be made to serve two purposes - starting and speed control.

From the torque equation

$$T = \frac{K s R_2}{R_2^2 + s^2 X_2^2}$$

For speeds close to synchronous speed ie when s is very small it can be seen that

$$T \propto \frac{s}{R_2}$$

Therefore for a constant torque slip can be increased (or speed reduced) by increasing the rotor resistance. This method of speed control is stepped and the larger the number of steps the smoother the speed control. This method of control is simple with low initial and maintenance cost. However the disadvantages include;

i) Reduction in speed is accompanied by reduction in efficiency.
ii) Speed does not only depend on resistance but also on load torque.
iii) External rotor resistance are considerably bulky and expensive.

<u>Example</u>

A 50 Hz, 440 V, 3-phase, 4 pole induction motor develops half the rated torque at 1,490 rpm. With applied voltage magnitude remaining at rated value, what would be its frequency if the motor has to develop the same torque at 1,600 rpm.

Solution.

Let new frequency $= f'$

$$\therefore f' = \frac{PN_s'}{120}$$

where, N_s' = new synchronous speed

$$\therefore f' = \frac{4N_s'}{120}$$

$$N_s' = \frac{N'}{1-s}$$

where N' = New motor speed = 1600 rpm

s = slip

$$\text{Slip, } s = \frac{N_s - N}{N_s} = \frac{N_s - 1490}{N_s}$$

$$N_s = \frac{120f}{p} = \frac{120 \times 50}{4} = 1500 \text{ rpm}$$

$$\therefore \text{Slip, } s = \frac{1500-1490}{1500} = 0.0067$$

$$\therefore N_s' = \frac{1600}{1-0.0067} = 1{,}610.7 \text{ rpm}$$

$$\text{and } f' = \frac{4 \times 1{,}610.7}{120} = 53.7 \text{ Hz}$$

Example

A 3-phase, 440 V, 1,000 rpm slip-ring induction motor is operating with 2% slip and taking a stator current of 50A. Speed of the motor is reduced at constant torque to 500 rpm using stator voltage control. Calculate the new value of stator current.

Solution

Let new stator current $= I_1'$

Stator current, $I_1 \propto sV$

$$\therefore \frac{I_1}{sV} = \frac{I_1'}{s'V'}$$

$$\therefore I_1' = I_1 \times \frac{s'V'}{sV}$$

where s' and V' are slip and supply voltage corresponding to the new stator current, I_1'.

When $I_1 = 50$ A

$s = 2\% = 0.02$

$V = 440$ V

$$I_1' = \frac{50 \times s'V'}{0.02 \times 440}$$

Slip at reduced speed, $s' = \frac{N_s - N'}{N_s} = \frac{1,000 - 500}{1,000} = 0.5$

Recall that for a constant torque T

$$V \propto \frac{1}{\sqrt{s}}$$

$$\therefore V\sqrt{s} = V'\sqrt{s'} \quad \text{or} \quad V' = V \times \sqrt{\frac{s}{s'}}$$

$\therefore$ New voltage, $V' = 440 \times \sqrt{\frac{0.02}{0.5}}$

$= 88V$

$\therefore$ New stator current, $I_1' = \frac{50 \times 0.5 \times 88}{0.02 \times 440}$

$= 250A.$

3.4. Electrical Braking of Polyphase Induction Motors

Although the simplest method of stopping any kind of motor is disconnect the motor from supply, when rapid and more positive action is required mechanical or electrical breaking is employed. However, when precise control and smoothness of operation is required electrical breaking holds many advantages over the mechanical breaking.

The motor is said to be under electrical breaking when the direction of developed torque is opposite to that of rotation. There are three main methods of electrical breaking namely;

i. Plugging or Counter-current breaking.
ii. Dynamic or rheostatic breaking
iii. Regenerative breaking.

Plugging or Counter-current Breaking

Plugging is achieved in an induction motor by simply interchanging any two of the three phases, thus reversing the direction of rotation of the magnetic field. At the instant of switching the motor to the plugging position the motor runs in the opposite direction to the magnetic field and the relative speed is twice the synchronous speed. The voltage induced in the rotor would therefore be twice the induced voltage at standstill. The windings must therefore be provided with the additional insulation to withstand this voltage.

During plugging period the motor acts as a brake, absorbing kinetic energy from the still revolving load causing its speed to fall. The associated power is dissipated as heat in the motor. Since the rotor is still drawing power from the stator the heat developed during breaking period is about three times the heat developed during starting or during blocked rotor test. The selection of a motor where plugging is to be applied is therefore decided not only by loading but also by braking conditions.

The expression for the breaking torque, neglecting stator impedance and magnetizing reactance is given as;

$$T_b = \frac{3 \times 60}{2\pi N_s} \cdot \frac{R_2 s E_2^2}{R_2^2 + s^2 X_2^2} \quad Nm$$

And the rotor current during breaking period is given as;

$$I_2 = \frac{sE_2}{\sqrt{R_2^2 + s^2 X_2^2}}$$

Dynamic or Rheostatic Breaking

The rheostatic breaking of a polyphase induction motor is achieved by disconnecting the stator winding from the AC supply and exciting it from a DC source, thus producing a stationary DC field. While there are several methods of connecting the stator winding to a DC source, the source of DC excitation may be from an independent source or from the AC mains through a transformer-rectifier set.

While the machine was operating normally as a motor its stator magnetic field was rotating at synchronous speed in the same direction as the rotor, though slightly faster than the rotor. However, when the stator windings are disconnected from the AC source and connected to a DC source the magnetic field becomes stationary, making the rotor conductors move past the field. The current induced into the rotor conductors under this condition will be opposite in direction to that corresponding to normal motor operation, thus producing a breaking torque.

The breaking torque is given by the expression

$$T_b = \frac{60}{2\pi N_s} \cdot 3(I_2')^2 \frac{R_2'}{s} \quad Nm$$

Regenerative Breaking

When an induction motor runs at a speed above synchronous speed it operates as a synchronous generator and feeds power back to the supply line. Thus regenerative breaking is an inherent characteristic of an induction motor. The 3-phase induction motor can be made to operate at speeds above synchronous speed by employing any of the processes,

i) Switching over to a low frequency supply in frequency controlled induction motors in order to reduce the speed of operation of the drive.

ii) Downward motion of a loaded hoisting mechanism such as crane hoists, excavators, lift etc

iii) Switching over to a large number of poles from a smaller one in a multi-speed squirrel cage motor.

Once the machine is driven above synchronous speed, the breaking operation automatically starts. The operating point would depend on the magnitude of load torque an the nature of torque speed characteristics of the machine during generating operation. By varying the resistance in the rotor circuit it is possible to operate at any speed above synchronous speed during breaking. If load torque exceeds maximum breaking torque, the system will become unstable.

This method is seldom used for breaking as it has the disadvantage of the possibility of breaking only at super-synchronous speed