CHAPTER - II

THEORETICAL BACKGROUND

2.1 INTRODUCTION

In most of the applications requiring variable speed, DC motors are widely used. One strong reason for the use of DC motors is its ability to provide a high torque at a low speed and wide speed range over which speed can be varied. After invention of fast switching devices like SCR, GTO, power transistors, and power FET, AC devices are being introduced in this field so that during the past few decades considerable attention has been paid by the industry sector to the induction machine for variable speed applications [1-10] because cage type induction motor have several advantages over dc machines, which are as follows :

1) It has very simple and extremely rugged, almost unbreakable construction.
2) Its cost is low and it is very reliable.
3) It has sufficiently high efficiency. In normal running condition, no brushes are needed, hence frictional losses are reduced. It has a reasonably good power factor.
4) It requires minimum maintenance.
5) It starts up from rest and needs no extra starting motor and has not to be synchronized.
6) Its starting arrangement is simple especially for squirrel-cage type motor.

Sophisticated control techniques, such as slip frequency control [2] flux control [3,8], vector control [5,8], phase locked-loop (PLL) control [9,10] etc., make possible high performance drives of induction motors. However, they require detection of rotational speed of induction motors. The conventional speed detectors attached to motor shafts such as tachogenerators, but they need extra consideration for maintenance. Therefore it is desirable to detect the rotor speeds without tachogenerators. Similarly measurement of the other parameters like current, voltage is also important to find out all the performance parameters. To understand the detailed behaviour of the induction motor, it is very essential to know the theoretical background of the motor. In the subsequent sections the basics of the A.C. machines have been discussed.

2.2 MOTOR PRINCIPLE

When three - phase stator windings are fed by a three phase supply then, a magnetic flux of constant magnitude but rotating at synchronous speed, is set up. The flux passes through the air gap, sweeps past the rotor surface and so cuts the rotor conductors which as yet, are stationary. Due to the relative speed between the rotating flux and stationary conductors, an emf is induced in the later according to Faraday's law of electromagnetic induction. The frequency of the induced emf is the same as the supply frequency. Its magnitude is proportional to the relative velocity between the flux and conductors and its direction is given by Flemming's right hand rule. Since the rotor bars or conductors form a closed circuit, rotor current is produced whose direction as given by Lenz's Law, is such as to oppose the very cause producing it. In this case, the cause which produces the rotor current is the relative velocity between the rotating flux of the stator and the stationary rotor conductors. Hence, to reduce the relative speed, the rotor starts running in the same direction as that of the flux and tries to catch up with rotating flux.

2.3 CONSTRUCTION

An induction motor consists of two main parts.

a) Stator :

The stator of an induction motor is, in principle the same as that of a synchronous motor or generator. It is made up of a number of stampings which are slotted to receive the windings. The stator carries a 3-phase windings and is fed from a 3-phase supply. It is wound for a definite number of poles, the exact number of poles being determined by the requirements of speed. Greater the number of poles, lesser the speed and vice versa.

b) Rotor :

i) Squirrel - cage rotor : Motors employing this type of rotor are known as squirrel - cage induction-motors.

ii) Phase-wound or wound rotor : Motors employing this type of rotor are called as slip ring motors.

2.4 SQUIRREL - CAGE ROTOR

Almost 90 percent of induction motors are squirrel cage type, because this type of rotor has the simple and most rugged construction imaginable and is almost indestructible. The rotor consists of a cylindrical laminated core with parallel slots for carrying the rotor conductors which, it should be noted clearly, are not wires but consist of heavy bars of copper, aluminium or alloys. One bar is placed in each slot, rather the bars are inserted from the end when semi-closed slots are used. The rotor bars are brazed or electrically welded or bolted to two heavy and stout short circuiting end-rings, thus giving us, what is so picturesquely called, a squirrel-cage construction.

It should be noted that the rotor bars are permanently short circuited on themselves, hence it is not possible to add any external resistance in series with the rotor circuit for starting purposes.

The rotor slots are usually not quite parallel to the shaft but are purposely given slight skew. This is useful in two ways :

i) It helps to make the motor run quietly by reducing the magnetic hum and

ii) It helps in reducing the locking tendency of the rotor i.e. the tendency of the rotor teeth to remain under the stator teeth due to direct magnetic attraction between the two.

2.5 THE ROTATING MAGNETIC FIELD

When the stator winding is connected to a three phase supply, currents will flow in each phase of this winding. These currents will be displaced from each other by 120° , as shown in Fig. 2.1. To be consistent, we shall assume that when the instantaneous currents are positive, they agree with the arrows in Fig. 2.2. Further more, for positive currents as shown, the currents will enter the phase windings at a, b and c and be directed into the page. Should a phase current be on the negative half-cycle of its sine wave, the current direction will reverse (i.e., it will be directed out of the page at a, b, or c).

Consider the instant of time $t = t_1$ in Fig. 2.3. At this time the current i_a is positive, i_b and i_c are negative. The resulting current directions in the phase windings at this time t_1 is then as illustrated in Fig. 2.3.a. The cumulative effect of these currents flowing in the phase windings is that the magnetic field in the phase windings is that the magnetic field is directed to the left. This is readily confirmed by the right-hand rule.

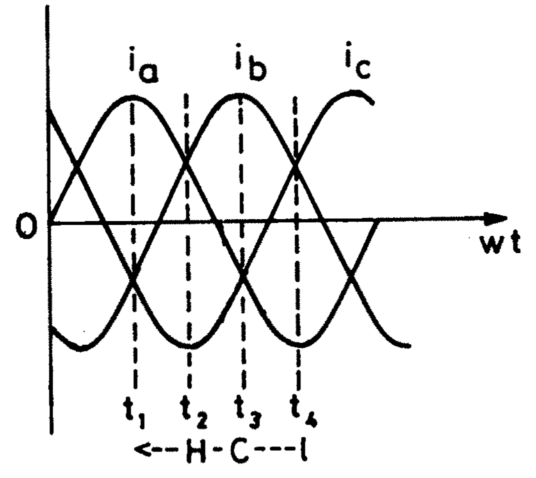

FIG. 2·1 - THREE PHASE CURRENTS IN STATOR WINDING.

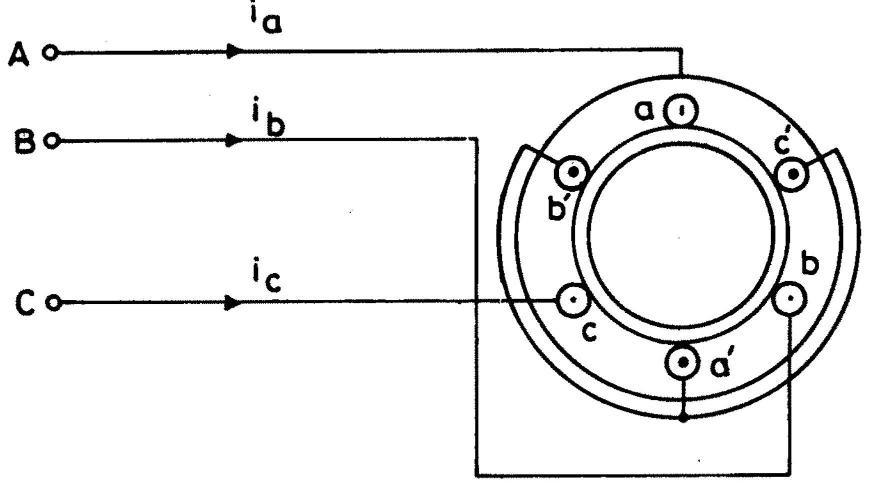

FIG. 2·2 - SIMPLIFIED TWO-POLE THREE-PHASE STATOR WINDING SHOWING POLARITIES ADOPTED FOR POSITIVE PHASE CURRENTS.

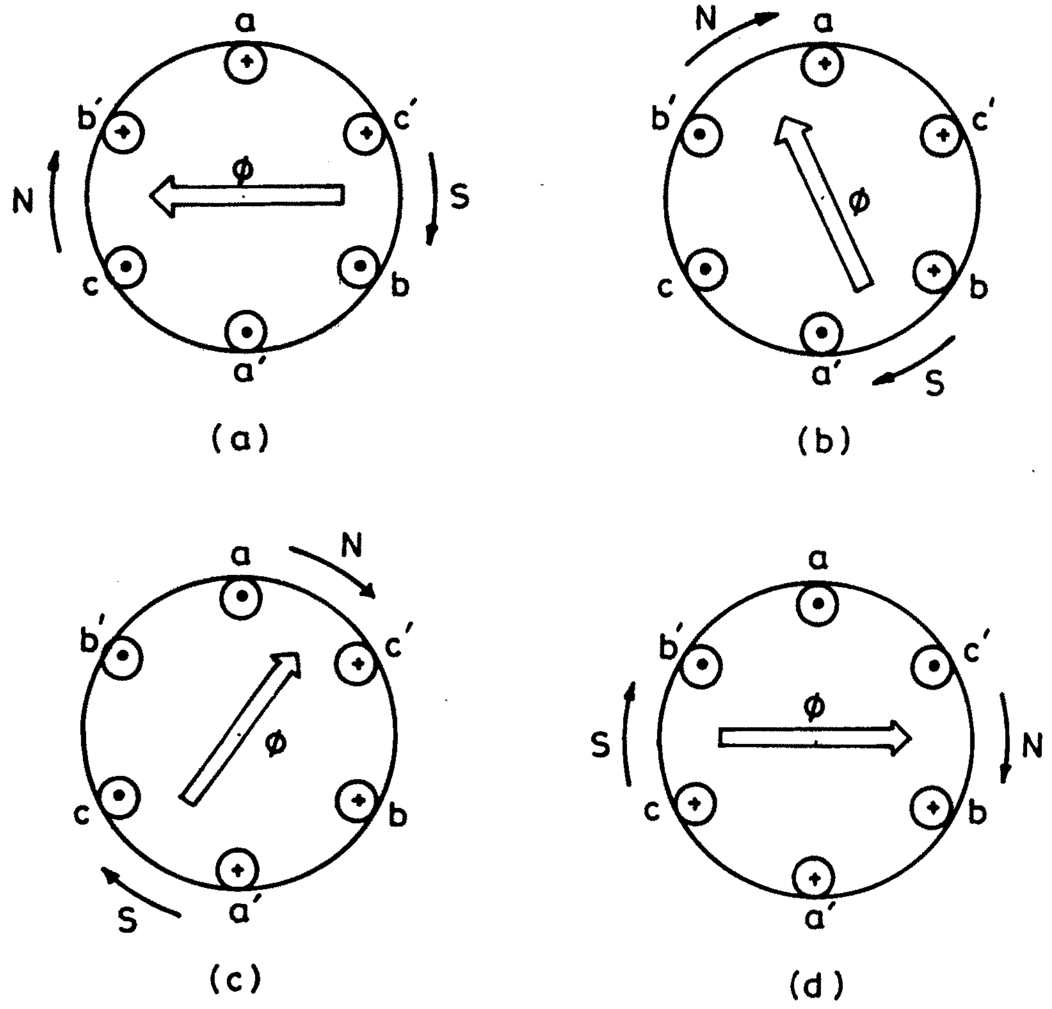

FIG. 2·3 - ROTATION OF THE STATOR FIELD DURING HALF A CYCLE OF THE LINE FREQUENCY. INSTANTS IN TIME INDICATED REFER TO THOSE IN FIG 2·1 (a) $t = t_1$; (b) $t = t_2$; (c) $t = t_3$; (d) $t = t_4$.

As this procedure is followed for the next three time intervals indicated in Fig. 2.1, the north pole will have rotated 180° in the clockwise direction, or one pole span, as Fig. 2.3. indicates. This rotation occurred during half a cycle of the supply frequency. Therefore, the field will revolve a distance covered by two poles for each cycle of the supply frequency. This implies that the speed of the rotating field is inversely proportional to the number of pole pairs and proportional to the frequency. Expressing this in formula form gives what is known as the synchronous speed n_s of the rotating magnetic field, namely,

$$n_s = f / (p/2) \quad r/s$$

$$= 120f / P \quad r/min. \qquad (2.1)$$

2.6 SLIP AND ROTOR SPEED

The rotor of an induction motor rotates in the same direction as that of the revolving field. It cannot do so at synchronous speed; other-wise, the rotor conductors rotate in unison with the field and no flux would be cut. There must always be relative motion between the rotating field and the rotor conductors; otherwise, there will be no induced rotor currents, hence no torque. The difference between the synchronous speed n_s and the rotor speed n_r is called the slip 's' and is expressed as a percentage of synchronous speed :

$$Slip = (n_s - n_r) / n_s \times 100\,\% \qquad (2.2)$$

The rotor speed may be expressed as

$$n_r = (1-s) \times n_s \quad r/min. \qquad (2.3)$$

where s is expressed as a decimal.

2.7 ROTOR - INDUCED VOLTAGE AND FREQUENCY

At standstill, when the rotor is at rest, the rotating field sweeps the rotor bars at its maximum rate. Under those conditions, the generated voltage in the rotor circuit will be maximum and determined by the number of turns on the rotor. As the field revolves, a back EMF is generated in the stator winding which is nearly equal to the impressed voltage. It thus follows that at standstill the flux sweeps the stator turns at the same rate as those in the rotor. This means that the induced voltages in the rotor and stator turns on a per phase basis are related by the turns ratio, as is the case in a transformer between primary and secondary. It also follows that the frequency of the rotor induced voltage equals the line frequency when the rotor is at rest. In this condition the slip s = 1.0 or 100% . As the slip decreases, the rate at which the flux sweeps across the conductors decreases proportionately and the rotor EMF becomes

$$E_R = s \times E_{BR} \qquad (2.4)$$

and the rotor frequency

$$f_R = s \times f \qquad (2.5)$$

where E_R = rotor - induced voltage at slip s

E_{BR} = blocked rotor- induced voltage per phase

f_R = rotor frequency

2.8 THE ROTOR CIRCUIT

From what has been discussed so far on the three-phase induction rotor, it is apparent that it is essentially a transformer with a short-circuited secondary that is free to move continuously with respect to the primary. It is therefore anticipated that a simplified equivalent circuit diagram resembles that of the single - phase transformer discussed. This is indeed the situation. It has been shown in section 2-7 that the induced rotor frequency per phase is sE_{BR}. Since this voltage acts in the short - circuited rotor winding, it will set up currents that will be limited only by the rotor impedance. This impedance is made of two components: (1) the rotor resistance R_R, and (2) the leakage reactance sX_{BR}, where X_{BR} is the rotor reactance at standstill. Since the reactance is a function of frequency, the leakage reactance is proportional to the slip. As a result, the rotor current becomes

$$I_R = sE_{BR} / \sqrt{R^2_R + (sX_{BR})^2} \qquad (2.6)$$

If both numerator and denominator of Eq. (2-6) are divided by the slip s, we obtain.

$$I_R = E_{BR} / \sqrt{(R_R / s)^2 + X_{BR}^2} \qquad (2.7)$$

The division by s has changed the point of reference from the rotor to the stator circuit. Translating Eq. (2.7) into an equivalent electrical circuit diagram, it becomes as shown in Fig. 2-4a.

Since it is convenient to deal with the actual rotor resistance R_R, the term R_R /s is split into two components :

$$R_R/s = R_R/s + R_R - R_R = R_R + R_R\ (1/s - 1) = R_R + R_R(1\text{-}s / s) \qquad (2.8)$$

and a corresponding circuit diagram is that of Fig. 2.4b. If Eq. (2.8) is now multiplied through by I_R^2, we obtain an equation representing power terms,

$$I_R^2 R_R/s = I_R^2 R_R + I_R^2 R_R (1\text{-}s) / s \qquad (2.9)$$

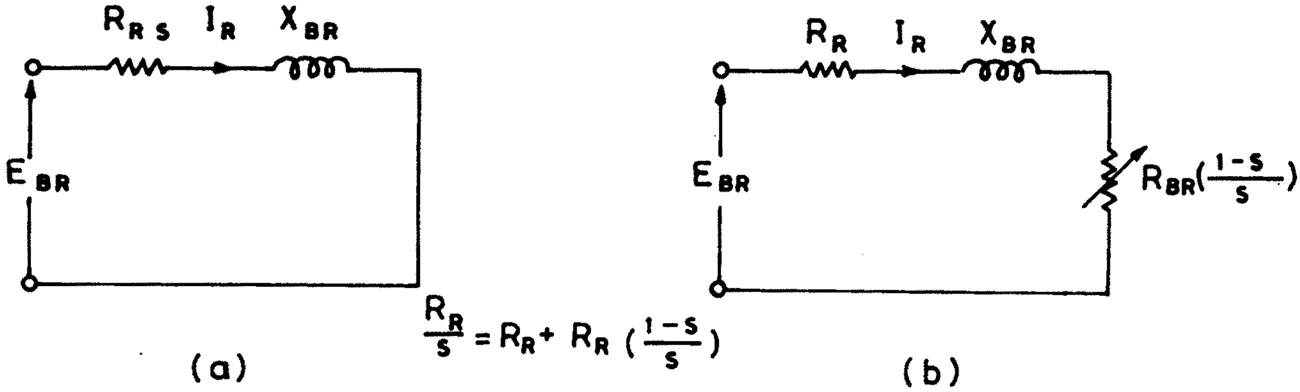

FIG. 2·4 – ROTOR CIRCUIT DIAGRAM ON A PER PHASE BASIS. RESISTIVE ELEMENT REPRESENTING ROTOR COPPER LOSS AND ROTOR POWER DEVELOPED: (a) COMBINED; (b) SEPERATED.

The left-hand side of the equation represents, the total power input to the rotor circuit, which is made up of two components : (1) the power dissipated as copper loss in the rotor circuit $I_R^2 R_R$ and (2) the electric power that is converted into mechanical power, $I_R^2 R_R[(1-s)/s]$. Thus on a per phase basis,

Rotor Power Input (RPI) = Rotor Copper Loss (RCL) + Rotor Power Developed (RPD)

where $$RPI = I_R^2 R_R/s \quad (2.10)$$

$$RCL = I_R^2 R_R \quad (2.11)$$

$$RPD = I_R^2 R_R (1-s)/s = RPI\,(1-s) \quad (2.12)$$

It is rather interesting to note that the mechanical output power is represented in the electrical circuit by a resistance having a value $R_R(1-s)/s$. In general, the power developed by a motor is the product of its torque and the angular velocity of the rotor. Therefore,

$$P_d = \omega_R T$$

It follows, then, that the developed torque by the motor is

$$T_d = RPD / \omega_R \quad \text{N.m.} \quad (2.13)$$

where $\omega_R = 2\pi n_R/60$ rad/s and n_R is the rotor speed in revolutions per minute at which the power is developed.

2.9 COMPLETE CIRCUIT DIAGRAM

So far, the rotor circuit was developed and it was shown that the power transformed across the air gap represents the rotor copper losses and the mechanical power developed by the motor. To complete the equivalent circuit diagram, the stator circuit must be included. The stator phase winding, having a resistance R_S and a leakage reactance X_S, also has magnetizing branch. The stator equivalent circuit can be represented by Fig. 2.5a.

At this point it remains to combine the rotor and stator circuit diagrams to yield an equivalent diagram, on a per phase basis. In doing so it must be realized that both circuits must be compatible. That is, the rotor parameters must be referred to the stator side. In other words, Fig. 2.4a or b can be joined to Fig. 2.5b, provided that E_{BR} equals E_1. To ensure this equality, the turns ratio between stator and rotor-phase windings must be accounted for, such that $E'_{BR} = \alpha E_{BR} = E_1$, where α represents this ratio and E'_{BR} denotes stator - referred rotor quantity. Having done so, the equivalent circuit referred to the stator side is that of Fig. 2.6.

The rotor current in Fig. 2.6 in stator terms is

$$I'_R = V_1 / \{(R_S + R'_{R/S}) + j(X_S + X'_R)\} \qquad (2.14)$$

Which enables calculation of the RPI, RCL and RPD according to Eqs. (2.10) to (2.12). The magnetizing current I_m is

$$I_m = V_1 / j\,X_m \qquad (2.15)$$

and therefore the motor line current

$$I_1 = I_m + I_R^1 \qquad (2.16)$$

Since the magnetizing branch is moved to the input terminals the stator quantities appear as part of the rotor circuit. This would result in a negligible error if $V_1 = E_1$ in Fig. 2.5b.

In practical work, this simplification in the normal operating range of the motor leads to insignificant errors and is therefore adopted as explained. However for efficiency calculations, the copper stator loss will be calculated as follows :

$$P_{cu\ stator} = 3 \times I_1^2\, R_S$$

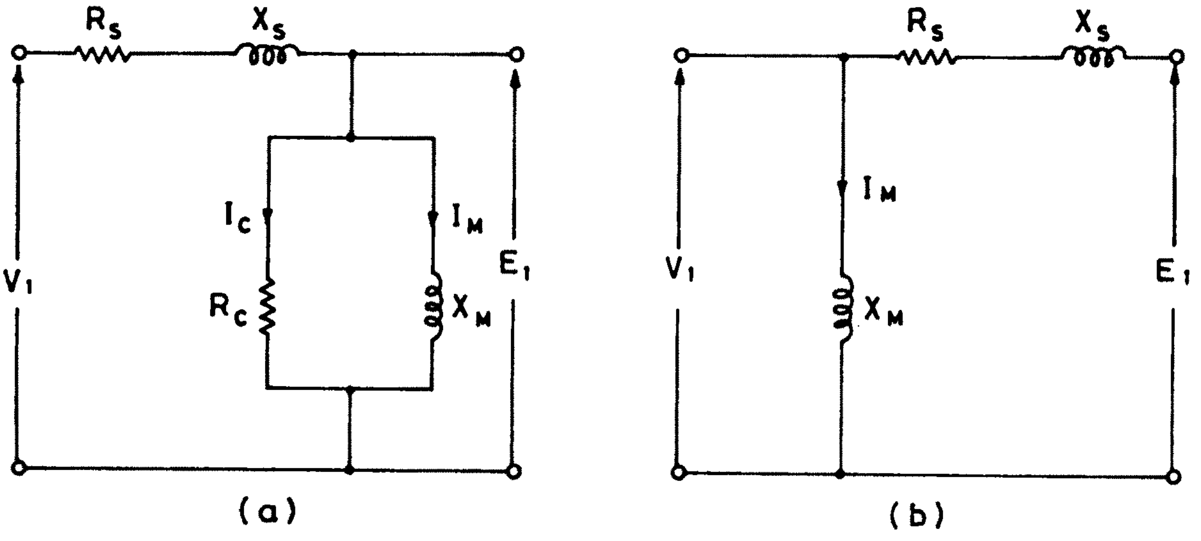

FIG. 2·5 – STATOR EQUIVALENT CIRCUIT DIAGRAM OF INDUCTION MOTOR. PER PHASE.

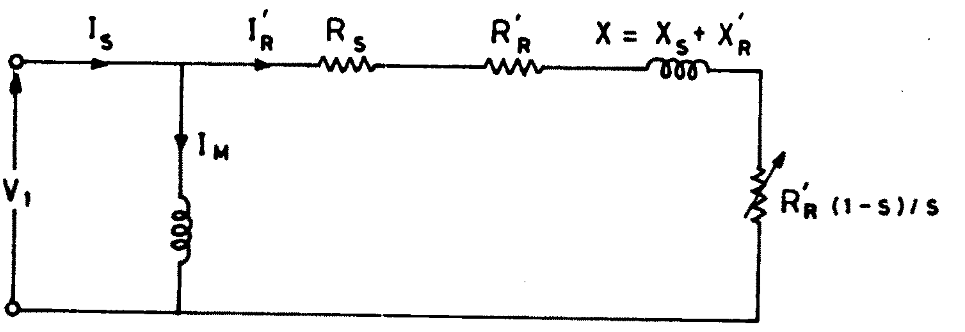

FIG. 2·6 – EQUIVALENT CIRCUIT DIAGRAM FOR THE INDUCTION MOTOR ON A PER PHASE BASIS REFERRED TO THE STATOR.

Furthermore, the output or shaft torque is

$$T = (RPD - \text{Mechanical Losses}) / \omega_R$$

where the mechanical losses include friction windage, and core losses.

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