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Modeling and Testing of Induction Motor: A Review

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***Abstract*— This paper is a review of the working of induction motors and its mathematical modelling. It also covers the basic terms involved in the study of the induction motor and also the speed control of induction motor is presented. The various performance characteristics are studied for torque slip characteristics and no load and blocked rotor test are performed on an induction motor and the results are presented here.**

***Keywords*— Induction motor; slip; rotor torque; speed control; mathematical modeling**

I. INTRODUCTION

The three phase induction motors shown in Fig. 1. are widely used in industries where a constant speed is essential. These motors are almost constant speed motors as they run at constant speed from no load to full load. As we shall see that the speed of these motors is frequency dependent, the speed control of these motors is a tedious job. However, the speed control of induction motor has been and is even now the center of interest for many engineers as induction motors are robust, need less maintenance, can operate at hazardous locations therefore it will be beneficial to use induction motors if the speed can be controlled.

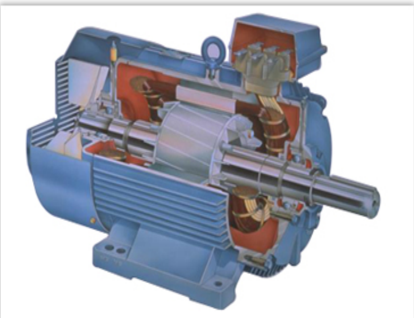


Fig. 1. Induction Motor

II. CONSTRUCTION DETAILS

A three phase induction motor mainly consists of two main parts:

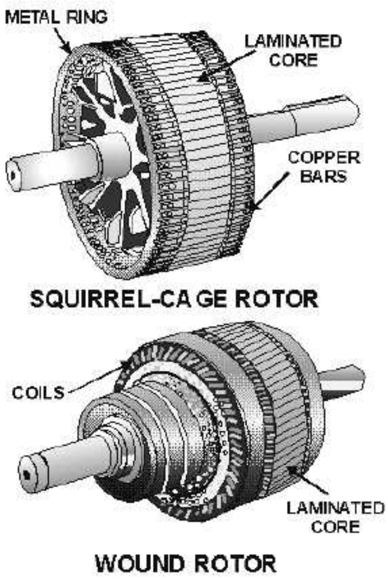
1. Stator
2. Rotor

1.Stator:The stator consists of a steel frame which encloses a hollow cylindrical core made up of thin laminations of silicon steel to reduce hysteresis and eddy current losses. A number of evenly spaced slots are provided on the inner periphery(fig1). The insulated conductors are placed in the stator slots and are connected to form a balanced three phase star or delta connection circuit.

2.Rotor:The rotor is rotating part of an induction motor. It is a hollow laminated core having slots on its outer periphery. The rotor winding may be one the following types.

I.Squirrel cage type

II. Wound type



I. Squirrel cage type: It consists of laminated cylindrical core having parallel slots on its outer periphery, in these slots one copper or aluminum bar is placed. All these bars are connected at each end by metal rings, called end rings. These bars, therefore, are permanently short circuited and therefore no external resistance can be connected.

II. Wound type: These consist of laminated cylindrical core and carries a three phase winding as in the stator. The open ends of the rotor winding is brought out and connected to three insulated slip rings mounted on the rotor shaft with one brush resting on each slip ring. The three brushes are connected to a three phase star connected rheostat. These resistances are included at starting to limit high circulating current in the short circuited rotor winding and to give a large starting torque. These resistances are gradually reduced to zero as the rotor attains its normal speed.

III. PRINCIPLE OF OPERATION

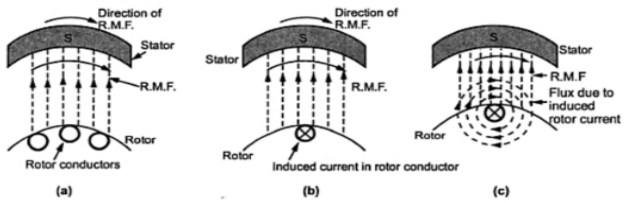


Fig. 2. Principle of Operation

When a three phase induction motor is energized by a three phase supply a rotating magnetic field is produced. This rotating magnetic field cuts the rotor conductors which are yet stationary. Due to the relative speed between rotating magnetic field and stationary rotor, an E.M.F is induced in the rotor conductors. Since the rotor circuit is short circuited, current starts flowing in the rotor conductors.

As the current carrying rotor conductors are placed in the magnetic field produced by the stator. As a result, mechanical force acts on the rotor conductors. The sum of this mechanical force on each of the rotor conductors produces a torque, which tends to move the rotor in the same direction as the rotating field. The fact that the rotor tends to move the same direction as that of the rotor can be explained by the Lenz's law. According to this law, the direction of the rotor current will be such that it tends to oppose the very cause of the current. Now the cause producing the rotor current is the relative speed between the rotating magnetic field and the rotor conductors. Hence, to reduce the relative speed, the rotor starts running in the same direction as that of the rotating magnetic field.

In practice the rotor can never reach the speed of stator field. If it does so, there will be no relative speed between the stator field and the rotor and hence no induced emf and no current in the rotor circuit and therefore no torque to drive the rotor. Practically, the friction and windage would immediately slow down the rotor speed. Hence the rotor speed (N) is always less than that of rotating magnetic field (RMF) known as synchronous speed of the stator (N_s).

The difference between the synchronous speed (N_s) and the rotor speed (N) is known as slip. It is usually expressed as percentage of synchronous speed *i.e.,*

$$\%slip, s = \frac{Ns - N}{Ns} \times 100$$

When the motor is stationary the rotor is stationary (N=0),therefore,

$$\%slip, s = \frac{Ns - 0}{Ns} \times 100$$

$$= \frac{Ns}{Ns} \times 100$$

$$= 100\%$$

$$or \quad s = 1$$

Rotor speed,

$$Nr = Ns(1 - s)$$

and synchronous speed is given by,

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

where, $P =$ Number of poles,

$f =$ Frequency

In an induction motor the change in slip from no load to full load is of the order of 0.1% - 0.3%. Therefore an induction motor is essentially a constant speed motor.

IV. MATHEMATICAL MODELING

A. Rotor Torque

The torque developed in an I.M. is directly proportional to the followings:

- Rotor current
- Rotor emf
- Power factor of the rotor circuit

Therefore,

$$T \propto E_2 I_2 \cos\varphi_2$$

$$T = K E_2 I_2 \cos\varphi$$

where,

I_2 =rotor current at standstill

E_2 =rotor emf at standstill

$\cos\varphi_2$ =rotor p.f at standstill

B. Starting Torque(T_s)

Let, I_2 =rotor current at standstill

E_2 =rotor emf at standstill

$\cos\varphi_2$ =rotor p.f at standstill

X_2 =rotor reactance per phase at standstill

R_2 =rotor resistance per phase at standstill

Rotor impedance/phase, $Z_2 = \sqrt{R_2^2 + X_2^2}$

Rotor current/phase, $I_2 = \frac{E_2}{Z_2} = \frac{E_2}{\sqrt{R_2^2 + X_2^2}}$

Rotor p.f., $\cos\varphi_2 = \frac{R_2}{Z_2} = \frac{R_2}{\sqrt{R^2 + X^2}}$

Starting torque, $T_s = K E_2 I_2 \cos\varphi_2$

$$= K E_2 \times \frac{E_2}{\sqrt{R_2^2 + X_2^2}} \times \frac{R_2}{\sqrt{R_2^2 + X_2^2}}$$

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

The supply voltage is generally constant, so that flux per pole φ set up by the stator is also fixed. This means the emf E_2 induced is also constant.

$$\therefore T_s = K_1 \frac{R_2}{R_2^2 + X_2^2} = K_1 \frac{R_2}{Z_2^2}$$

where K_1 is another constant.

The value of K is, $K = \frac{3}{2\pi} N_s$

Here N_s is in r.p.s.

C. Torque Under Running Condition:

Let, I_2 =rotor current at standstill
E_2 =rotor emf at standstill
$\cos \varphi_2$ =rotor p.f at standstill
X_2 =rotor reactance per phase at standstill
R_2 =rotor resistance per phase at standstill

Rotor emf/phase, $E_2' = sE_2$

Rotor reactance/phase, $X_2' = sX_2$

Rotor impedance/phase, $Z_2' = \sqrt{R_2^2 + X_2^2}$

Rotor current/phase,

$$I_2' = \frac{E_2'}{Z_2'} = \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

Rotor p.f.,

$$\cos \varphi_2' = \frac{R_2}{\sqrt{R^2 + (sX_2)^2}}$$

Running torque,

$$Tr \propto E_2' I_2' \cos \varphi_2'$$
$$\propto \varphi I_2' \cos \varphi_2'$$
$$(\because E_2' \propto \varphi)$$

$$\propto \varphi \times \frac{sE_2'}{\sqrt{R_2^2 + (sX_2)^2}} \times \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

$$\propto \frac{\varphi s E_2 R_2}{R_2^2 + (sX_2)^2}$$
$$= \frac{K \varphi s E_2^2 R_2}{R_2^2 + (sX_2)^2}$$
$$= \frac{K_1 s E_2^2 R_2}{R_2^2 + (sX_2)^2}$$
$$(\because E_2 \propto \varphi)$$

If the supply voltage V is constant, then stator flux and hence E_2 will be constant,

$$\therefore \quad Tr = \frac{K_2 s R_2}{R_2^2 + (sX_2)^2}$$

where K_2 is another constant.

V. TORQUE SLIP CHARACTERISTICS

The curve drawn between the torque and the slip for a particular value of rotor resistance is known as torque-slip characteristics.

The following points may be noted by the torque-slip characteristics:

1. At s=0, T =0 so that the torque - slip curve starts from the origin.

2. At normal speed, slip is small, so that sX_2 is negligible as compared to,

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

Hence a torque slip curve is a straight line from zero slip to a slip that corresponds to full load.

3. As the slip increases beyond the full load slip, the torque increases and becomes maximum at $s = \frac{R_2}{X_2}$. This maximum torque is known as a pull out torque or breakdown torque. Its value is almost twice that of full load torque when the motor operates at its rated voltage and frequency.

4. When the slip increases beyond the maximum torque, the term $s^2 X^2$ increases very rapidly, so that R_2^2 may be neglected as compared to.

$$T \propto \frac{s}{s^2 X_2^2}$$
$$\propto \frac{1}{s}$$

as X_2 is constant

Thus the torque is now inversely proportional to slip. Hence the torque slip characteristics are a rectangular parabola.

VI. TESTS ON THE INDUCTION MOTOR

A. No Load Test:

No load test is performed to determine the no load current, no load power factor, windage and friction losses, no load resistance and reactance. Since there is no power output on no load, the power supplied to the stator furnishes its core loss and the friction and windage losses in the rotor. The circuit diagram for the no load test is shown in Fig. 3.

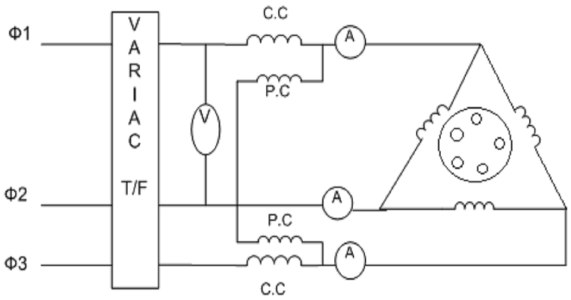


Fig. 3. No Load Test

Procedure for no load test:

1. The three phase Variac is kept at '0' position and switched on the main supply.
2. The voltage is increased slowly through the variac upto the rated voltage of induction motor.
3. Readings of voltmeter, ammeter, and voltmeter was taken at different value of voltages.

B. Blocked Rotor test:

The blocked rotor test is also known as locked rotor test or short circuit test. This test is employed to find the short circuit current of the rotor circuit. This test is performed at the rated current of the induction motor. The circuit diagram for blocked rotor test is shown in Fig. 4.

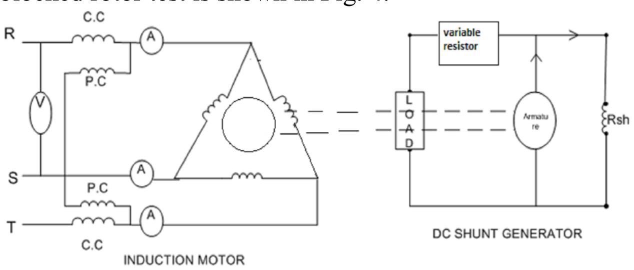


Fig. 4. Blocked Rotor Test

Procedure for blocked rotor test:

1. The three phase Variac is kept at '0' position before switching "ON" the main supply.
2. Block the rotor by applying external load or by any means.
3. Increase the voltage through Variac slowly up to the rated current of the induction motor is reached.
4. Take one or maximum of two readings of all the instruments..
5. Switch off the main supply.

C. Calculations:

1. *For no load test:*

$$\text{Wattmeter constant} = \frac{VI\cos\varphi}{Fullscale} = \frac{600\times5\times0.2}{150} = 4$$

$$P = \sqrt{3}VI\cos\varphi$$

$$276 = \sqrt{3}\times V\times2.75\times\cos\varphi$$

$$\therefore \quad \cos\varphi = 0.144$$

$$I_{ph} = \frac{I_o}{\sqrt{3}} = \frac{2.75}{\sqrt{3}} = 1.58A$$

$$V_{ph} = 400V$$

$$I_w = I_{ph}\times\cos\varphi$$

$$= 0.26\times1.58\times0.144$$

$$= 0.2275A$$

$$I_a = I_{ph}\sin\varphi$$

$$= 1.58\sqrt{1-(0.144)^2}$$

$$= 1.56A$$

$$R_o = \frac{V_o}{I_w} = \frac{400}{0.2275} = 1758\Omega$$

$$X_o = \frac{V_o}{I_a} = \frac{400}{1.56} = 256.14\Omega$$

$$Z_o = \sqrt{R_o^2 + X_o^2}$$

$$= \sqrt{1758^2 + 256.14^2}$$

$$= 1776.56\Omega$$

2. *For Block Rotor Test:*

$$I_{01} = \frac{I_{sc}}{\sqrt{3}} = \frac{5}{\sqrt{3}} = 2.88A$$

$$R_{01} = \frac{\left(P/\sqrt{3}\right)}{Isc^2} = \frac{369}{\sqrt{3}\times5^2} = 4.85\Omega$$

$$Z_{01} = \frac{V_{01}}{I_{01}} = \frac{76}{2.88} = 26.38\Omega$$

$$X_{01} = \sqrt{Z_{01}^2 - R_{01}^2} = \sqrt{(26.38)^2 - (4.85)^2} = 25.93\Omega$$

VII. SPEED CONTROL OF INDUCTION MOTOR

An induction motor essentially runs at constant speed as the load is varied. Some industrial drives, however, require several different speeds or even continually variable speeds The induction motor, being most rugged motor with almost negligible maintenance, has been and even now the center of interest for electrical engineers to make it run successfully at different speeds.

The operating speed of a 3-phase induction motor is given by,

$$Nr = Ns(1-s)$$

or,

$$Nr = \frac{120f}{P}(1-s)$$

From above equations, it can be noted that, the speed of an induction motor depends on synchronous speed which depends on the number of poles, frequency, and slip. Hence, the speed of an induction motor can be controlled by controlling the number of poles, frequency and slip of the motor.

Methods of speed control of induction motor:

A. Pole changing method:

A change in the number of poles, changes the synchronous speed and therefore, the induction motor operating speed. Since three numbers of poles can be changed only by even numbers, the speed control is not continuous but a stepped one. With pole-amplitude modulation, a finer control in the number of poles and, therefore, the speed can be controlled.

Sometimes induction machines have a special stator winding capable of being externally connected to form two different number of pole numbers. Since the synchronous speed of the induction machine is given by:

$$Ns = \frac{Fs}{P}$$

where p is the number of pole pairs, this would correspond to changing the synchronous speed. With the slip now corresponding to the new synchronous speed, the operating speed is changed. This method of speed control is a stepped variation and generally restricted to two steps. If the changes in stator winding connections are made so that the air gap flux remains constant, then at any winding connection, the same maximum torque is achievable. Such winding arrangements are therefore referred to as constant-torque connections. If however such connection changes result in air gap flux changes that are inversely proportional to the synchronous speeds, then such connections are called constant-horsepower type.

B. Stator frequency control:

The expression for the synchronous speed indicates that by changing the stator frequency the rotor speed can be changed. This can be achieved by using power electronic circuits called inverters, which convert DC to AC of desired frequency. Depending on the type of control scheme of the inverter, the AC generated may be variable-frequency-fixed-amplitude or variable-frequency-variable-amplitude type. Power electronic control achieves smooth variation of voltage and frequency of the AC output. This when fed to the machine is capable of running at a controlled speed. However, consider the equation for the induced emf in the induction machine.

$$V = 4.44 N \varphi_m F$$

where N is the number of the turns per phase, φ_m is the peak flux in the air gap and F is the frequency. Note that in order to reduce the speed, frequency has to be reduced. If the frequency is reduced while the voltage is kept constant, thereby requiring the amplitude of induced emf to remain the same, flux has to increase. This is not advisable since the machine likely to enter deep saturation. If this is to be avoided, then flux level must be maintained constant which implies that the voltage must be reduced along with frequency. The ratio is held constant in order to maintain the flux level for maximum torque capability.

C. Line voltage control:

The electromagnetic torque of an induction motor is approximately proportional to the stator terminals. The stator voltage and consequently the torque and speed of an induction motor, can be varied by inserting rheostat, a saturable reactor or an auto transformer in the supply mains. More recently, thyristors in series with the supply mains are used to control the voltage across the stator winding.

VIII. CONCLUSIONS

The construction of Induction motor is studied and performed no load and blocked rotor test on it and torque slip curve is studied, observation table of no load and blocked rotor test is studied. It is observed from the rotor speed equation that the speed of an inaction motor can be controlled by pole changing, stator frequency control, line voltage control methods.

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Table.1 Observation Table(For No Load Test)

Sl. No.	V_o (in volts)	I_o (in Amp)	W_1			W_2			Total power (W_1+W_2)	$\cos\varphi$	V_o^2
			Wattmeter Reading	Wattmeter constant	Actual power	Wattmeter Reading	Wattmeter constant	Actual power			
1.	400	2.75	145	4	580	-76	4	-304	276	0.145	160000
2.	340	2.07	93	4	372	-45	4	-180	192	0.157	115600
3.	280	1.70	62	4	248	-26	4	-104	144	0.174	78400
4.	220	1.35	40	4	160	-11	4	-44	116	0.251	48400
5.	160	1.05	22	4	88	-8	4	-32	56	0.192	25600
6.	160	1.06	22	4	88	-8	4	-32	56	0.192	25600
7.	220	1.30	40	4	160	-11	4	-44	116	0.234	48400
8.	280	1.65	59	4	236	-25	4	-100	136	0.169	78400
9.	340	2.10	94	4	376	-45	4	-180	196	0.158	115600
10.	400	2.08	144	4	576	-75	4	-300	276	0.142	160000

Table.2 Observation Table For Blocked Rotor Test:

Sl. No.	V_{sc} (in volts)	I_{sc} (in Amp)	W1			W2			Total Power	$\cos\varphi_{sc}$
			Wattmeter Reading	Wattmeter constant	Actual power	Wattmeter Reading	Wattmeter constant	Actual power		
1.	76	5	79	4	316	12	4	48	369	0.55