Frequency Variation in Rotor Current on Changing Mechanical Load in Three Phase Induction Motor

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Abstract - *This paper presents a practical as well as theoretical study of the frequency variation behavior of an electric three-phase induction machine under different load condition (from no load to full load condition gradually up to some extent). In this paper authors studied and verified the power factor improvement by Phasor diagram and by observed tabulated value of induction machine on increasing mechanical load. The observation is done by hardware analysis on 5HP, 300V, 50Hz three-phase squirrel cage induction machine in the lab under normal conditions. The result is shown at the graph which is drawn by using Microsoft excel 2007.*

Key Words: **Introduction, Frequency of stator current, Rotor current, Variation in frequency of rotor emf, Power factor analysis.**

1.INTRODUCTION

A three-phase induction motor is a singly excited A.C. machine in the sense that it is supplied power from a single A.C. source. Its stator winding is directly connected to A.C. source, whereas its rotor winding receives its energy from stator by means of induction (i.e. transformer action). Balanced three-phase current in three-phase windings produce a constant-amplitude rotating m.m.f. wave. The stator produced m.m.f. wave and rotor-produced m.m.f. wave, both rotate in the air gap in the same direction at synchronous speed. These two m.m.f. waves are thus stationary with respect to each other, consequently the development of steady electromagnetic torque is possible at all speeds but not at synchronous speed. The stator and rotor m.m.f. waves combine to give the resultant air-gap flux density wave of constant amplitude and rotating at synchronous speed, it is called asynchronous machine.

It is the most popular type of A.C motor. It is very commonly used for industrial drive since it is cheap, robust, efficient and reliable. It has good speed regulation and high starting torque. It requires little maintenance. It has a reasonable overload capacity. Although traditionally used in fixed-speed service, induction motors are increasingly being used with variable-frequency drives (VFDs) in variable-speed service. VFDs offer especially important energy savings opportunities for existing and prospective induction motors in variable-torque centrifugal fan, pump and compressor load applications. Squirrel cage induction motors are very widely used in both fixed-speed and variable-frequency drive (VFD) applications.

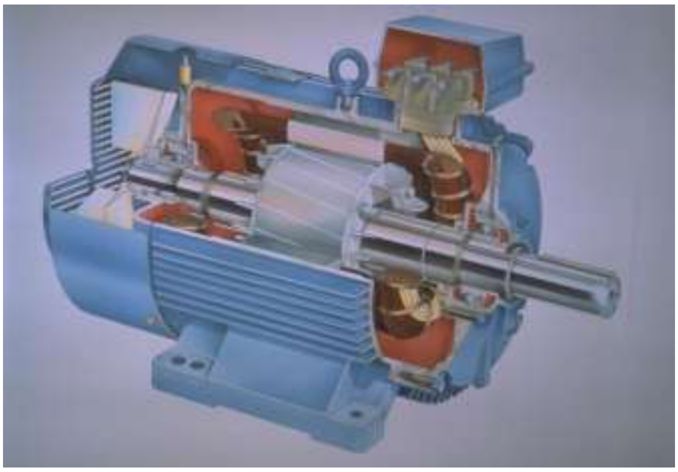

Fig -1: Cut set model of induction motor

1.1 Principle of operation

The stator winding of a 3-phase induction motor is connected to 3-phase balanced supply. The flow of 3-phase currents in the 3-phase stator winding produces a rotating magnetic field due to distributed winding of stator. The speed of rotating field is the synchronous speed,

$$n_s = 2f/P \text{ rps.}$$

The rotating flux wave cuts the stationary rotor conductors $P.n_s$ times per second and therefore e.m.fs. are induced in the rotor conductors. As the rotor circuit is short-circuited, these induced e.m.fs give rise to current in the rotor conductors. The interaction of these rotor currents with rotating flux wave produces torque in the rotor of a three-phase induction machine and consequently, rotor begins to rotate. As per Lenz's law, the developed torque must oppose (or minimize) the cause, that is flux cutting action. This is possible only if the developed torque forces the motor to rotate in the direction of rotating field. When this happens, the relative speed between rotating flux and rotor conductors is reduced and therefore flux cutting action (time per sec) also gets reduced. For example, if rotor speed is n_s rps in the direction of rotating flux wave, the relative speed between rotating flux wave and rotor conductors becomes ($n_s - n_r$) rps and the flux cutting action reduced from $P.n_s$ times per sec to $P(n_s - n_r)$ times per sec as demanded by

Lenz's law. This shows that rotor must rotate in the direction of rotating magnetic field when three-phase supply is given to stator of a three-phase induction machine. If rotor is assumed to run at synchronous speed n_S in the direction of rotating field, then there would be no flux-cutting action, no e.m.f. in rotor conductors, no current in rotor bars and therefore no developed torque. Thus, the rotor of three-phase induction motor can never attain synchronous speed [9].

1.2 Slip of induction motor

Slip S, is defined as the difference between synchronous speed and operating speed, at the same frequency, expressed in rpm, or in percentage or ratio of synchronous speed. Thus,

The ratio of slip speed and synchronous speed is known as slip [10].

$$\text{Slip} = \frac{N_s - N_r}{N_s}$$

Where,
$(N_s - N_r)$ is slip speed
N_s is the synchronous speed (in rpm) and,
N_r is the rotor speed (in rpm)

Slip, which varies from 0 at synchronous speed and 1 when the rotor is at rest, determines the motor's torque. Since the short-circuited rotor windings have small resistance, even a small slip induces a large current in the rotor and produces significant torque. At full rated load, slip varies from more than 5% for small or special purpose motors to less than 1% for large motors. These speed variations can cause load-sharing problems when differently sized motors are mechanically connected [11].

1.3 FREQUENCY OF STATOR AND ROTOR CURRENT

It has been shown that rotor starts running in the direction of rotating magnetic field. At standstill, rotor conductors are being cut by rotating flux wave at synchronous speed n_S, therefore frequency f_r of the rotor e.m.f. and current is equal to the line frequency f. When rotor revolves at a speed of n_r r.p.s. in the direction of rotating flux wave, the relative speed between synchronously rotating flux and rotor conductors becomes $(n_S - n_r)$ rps.
Stator frequency,

$$f = \frac{PN_s}{120} \qquad \dots (1)$$

Where, P is the number of poles in stator.
N_s is the synchronous speed (i.e., stator flux speed in rpm.)
At starting,
Relative speed between rotating flux and
Rotor conductor = $N_s - 0 = N_s$

Then,

Frequency of induced voltage in rotor conductor is equal to the supply frequency. (i.e., $f_r = f$).
Where f_r is rotor frequency.
At running condition, rotor rotates at speed of N_r,
Then,
Relative speed = $(N_s - N_r)$
Rotor frequency

$$f_r = \frac{P(N_s - N_r)}{120}$$

Here, we have seen that the frequency in rotor is depending upon the relative speed between rotor conductor and stator flux.
So,
We can say that the rotor-induced e.m.f. is variable due to frequency variation.
We assume that the supply is given to the stator is sinusoidal in nature that's why the induced e.m.f. in rotor is also sinusoidal in nature as

$$E_2 = E_{2m} \sin \omega t \qquad \dots (4)$$

Where, $\omega = 2\pi f$

1.4 VARIATION IN ROTOR E.M.F.

From equations (1) and (2),
At starting condition,
Frequency of rotor emf, $f = \frac{PN_s}{120}$
And at running condition,

$$f_r = \frac{P(N_s - N_r)}{120} \qquad \text{(From eq. 3)}$$

$$\frac{f_r}{f} = \frac{(N_s - N_r)}{N_s} = Slip\ (S)$$

So,

$$f_r = Sf \qquad \dots (5)$$

Thus, the product of slip S and the line frequency f gives the frequency of the rotor e.m.f. and current in an induction machine. It is for this reason that f_r is also called the slip frequency.
At running condition,
Relative speed between rotor and air gap flux
$= (N_s - N_r)$
We know that,
Induced emf ∝ relative speed
Assumed that,
E_{20} : induced rotor emf at starting
E_{2S} : induced rotor emf at any slip (running condition)
Then,
It is known that E_{20} is directly proportional to the synchronous speed of the machine. It can re-written as,

$$E_{20} \propto N_s$$

Moreover, the value of E_{2S} is directly proportional to the relative speed between speed of air gap flux (synchronous speed) and the speed of rotor. It can express mathematically as,

$$E_{2S} \propto (N_s - N_r)$$

After taking the ratio of E_{2S} and E_{20} found that,

$$\frac{E_{2S}}{E_{20}} = \frac{(N_s - N_r)}{N_s}$$

Thus,

$$E_{2S} = SE_{20} \quad \text{... (6)}$$

Thus, we can say that the induced rotor e.m.f. at any slip S is the slip times of the induced e.m.f. at standstill condition of rotor[10].

In addition, the power factor of rotor current is

$$\cos\varphi = \frac{R_2}{\sqrt{R_2^2 + SX_{20}^2}} \quad \text{... (7)}$$

Note that the above expression of cos $\varphi$is the power factor of rotor current only. This is not the expression of supply power factor. The analysis of three-phase supply power factor is following in the next heading by Phasor analysis of induction machine.

1.5 PHASER DIAGRAM ANALYSIS

CASE-I

The complete induction machine Phasor diagram at no load is drawn in Fig. 2, where m.m.fs. are not shown for the sake of clarity. At no load, E_2 is equal to voltage drop in rotor. The core-loss component of stator current, i.e. I_C is in phase with E_1. The stator no-load current is $I_0 = I_e + I_m$ and the stator load current is $I_1 = I_1' + I_0$. The power factor angle Θ_1 (between V_1 and I_1) at the stator terminals is very high i.e. stator power factor is very poor at no-load condition of a three-phase induction machine [10].

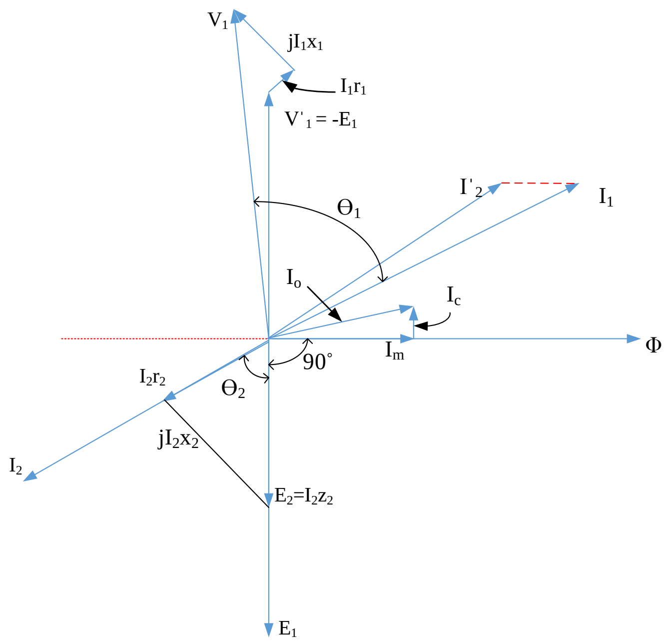

Fig -2: Phasor diagram of IM at no load

CASE-II

At any slip S,

The Fig.3, which is following drawn reveals that full load power factor at the stator terminal, has considerably improved (0.8 to 0.9 lagging) from its power factor at no load [10].

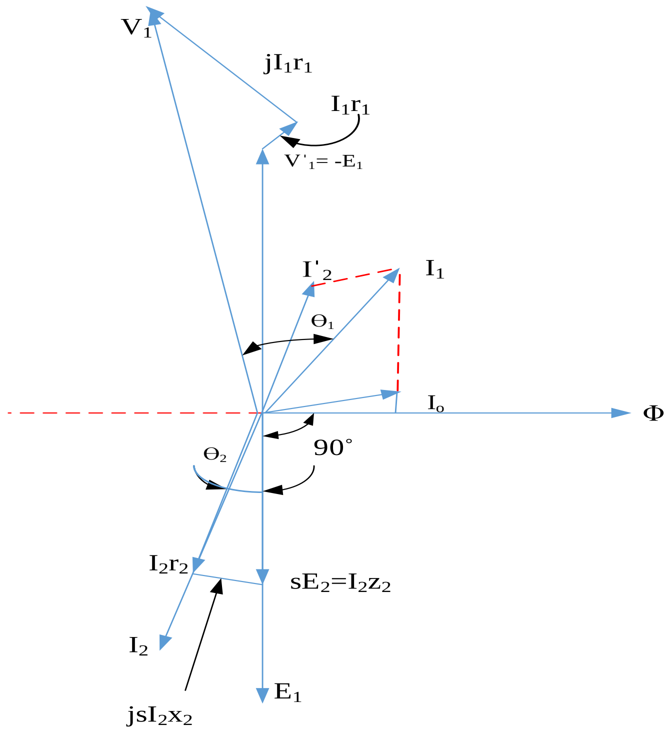

Fig -3: Phasor diagram of IM on load at slip S

In the Phasor diagram of Figs. 2 and 3, all quantities have per phase values. By seeing the Fig.2 and Fig.3 we can analyze that on increasing the mechanical load on a three-phase induction motor, the power factor of supply increases continuously up to some extent.

2. OBSERVATIONS

We observe the Induction Machine on different load conditions. By increasing the load from 0 to certain extent, the following table is obtained (Table 1).

According to Table 1, when we increase the load, the rotor current frequency and the slip of machine increase continuously. Hence, the power factor of supply increases also.

Over a motor's normal load range, the torque's slope is approximately linear or proportional to slip because the value of rotor resistance divided by slip,R_r'/S dominates torque in linear manner. As load increases above rated load, stator and rotor leakage reactance factors gradually become more significant in relation to R_r'/S such that torque gradually curves towards breakdown torque. As the load torque, increases beyond breakdown torque the motor stalls.

Table -1:

Torque of Motor (N-m)	Slip (in %)	Rotor current frequency (Hz)	Power factor
0.000	0.133	0.066	0.327
1.813	1.000	0.500	0.350
2.719	1.330	0.665	0.494
3.626	1.667	0.833	0.447
4.079	2.200	1.100	0.470
4.985	2.600	1.300	0.499
5.439	2.733	1.366	0.500
5.892	3.333	1.665	0.506
6.345	3.400	1.700	0.507
7.252	4.333	2.165	0.509

2.2 Results

The result obtained from the Table1 analyze with the help of graph as shown below.

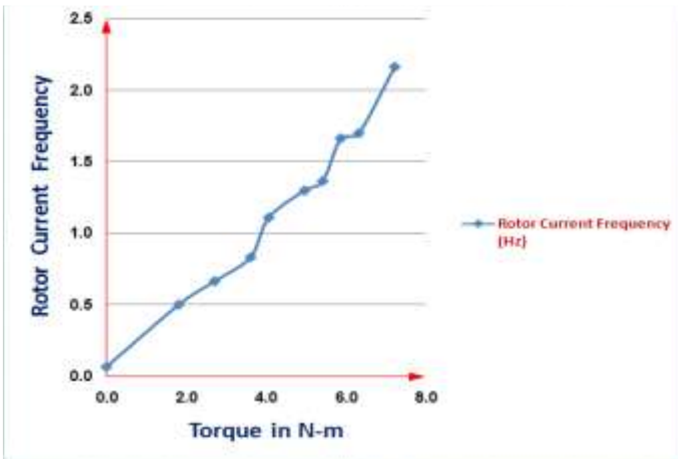

Chart -1: Variation of Rotor current frequency versus Torque

Here we can see that in above Fig. 4 that is plotted between rotor current frequency and developed torque in the three-phase induction machine, by increasing the value of torque due to increase mechanical loading, the rotor current frequency increase continuously. The increase in frequency is carried due to increase in the value of slip S and the increment in slip is the result of increased mechanical load on machine [11].

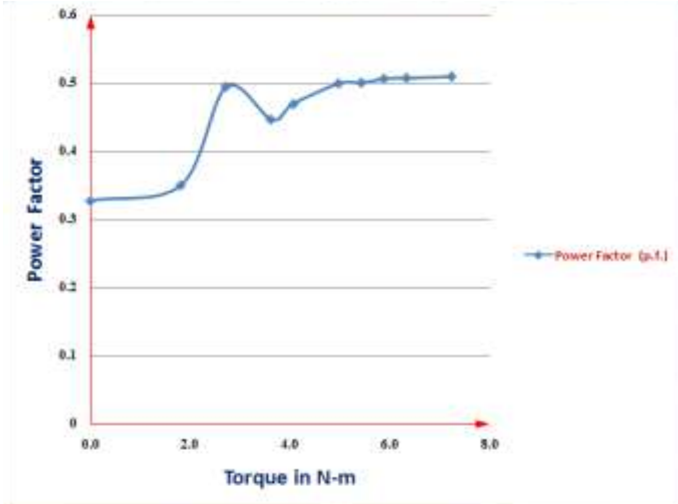

Chart -2: Variation of Power factor versus Torque

The power factor of induction motors varies with load, typically from around 0.85 or 0.90 at full load to as low as about 0.20 at no-load, due to stator and rotor leakage and magnetizing reactance[9]. Power factor can be improved by increasing the mechanical loading. In the Fig. 5, we can see that on increasing the value of torque due to increase the mechanical load, the power factor improves continuously as above in fig.

3. CONCLUSION

In this paper, an operation on the three-phase induction machine at different load condition has been carried and the outcome of operation (i.e., Rotor current frequency and Power factor improvement) studied and verified.

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