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Role of stored energy on operation of squirrel cage induction motor during voltage sag conditions

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Abstract: - *Voltage sag being one of the biggest problems in power quality, a method for analysis of effects of voltage sag on performance characteristics of induction motor is proposed in this paper. Induction motor being most popular in industry, it is very important to carry out studies about the effects of power quality on operational performance of induction motor. The major effects of voltage sag on operation of induction motor are speed loss and fluctuations in torque but not all sag conditions results in above effects. This paper covers study and role of stored energy in induction motor during its operation which is important to consider during voltage sag conditions to differentiate between tolerable and vulnerable voltage sag. Also load types and performance criteria for load can also be considered to clearly state the adverse effect of voltage sag on application.*

Index Terms: - *Voltage sag, energy stored in magnetic field and mechanical system, Electrical & Mechanical time constants, Induction motor*

I. INTRODUCTION

According to principle of operation of induction motor, the effect of supply voltage reduction is directly on torque developed in rotor which in turn causes reduction in rotor speed.

The change in rotor speed results in increase in slip, reduction output power of motor. This further increases rotor current, rotor Cu loss and accordingly increases stator current and stator Cu loss [1].

But practically not all voltage sag conditions results in above stated effects. The reason being, use of stored energy in induction motor during sag conditions.

Three phase induction motor has three elements which stores some of the energy during its operation. These three elements are a) Stator winding, b) Rotor winding & c) Rotor [2]

When sag initiates, motor lags input energy required to maintain its normal output speed, torque and power.

During this, energy stored by induction motor previously comes in to action and serves for the lack of energy for rated output. If it succeeds to fulfill the lack of energy, there will not be any effect of voltage sag observed further, if it isn't sufficient then there will be the effect of sag observed as stated above.

The concept of stored energy in magnetic field and mechanical system and respective concept of time constants is discussed in II. Method of analysis to obtain tolerable and vulnerable voltage sag conditions is given in III. The mechanical load type also plays important role in deciding intensity of effect of voltage sag on output power to the load. So, two most common types of mechanical load i. e. square exponential & cubic exponential loads and

accordingly effect of speed loss on output power is discussed for both in IV.

II. Energy Stored In Induction Motor

A) Energy stored in an inductor

According to basic concepts of electrical engineering, when current I passes through an inductor of inductance L , energy is stored in it, which is given by formula[2],

$$E = \frac{1}{2} L I^2 \text{ joules} \qquad (1)$$

As induction motor contains to windings, namely stator and rotor. Thus both windings being inductive, will store energy when current will pass through them. Thus as per above stated equation, amount of energy stored in stator and rotor windings can be given as below [2],

Energy stored in stator

$$\text{(E-stator)}=\frac{1}{2} L_1 {I_1}^2 \text{ joules} \qquad (2)$$

Energy stored in rotor

$$\text{(E-rotor)} = \frac{1}{2} L_2 {I_2}^2 \text{ joules} \qquad (3)$$

B) Energy stored in a rotating mass

According to basic concepts of mechanical engineering, when a mass of inertia J rotates with angular speed of ω rpm, it stores an amount of energy given by formula [2],

$$E = \frac{1}{2} J \omega^2 \text{ joules} \qquad (4)$$

This concept is also applicable for rotor and thus mechanical energy is stored in rotor which can be given by equation [2],

$$\text{E-mech} = \frac{1}{2} J \,\omega_r^{\,2} \qquad (5)$$

Where, $\omega_r = \frac{2\,\pi\, N_r}{60}$

C) Time constants of induction motor

In the equations of energy stored in inductor, inductance is constant value and current is variable. Current flowing through inductor is instantaneous value of current and is time dependent. When this energy is to be given back to motor, current must reach zero value, but value of current doesn't change suddenly and takes some time. To characterize this time, the term time constant is stated as given below.

D) Electrical Time Constant

The time required for current to reach 63.2% of its final value for a fixed voltage level.

$$\tau_e = \frac{L}{R} \qquad (6)$$

Where, L = inductance in henries
R = resistance in ohm

Similarly, in the equations of energy stored in rotating mass, inertia is constant value and angular speed is variable. Speed of rotor also takes some time to change its value and this time is characterized as given below.

E) Mechanical Time Constant

In a simple first order system, time required for the motor's speed to attain 63.2 % of its final value for a fixed voltage level.

Expression for the Mechanical Time Constant is:

$$\tau_{M(SINE-SINE)} = \frac{RJ}{K_E\,K_T} \qquad (7)$$

Where , J = inertia in Nm/A
R = Resistance

KE = 0-peak value of the phase-phase back EMF (Volt/rad/sec).

KT = Torque constant in Nm/ amp

In general values of both mechanical and electrical time constants are in the range of 5 to50 milliseconds

III. Analysis Of Effect of Voltage Sag on Performance of Induction Motor

The effect of voltage sag on performance of induction motor is generally loss of speed and torque but as stated above not all voltage sag will affect the performance of induction motor. The role of energy stored in induction motor also has to be studied. For this purpose, calculations and analysis is done by using an excel file and effect of three voltage sag conditions for same duration is obtained.

Table1 shows input data required for analysis by this method. Table 2 shows values of constant parameters and Table 3 shows values variable parameters during normal operation of motor and during sag conditions. Table 4 shows comparison of stored and missing energy required for normal operation of motor and accordingly effect on performance of motor.

Table1: input data

HP rating -	3	HP
Rated Voltage (V1) -	415	V
Frequency (f) -	50	Hz
Pole pairs -	2	
Stator resistance (r1) -	3.3805	Ohm
Stator self inductance L1	0.0113	H
Rotor resistance (r2) -	3.38	Ohm
Rotor self inductance (L2)	0.0113	H
Mutual Inductance (Lm) -	0.3120	H
Inertia of rotor (J) -	0.003985	Kg/Nm2
Rotor speed (Nr) =	1420	rpm

Table 2: constant parameters

Parameter	Value	Unit
Frequency (f) -	50	Hz
No. of Poles (P) -	4	
Synchronous Speed (Ns) -	1500	rpm
Stator resistance (r1) -	6.2164	ohm
Stator reactance (x1) -	239.2362	ohm
Rotor resistance (r2) -	2.8722	ohm

Angular synchronous speed Ws	157.1429	rpm

magnetizing reactance	198.8894	ohm

Table : 3 : Variable parameters for normal and 90% sag Voltage condition

Stator Voltage V	Time (Duration)Sec	Per phase voltage V1	Electromagnetic Torque Te	Rotor Speed Nr	Output Power (Pout)	Angular Speed	Slip	Rotor Current	Energy Stored in Rotor Magnetic Field	Mechanical Energy Stored in Rotor	Stator current	Energy Stored stator Magnetic Field	Energy Stored in air gap	Total Energy Stored
Normal Supply Voltage														
415	7	239.600362	17.294	1420	2220	148.762	0.0533	3.45107	0.067291	44.09423	4.2186	0.10055176	0.09193	44.354
Without considering stored energy														
373.5	7	215.640326	14.008	1401.23	2201.94	146.796	0.0658	3.78095	0.08077	42.93651	4.395	0.10913601	0.05884	43.18526

Table 4 Calculation of stored and missing energy for 90% sag voltage

Supply Voltage	Duration	Eout during Normal Supply	Eout During Sag	Missing Energy	Stored Energy
373.5	3.5	7770	7706.79	63.2099	44.354

A) Threshold line between tolerable and vulnerable voltage sag

Once stored energy in induction motor is calculated, then it becomes easy to decide which sag conditions will affect performance of motor by how much extent. It is a curve drawn by joining those voltage sag conditions for which missing energy required for normal output of motor is equal to addition of stored energy in induction motor. Voltage sag having magnitude and duration which comes out to be below this line will not affect performance of motor. Voltage sag having magnitude and duration which comes out to be above this line will affect performance of motor. This threshold line can be drawn as shown in fig (3.1)

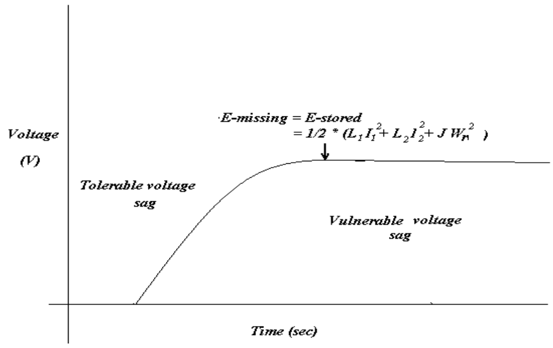


Fig 3.1 Threshold line between tolerable and vulnerable voltage sag

IV. Intensity of Effect of Voltage Sag In Respect Of Load Type.

Mechanical loads exhibit wide variation of speed-torque characteristics. Load torque are generally speed dependent and can be represented by an empirical formula such as,

Fig. 3.1 Speed Torque Characteristics

The mechanical power of load is given by equation (9), where $\boldsymbol{\omega}$ is the angular speed in rpm. Fig. (2) shows the mechanical power characteristics that corresponds to the loads shown in fig 1.

$$P = T\boldsymbol{\omega} \quad , \quad \omega = \frac{2\,\pi\,\mathrm{N}}{60} \qquad (9)$$

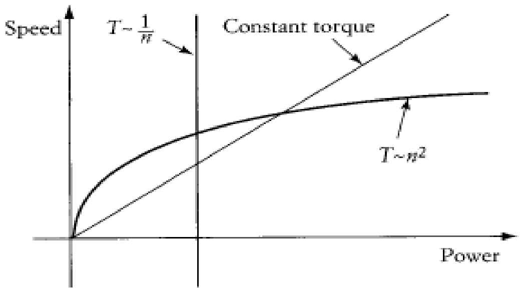


Fig. 3.1 Speed Power Characteristics

Two major load types from above are,

1. Torque proportional to speed

In this load torque is directly proportional to speed, therefore output power as given in equation 4.2 is proportional to square of speed, thus called square exponential load.

$$P_{out}\ \alpha\, N^2 \qquad (10)$$

Thus, any change in speed will cause its squared change in output power.

2. Torque proportional to square of speed

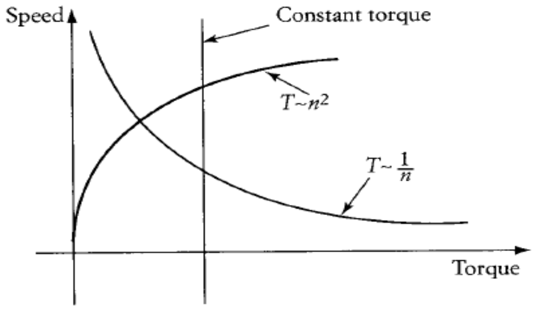
In this load torque is directly proportional to square of speed, therefore output power as given in

$$T = CT_r \left(\frac{N}{N_r}\right)^k \qquad (8)$$

Where C is proportionality constant,

T_r is the load torque at speed N_r,

N is the operating speed, and k is an exponential coefficient representing the torque dependency on speed. Fig. 1 shows typical characteristics of various mechanical loads [3].



equation 4.2 is proportional to cube of speed, thus called square exponential load.

$$P_{out}\ \alpha\, N^3 \qquad (11)$$

Thus, any change in speed will cause its cubic change in output power [3].

The effects of voltage sag analyzed above on speed will cause change in output power of mechanical load.

V. CONCLUSION

The influence of voltage sag on performance of induction motor will depend upon amount of energy stored by motor. As energy stored by stator and rotor winding depends upon self inductances of both windings, its value can be changed by changing self inductances. Similarly, energy stored by rotor depends upon inertia of rotor. Hence concept of stored energy can also be considered while selection of parameters for design of motor to increase its immunity to voltage sag.

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