

Possible Faults in Induction Motor: An Overview

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Abstract

The induction motors are susceptible to many types of fault in industrial applications. A motor failure that is not identified in an initial stage may become catastrophic and the induction motor may suffer severe damage. Thus, undetected motor faults may cascade into motor failure, which in turn may cause production shutdowns. Such shutdowns are costly in terms of lost production time, maintenance costs, and wasted raw materials. Significant efforts have been dedicated to induction machine fault diagnosis during the last two decades and many techniques have been proposed. Thus, a brief description of the common faults is presented in the paper. The purpose of this paper is to introduce in a concise manner the fundamental theory for fault detection of induction motor.

Keywords-Electrical Machines, Condition Monitoring, Fault Diagnosis

1. INTRODUCTION

Induction motors are complex electro-mechanical devices utilized in most industrial applications for the conversion of power from electrical to mechanical form. Induction motors are used worldwide as the workhorse in industrial applications. Such motors are robust machines used not only for general purposes, but also in hazardous locations and severe environments. A motor failure that is not identified in an initial stage may become catastrophic and the induction motor may suffer severe damage. Thus, undetected motor faults may cascade into motor failure, which in turn may cause production shutdowns. It has now become very important to diagnose faults at their very inception; as unscheduled machine downtime can upset deadlines and cause heavy financial losses. The major faults of electrical machines can broadly be classified as the following [1]: Stator faults resulting in the opening or shorting of one or more of a stator phase winding, Abnormal connection of the stator windings, Broken rotor bar or cracked rotor end-rings, Static and /or dynamic air-gap

irregularities, Bent shaft (akin to dynamic eccentricity) which *can* result in a rub between the rotor and stator, causing serious damage to stator core and windings, Shorted rotor field winding, and Bearing and gearbox failures. These faults produce symptoms one by one given below: Unbalanced air-gap voltages and line currents, Increased torque pulsations, Decreased average torque, Increased losses and reduction in efficiency, and Excessive heating. The diagnostic methods to identify the above faults may involve several different types of fields of science and technology. They can be described as [2]: Electromagnetic field monitoring, search coils, coils wound around motor shafts (axial flux related detection), Temperature measurements, Infrared recognition, Radio frequency emissions monitoring, Noise and vibration monitoring, Chemical analysis, Acoustic noise measurements, Motor current signature analysis, Model, artificial intelligence and neural network based techniques. Of the above types of faults i) bearing, ii) the stator or armature faults, iii) the broken rotor bar and end ring faults of induction machines and iv) the eccentricity related faults are the most prevalent ones and thus demand special attention. Thus, these faults and their diagnosis techniques will be discussed briefly in the next sections. Many condition monitoring methods have been proposed in different papers for different type of rotating machine faults detection and localization. In fact, large electro-machine systems are often equipped with mechanical sensors, primarily vibration sensors based on proximity probes. Those, however, are delicate and expensive [3]. Moreover, in many situations, vibration monitoring methods are utilized to detect the presence of incipient failure.

However, it has been suggested that stator current monitoring can provide the same indications without requiring access to the motor. This technique utilizes results of spectral analysis of the stator current (precisely, the supply current) of an induction motor to spot an existing or incipient failure of the motor or the drive system.

2. FAULT DIGNOSIS IN ELECTRICAL MACHINES

Electrical machines are extensively used and core of most engineering system. These machines have been used in all kinds of industries. An induction machine is defined as an asynchronous machine that comprises a magnetic circuit which interlinks with two electric circuits, rotating with respect to each other and in which power is transferred from one circuit to the other by electromagnetic induction [6]. It is an electromechanical energy conversion device in which the energy converts from electric to mechanical form. The energy conversion depends upon the existence in nature of phenomena interrelating magnetic and electric fields on the one hand, and mechanical force and motion on the other. The rotor winding in induction motors can be squirrel-cage type or wound-rotor type. Thus, the induction motors are classified into two groups [4]: Squirrel-cage and Wound-rotor induction motors.

The squirrel cage induction motor consist of conducting bars embedded in slots in the rotor iron and short circuited at each end by conducting end rings. The rotor bars are usually made of copper, aluminium, magnesium or alloy placed in slots. Standard squirrel cage rotors have no insulation since bars carry large currents at low voltages. Another type of rotor, called a form-wound rotor, carries a poly phase winding similar

to three phase stator winding. The terminals of the rotor winding are connected to three insulated slip rings mounted on the rotor shaft. In a form-wound rotor, slip rings are connected to an external variable resistance which can limit starting current and associated rotor heating. During start-up, inserting external resistance in the wound-rotor circuit produces a higher starting torque with less starting current than squirrel-cage rotors [4]. This is desirable for motors which must be started often. The squirrel-cage induction motor is simpler, more economical, and more rugged than the wound-rotor induction motor. A squirrel-cage induction motor is a constant speed motor when connected to a constant voltage and constant frequency power supply. If the load torque increases, the speed drops by a very small amount. It is therefore suitable for use in constant-speed drive systems [5, 6]. On the other hand, many industrial applications require several speeds or a continuously adjustable range of speeds. DC motors are traditionally used in adjustable drive systems. However, since DC motors are expensive, and require frequent maintenance of commutators and brushes. Squirrel-cage induction motors are preferred because they are cheap, rugged, have no commutators, and are suitable for high-speed applications. In addition, the availability of solid state controllers has also made possible to use squirrel-cage induction motors in variable speed drive systems. The squirrel-cage induction motor is widely used in both low performance and high performance drive applications because of its roughness and versatility.

Electric machines are frequently exposed to non-ideal or even detrimental operating environments. These circumstances include overload, insufficient lubrication, frequent motor starts/stops, inadequate cooling, etc. Under these conditions, electric motors are subjected to undesirable stresses, which put the motors under risk of faults or failures [7]. There is need to improve the reliability of motors due to their significant positions in applications. Consider that three-phase sinusoidal currents are impressed in the three-phase stator windings, which are given as:

$$\begin{aligned} i_a &= I_m \cos \omega_e t \\ i_b &= I_m \cos(\omega_e t - \frac{2\pi}{3}) \\ i_c &= I_m \cos(\omega_e t + \frac{2\pi}{3}) \end{aligned} \tag{1}$$

where

I_m : the magnetizing current;

ω_e : the stator or line frequency.

Each phase winding will independently produce a sinusoidally distributed magnetic motive force (MMF) wave, which pulsates about the respective axes. At spatial angle, the instantaneous MMF expressions can be given as:

$$\begin{aligned}
F_a(\theta) &= Ni_a \cos \theta \\
F_b(\theta) &= Ni_b \cos(\theta - \frac{2\pi}{3}) \\
F_c(\theta) &= Ni_c \cos(\theta + \frac{2\pi}{3})
\end{aligned} \tag{2}$$

where

θ : the torque angle;

N : the number of turns in a phase winding.

The resultant MMF at angle θ is given as:

$$\begin{aligned}
F(\theta) &= F_a(\theta) + F_b(\theta) + F_c(\theta) \\
&= Ni_a \cos \theta + Ni_b \cos(\theta - \frac{2\pi}{3}) + Ni_c \cos(\theta + \frac{2\pi}{3})
\end{aligned} \tag{3}$$

Substituting Equations (1) in (3), the $F(0, t)$ expression can be written as:

$$F(\theta, t) = \frac{3}{2} NI_m \cos(\omega_e t - \theta). \tag{4}$$

Equation (4) indicates that a sinusoidally distributed MMF wave of peak value $3/2 NI_m$ is rotating in the air gap at frequency ω_e . In a two-pole motor, $F(0, t)$ makes one revolution per cycle of current variation. This means that for a P -pole motor, the rotational speed can be given as:

$$N_e = \frac{60 f_e}{P}$$

where

N_e : the synchronous speed;

f_e : the stator frequency;

P : the number of poles.

If the motor rotor is initially stationary, its conductors will be subjected to a rotating magnetic field, inducing current in the short-circuited rotor at the same frequency. The interaction of air gap flux and rotor MMF produces torque. At synchronous speed of the motor, the rotor cannot have any induction, and therefore, torque cannot be produced. At any other speed $r N$, the speed differential $N_e - Nr$, called slip speed, induces rotor current and torque is developed. The slip S is defined as:

$$S = \frac{N_e - N_r}{N_e} = \frac{\omega_e - \omega_r}{\omega_e} = \frac{\omega_{sl}}{\omega_e}$$

where

N_r : the rotor speed;

W_r : the rotor frequency;

W_e : the slip frequency.

The rotor voltage is induced at slip frequency, which correspondingly produces slip frequency current in the rotor. The torque expression can be derived as:

$$T_e = \frac{3}{2} P I_r^2 \frac{R_r}{S \omega_e}$$

where

I_r : the rotor current;

R_r : the rotor resistance.

3. INDUCTION MOTORS AND THEIR FAULTS

Induction motors are critical component of many industrial processes and are frequently integrated into commercially available equipment and industrial processes. However, environmental, duty, and installation issues may combine to accelerate motor failure far sooner than the designed motor lifetimes. Induction motors are subject to many different types of faults. The major faults can broadly be classified as the following [13]: (a) bearing failure, (b) rotor faults include broken bar, winding faults, and cracked rotor end-rings, (c) eccentricity-related, (d) stator faults include opening and shorting of windings. The induction motor faults can be categorized into two types: mechanical and electrical..

A. Mechanical Faults

1) Eccentricity

Eccentricity of motor stator and rotor is one of the basic faults in induction motors that contribute toward a considerable percentage of the motor faults. When eccentricity becomes large, the resulting unbalanced radial forces can cause stator to rotor rub, and this can result in damage of the stator and rotor. Some reasons for eccentricity include: elliptical stator inner cross-section, relative misalignment of rotor and stator in the fixing and commissioning stage, wrong placement of bearing, misalignment of load axis and rotor shaft, mechanical resonance in critical speed, unbalanced load and rotor axis slanting.

The rotor symmetry axis O_r , the stator symmetry axis O_s and rotor rotation axis O_w coincide with each other in an ideal symmetrical motor. The occurrence of eccentricity means the separation of one of these axes from the other two, or a separation of all the axes. There are different types of eccentricity depending on the separation of the axes. When axis O_s separates from the other two axes, static eccentricity occurs. In this case, the position of minimum (and maximum) air gap versus stator is static. When axis O_r separates from two other axes, the position of minimum (and maximum) air gap versus stator rotates with the rotor and is therefore called dynamic eccentricity. In reality, both static and dynamic eccentricities tend to

co-exist. When all three axes are separate from each other, the eccentricity is called the mixed eccentricity.

The symptoms caused by eccentricity in induction motor can be summarized as following: Mechanical Vibration; Asymmetry and deviation of air gap flux, voltages and line currents; Increasing torque and speed variations; Decreasing average torque; Increasing losses and decreasing efficiency; Rising temperature.

Eccentricity fault causes radial unbalanced magnetic pull between the inner stator and outer rotor circumferences. This gradually damages the motor due to rubbing of the stator and rotor, and also damages the stator winding and the rotor cage. In addition, any eccentricity in the induction motor generates excessive mechanical stress and more rubbing and fatigue of the bearing. Unless detected early, these effects may progress into a stator to rotor hub causing a major breakdown of the motor.

ii) Broken bar fault

Induction motor rotors are of two types: cast and fabricated. Previously, cast rotors were only used in small motors. However, with the advent of cast ducted rotors, casting technology can be used even for the rotors of motors in the range of 3000 kW. Cast rotors can almost never be repaired once faults such as broken rotor bars develop in them. Fabricated rotors are generally found in larger or special application motors. A broken rotor bar produces a backward rotating field because of the rotor asymmetry. A broken rotor bar leads to an enhanced field around the fault because of the lack of local demagnetizing slip frequency induced current in these rotor slots. The flux density becomes progressively higher in magnitude close to the fault. The results show that, in case of one broken bar, the degradation in the steady state torque performance is in the order of 2-4%, whereas for three and five broken bars it is between 10-15%, for a motor with 40 rotor bars.

Motor rotor faults are caused by a combination of various stresses that act on the rotor. Broken rotor bar is a common fault of motor rotor. It can be caused by the following reasons: Thermal stresses due to thermal overload and unbalance, hot spots, or excessive losses, sparking; Magnetic stress caused by electromagnetic forces, unbalanced magnetic pull, electromagnetic noise, and vibration; Residual stresses due to manufacturing problems; Dynamic stress arising from shaft torques, centrifugal forces, and cyclic stresses; Environmental stresses caused by for example contamination and abrasion of rotor material due to chemicals or moisture; Mechanical stresses due to loose laminations, fatigued parts and bearing failure.

iii) Bearing failure

Bearing failure is usually progressive but ultimately its effect upon the motor is catastrophic. Installation problems are often caused by improperly forcing the bearing onto the shaft or in the housing. This produces physical damage in the form of brinelling or false brinelling of the raceways which leads to premature failure. Misalignment of the bearing is also a common result of defective bearing installation. The mechanical displacement resulting from damaged bearing causes the motor airgap to vary in a manner that can be described by a combination of rotating eccentricities moving in both directions. Rolling element, sleeve and pad bearings are

used in induction motors as guide and thrust bearings and fail when the load upon the bearing is excessive or its lubrication fails. Bearing failure is accompanied by a rising temperature at the bearing surface, in the lubricant and in the bearing housing. Since bearings support the rotor, any bearing failure will produce a radial motion between the rotor and stator of the motor. An important consequence of bearing deterioration for induction motors is the motor rotor becomes eccentric in the stator bore causing a degree of static and dynamic eccentricity, disrupting the fine balance between the magnetic forces of adjacent poles, and placing more load on the bearing. This also caused an increase in vibration as the shaft dynamics are affected by the altered airgap and bearing stiffness. Bearing can also be damaged by the flow of shaft currents.

B. Electrical Faults

Induction motor rotor windings consist of insulated copper bars driven into the slots in the case of a laminated rotor or aluminium bars cast directly into the rotor. The rotor winding is insulated with epoxy-glass laminates or polyester based materials. The principal stresses of concern on rotor windings are thermal and mechanical. Although the rotor winding of a squirrel cage induction motor is exceptionally rugged, faults do occur particularly on the motors when they are subjected to arduous thermal and starting duty, which causes high temperatures in the rotor and high centrifugal loadings on the end rings of the cage. The early indications of these faults are pulsations in the speed, supply current and stray leakage flux of the motor [17]. Faults on the rotor windings of induction motor have not been easy to detect because there is not necessarily an electrical connection to the winding and it is difficult to measure the low-frequency currents induced in the rotor winding.

The insulation system is potentially one of the intrinsically weakest components of an induction motor. Stator winding insulation is a laminated system consisting of numerous layers of mica-paper tape on a fibreglass backing material impregnated and consolidated with a synthetic resin, usually epoxy or polyester-based [16].

Two main classes of induction motor stator winding faults can be considered [16]: (a) asymmetry in the stator windings such as an open-phase and (b) short-circuit of a few turns in a phase winding. The open-phase leads the motor to operate with a reduced torque. The resultant short circuit between the copper turns causes a significant circulating current to flow in the coil leading to rapid deterioration and failure. Turn failures tend to be very destructive, and involve burning of the insulation and localized melting of the copper conductors. Often, failures resulting from breakdown of the inter-turn insulation are inferred from the location of the puncture, typically at or near the core exit, and the electrical position in the winding, typically the first or second coil from the line end. The models of the induction motor are key items and are very different for two classes. In the case of winding asymmetry, the winding parameters are changed in the usual motor models, while in the case of shorted turns, the structure of the equations changes because of the increased number of state variables. Stator winding insulation is affected by all of the following stress: thermal, electrical, environmental and mechanical; however, the extent to which these stresses in normal operation will cause problems in the short-or long-term will depend on factors such as the operating mode and type of ambient cooling conditions. For

example, air-cooled motor tend to be subject to higher rates of the thermal ageing compared to generators with direct liquid cooling of the stator winding. Further, generators with this type of cooling usually operate in a compressed hydrogen atmosphere thus eliminating oxidation.

4. CONCLUSION

This paper presented basic theory of fault diagnosis of electric machines. Different types of faults of induction motor such as bearing, stator, rotor and eccentricity related faults and their diagnosis techniques has been presented in this paper. The motor faults are due to mechanical and electrical stresses. Mechanical stresses are caused by overloads and abrupt load changes, which can produce bearing faults and rotor bar breakage. On the other hand, electrical stresses are usually associated with the power supply. It is clear from various literatures that current monitoring and electrical monitoring are by far the most preferred techniques to diagnose fault. However, theoretical analysis and modeling of machine faults are indeed necessary to distinguish the relevant frequency components from the others that may be present due to time harmonics, machine saturation, etc.

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