Review on Fault Diagnosis in Three-Phase Induction Motor

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ABSTRACT

This paper investigates different types of faults for electrical machines with reference to an induction motor and to papers published in the last ten years. A comprehensive list of references is reported and the faults are classified into the following main types: 1) Rotor faults; 2) Stator faults; 3) Mechanical faults; 4) Electrical faults. Fault diagnosis of rotating electrical machines has received intense research interest. Therefore many researchers have studied motor-diagnosis methods to prevent sudden stops in motor systems. The development of portable devices that make the reliable diagnosis of faults in electric motors possible has become a challenge for many researchers and maintenance enterprises. The objective of this paper is to identify various such diagnosis techniques that can be applied for automatic condition monitoring of induction motors and can be extended easily to other electrical machines also.

1. INTRODUCTION

The SQUIRREL-GAGE induction motors are most widely used electrical machines for industrial commercial and domestic applications. They are more widespread than any other electric machine in industry due to their intrinsic ruggedness and reduced cost. Surveys have found that these machines demand around 40-50% of the total energy generated in a developed country [1]. These machines have created a revolution in world economy as most of the production processes in a developed country is carried out by utilizing an induction machine. Recently, the use of adjustable speed drives has also spread in many applications. Hence, sudden failures in these machines can be catastrophic for the processes in which they are involved. These machines are therefore seeking more attention from researchers to diagnose the various faults occurring in these machines and to develop various monitoring and signal processing techniques that can be applied for prognosis.

Electrical machines and drive systems are subject to many different types of faults. (Fig.1.) [2] These faults include: 1) Stator faults which are defined by stator winding open or short-circuited; 2) Rotor faults which include rotor winding open or short circuited and broken bar (s) or cracked end-ring for squirrel cage machines; 3) Mechanical faults such as bearing damage, eccentricity, bent shaft, and misalignment; and 4) failure of one or more power electronic components of the drive system.

Induction machines are highly symmetrical machines, so any kind of fault modifies their symmetrical properties.

Characteristics fault frequencies therefore appear in the measured sensor signals, depending on the type of fault. The attempt of this paper is to identify the causes responsible for these faults, to investigate various monitoring and signal processing techniques used for fault detection and diagnosis.

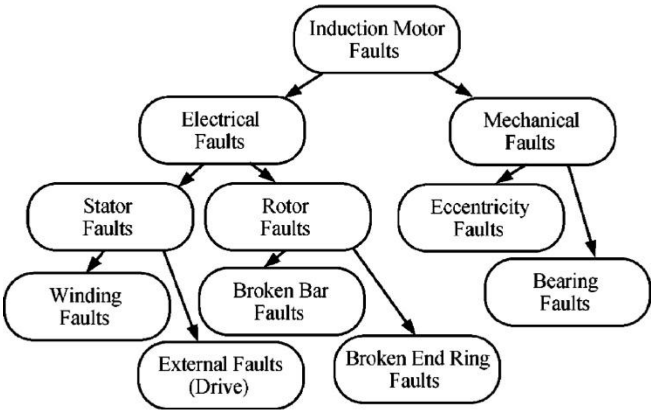

Fig.1.classification of induction motor faults [2]

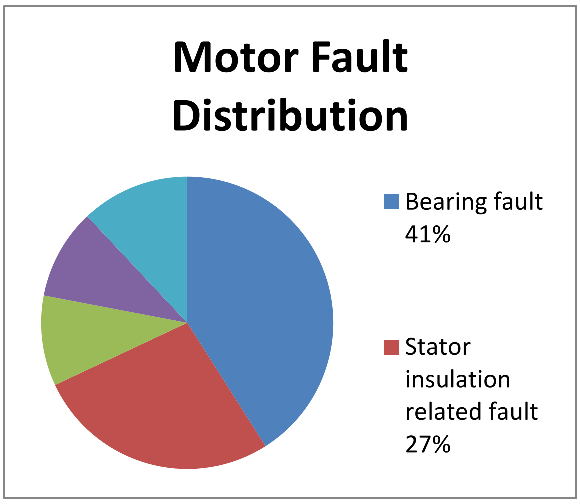

Fig.2. Distribution of faults in induction motor

The factors responsible for failure of three-phase induction motor are highlighted in (Fig.2). It is evident from the chart that the highest contributor for failure in a three-phase induction motor is the bearing fault. This fault is categorised as a mechanical fault.

2. MECHANICAL FAULT

About 40-50% of induction motor faults are related to mechanical defects. Classification of these faults includes the following:
1) damage in rolling element bearing; 2) eccentricity

A. Bearing Faults

Most electrical machines use either ball or rolling element bearings which consists of outer and inner rings. Balls or rolling elements rotate in tracks inside the rings. Bearing faults may be reflected in defects of outer race, inner race, ball or track. Vibrations, internal stresses, inherent eccentricity, and bearing currents have effective influence on the development of such faults.

Taking a step back and looking at the big picture, it is found that motors which were controlled using variable frequency drives tend to show more premature failures. Variable frequency drives (VFDs, ADSs, or inverters) regulate the speed of motor by converting sinusoidal line AC voltage to DC voltage, and then back to pulse width modulated (PWM) AC voltage of variable frequency. The switching frequency of these pulses ranges from 1 kHz up to 20 kHz and is referred as the “Carrier frequency”. The ratio of change of the $\Delta V/\Delta T$ creates a parasitic capacitance between the motor stator and the rotor, which induces a voltage on the rotor shaft. If this voltage referred as “Shaft voltage”, builds up to a sufficient level, it can discharge to ground through the bearings. This current is called as “bearing current”. (Fig.3)

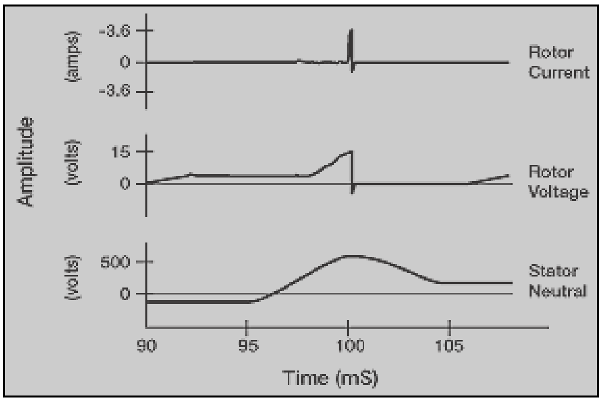

Fig.3. Time-Vs-Amplitude [19]

The bearing current results from voltage pulse overshoot created by the fast-switching IGBT in the VFD. Other reasons of shaft voltage include non-symmetry of motor’s magnetic circuit, supply unbalances, transient conditions and others. Any of these conditions can create bearing currents. Shaft voltage accumulates on the rotor until it exceeds the dielectric capacity of the motor bearing lubricant, then the voltage discharges in a short pulse to ground through the bearing. After discharge, the voltage again accumulates on the shaft and the cycle repeats itself.

This random and frequent discharging has an electric discharge machining (EDM) effect, causing pitting of bearings rolling elements and raceways. The first effect of bearing current damage is the audible noise created by rolling elements riding over these pits in the bearing race. This deterioration causes a groove pattern in the bearing race, which indicates that the bearing has sustained severe damage. This can lead to complete bearing failure.

Bearing faults may be reflected in defects of outer race, inner race, ball or track. (Fig.4.) [13]. Fault in the load part of the drive system, load imbalance, shaft misalignment, gearbox faults, or bearing faults, gives rise to a periodic variation of the induction machine load torque. Torque oscillations already exist in a healthy motor owing to space and harmonics of the air-gap field but fault-related torque oscillations are present at particular frequencies often related to the shaft speed.

Shaft vibration frequencies associated with different ball-bearing faults were given in [3]. Different fault gives rise to different harmonic frequencies which are listed below:

$$F_C = 1/2 \ FR\ (1\text{-}Db\cos\beta/Dc) \qquad (1)$$

$$F_o = N_B/2\ FR\ (1\text{-}Db\cos\beta/Dc) \qquad (2)$$

$$F_I = N_B/2\ FR\ (1+Db\cos\beta/Dc) \qquad (3)$$

$$F_B = DC/DB\ FR\ [1-(Db\cos\beta/Dc)^2] \qquad (4)$$

They define cage fault frequency, outer raceway fault frequency, inner raceway fault frequency, ball fault frequency.

Typically bearing faults are detected through vibration signals. Internal vibrations are caused by asymmetries and construction details. Vibration and current have different natures. Vibration is acceleration, and is bound to the square of the frequency, while current is a displacement. Hence current is mainly sensitive to low-frequency phenomena. Link between vibration and current component was presented using two different approaches and vibration was seen as a torque component that generates two frequency components Fbe in the stator current [7]

$$Fbe=|f \pm kfcar|. \qquad (5)$$

Industrial systems are however, still based on vibration signals as they are the only reliable media. However, use of electrical signals is, preferable in many applications. Extensive research activity focuses on bearing fault detection based on current Signals. Current signals can be used for bearing fault detection only in the case of large failures where it is desirable to detect incipient faults that quickly degenerate into other defects.

There are a number of papers dealing with the detection and diagnosis of faults in rolling-element bearing based on the analysis of current [5]-[6]. It was shown that mechanically induced speed oscillations give rise to sidebands components of the fundamental stator current frequency. It was also demonstrated that shaft misalignment causes modulation of current by the shaft rotational frequency. The use of dedicated signal processing techniques is therefore essential to extract the fault signature from current efficiently.

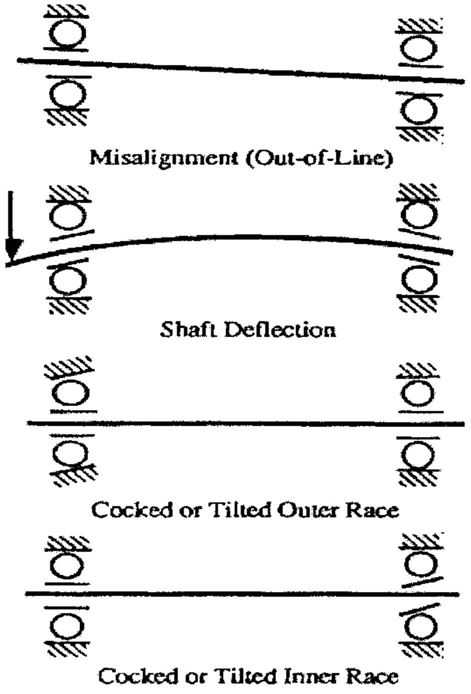

Fig.4. Four types of rolling –bearing misalignment [13]

B. Eccentricity Faults

The eccentricity of a cylinder rotating around an air gap can be classified as static, dynamic, or mixed eccentricity (Fig.5.).[4] Air gap eccentricity is one of the common failure conditions in an induction motor. For static eccentricity the centre of rotation is displaced from the original centre, for dynamic eccentricity, the centre of rotation is at origin while the cylinder is displaced. Finally, for mixed eccentricity, both the cylinder and centre of rotation are displaced from their respective origin. An eccentricity may be caused by many problems such as bad bearing positioning during the motor assembly, worn bearings, bent rotor shaft or operation under a critical speed creating rotor whirl [8]. The eccentricity causes extensive stressing on the machine and greatly increases the bearing wear. Also, the radial magnetic field owing to the eccentricity can act on the stator core exposing the stator windings to potentially harmful vibrations. More recently, the rotor eccentricity was evaluated through different signal analysis such as vibration, flux and current [9].

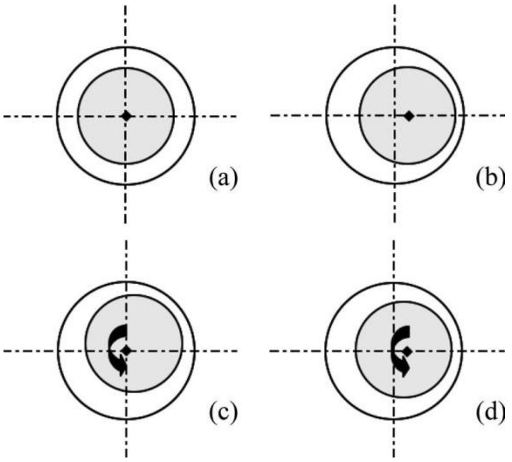

Fig.5. (a) Without eccentricity (b) Static eccentricity (c) Dynamic eccentricity (d) Mixed eccentricity [4]

Under mixed eccentricity conditions, the stator currents contain the following frequencies [10]:

$$F_{ecc}=|f\pm k(1-s)/p\ f| \qquad (6)$$

Where s is the machine slip. Since the frequencies related to the eccentricity and to the load torque overlap on the current sidebands, the frequencies provided by (6) are no longer enough for the diagnosis [7], [11], [12].

The model of eccentricity using both analytical and finite element (FE) approach is still investigated so that it can be improved.

3. DIAGNOSIS OF STATOR AND ROTOR FAULTS

The analysis of induction machines with stator faults has been considered only recently. Detection of any machine failure at an early stage is of great concern in order to replace damaged parts, allowing remarkable cost reduction and avoiding downtime. Fault detection and prognosis of rotor faults are critical for industrial applications, although rotor faults share only about 10-20% of the overall induction machine faults [14]. In fact, the breakage of a bar (s) leads to high current in adjacent bars, thus leading to further breakage and stator faults as well.

A. Stator Faults

Various causes/stresses leading to stator faults can be classified into four main types as: [15]

1) Thermal stress:

For every 10 C rise in temperature, the insulation life gets halved due to thermal aging. If operating temperature becomes extremely high, the insulation becomes vulnerable to other influencing factors or stresses that can cause failure [16]. If insulation loses its physical integrity, its resistance to other dielectric, mechanical and environmental stress reduces. By reducing the operating temperature, or by increasing the grade of insulating material used, thermal aging can be minimised.

During start-up, stator current is five to eight times more than the actual normal current; therefore if the motor is subjected to repeated start-ups, the winding temperature will rapidly increase. Also voltage imbalance per phase causes winding temperature to increase with large currents [16]. It has been estimated that the winding temperature also increases with load. Therefore to operate the motor at a specific load, insulation system should be selected accordingly, to meet a rating that is well above the operating temperature.

2) Electrical stresses:

The relation between voltage stresses generated in a motor and its insulation life must be considered while selecting the insulating material. Transient voltages result in reduced winding life or premature failure. These conditions can be caused due to insulation failure, variable frequency drives, opening and closing of circuit breakers, current-limiting fuses, capacitor switching, three-phase faults, line-to-line, line-to-ground, multiphase line-to-ground faults.

3) Mechanical stresses:

These stresses may be due to rotor striking the stator, caused due to shaft deflection, misalignment, bearing failures...If the rotor strikes the stator, while the motor is running; it results in premature grounding of the coil in the stator slot caused by excessive heat generated at the point of contact. If the strike is during start-up, the stator lamination causes puncturing of coil insulation, resulting in grounding of coil. There can be other factors also, which can cause winding failures like: loose nuts and bolts, rotor fan blades, striking the stator or foreign particles striking the stator, causing the stator to overheat and fail.

4) Environmental stresses/contaminations:

Presence of foreign particles could cause various ill effects on the function of motor like premature bearing failure, breakdown of insulation system caused due to reduction in heat dissipation. So steps should be taken to prevent the foreign particles from interacting with motor surface.

To summarize, all the factors responsible for stator winding failure, can be minimised by carefully designing the induction machine and carrying out proper maintenance. Since some of the phenomena are random and uncontrollable, early diagnosis of an induction motor can be more helpful to record these failures and prevent complete failure of the machine.

From the view-point of signal processing and data clustering, researchers view stator winding failures accounting to: 1) stator winding open-phase failure; 2) stator winding short-circuit failure. Open-phase failure allows the machine to operate with a reduced torque while short-circuit failure leads to complete failure of the machine in a short time. A short circuit is the most difficult failure to detect. If left undetected the motor might keep on running, and heating in the shorted turns would cause critical insulation breakdown.

The analysis of turn-to-turn short-circuit in a stator winding can be made by different models. Four main approaches used, in the event of shorted turns are: 1) Analysis of Magneto motive forces (MMF); 2) Finite element (FE) approach; 3) Winding function approach; 4) Dynamic mesh reluctance approach.

Abnormal frequencies, which appear in the stator current, are functions of a number of variables due to MMF distribution and the permeance-wave representation of the air gap. These abnormal harmonic frequencies can be made independent of the type of drive-systems or control techniques, by using MCSA as the online motor diagnosis technique. The short-circuit current flowing in the interturn short circuit winding initiates a negative MMF, which reduces the net MMF of the motor phase , therefore waveform of airgap flux, which is changed by the distortion of MMF, induces harmonic frequencies in stator-winding currents as [17].

$$F_{stator} = \{n/p\ (1-s) \pm k\}\ f_o \qquad (7)$$

Where p= number of pole pairs, n= 1, 2, 3... And k= 1, 3, 5....respectively.

Dynamic mesh reluctance approach is used to estimate the time available to shut down the machine after a short-circuit event. The worst case is when the number of shorted turns are small, for which lead time is around a few seconds. The lead time can however be slightly increased, weakening the magnetizing field.

An insightful comparative analysis of the four approaches is still under discussion. One of the simplest but most efficient methods is the continuous monitoring of the negative sequence of the stator current, which helps in the detection of electrical or magnetic non-rotational asymmetry of induction machine or an asymmetry in the supply voltage. Many proposals have been presented for use of negative sequence of stator current that is sensitive to different phenomena beyond stator asymmetry [18]. An effective diagnostic procedure should distinguish between negative sequence caused by short-circuit that must be linked to few fundamental parameters of the machine; and the negative sequence caused by unbalanced voltages, saturation winding asymmetries, and eccentricity.

In order to take into account the effects of unbalanced voltages, both current and voltage signals are acquired and a procedure is proposed to disconnect the machine before a complete failure. By means of current and voltage signals, the negative sequence impedance is computed, which is quiet constant unless a failure occurs in the machine. using negative sequence of stator current it is also possible to compute the cross-admittance between voltages and current sequences and their variation with machine load.

In summary, extensive research is focussed on stator fault detection with special reference to short circuits. Fault detection and periodic monitoring of stator turn-to-turn insulation is the most effective method. The surge test and the offline partial discharge (PD) test are the most common techniques gaining popularity for assessing turn-to-turn insulation.

B. Rotor Faults

One of the most dangerous faults in the induction motor is the rotor bar (s) breakage. Of particular importance is the occurrence of this fault in large motors that drive loads with high inertias and long start-ups. Often these are most expensive motors and the most critical to be repaired without downtime. Rotor bar (s) breakage can be caused by thermal stress, electromagnetic forces, electromagnetic noise, vibration, centrifugal forces, environmental stress, mechanical stress owing to lose laminations, fatigue parts, or bearing failure. This fault can also be caused due to high current forces and temperature gradients appearing in the rotor cage, due to which circulation of current through bar (s) is interrupted. The fault usually starts in the junction point between the bars and short-circuit end ring. It is a type of progressive fault, which even propagates to the adjacent bars without indicating any symptoms of abnormal operation of the machine. Only when the condition is critical, the fault becomes evident, and the repair action impossible, leading to catastrophic failure.

Two different types of squirrel-cage rotors exist in induction motors: 1) cast; and 2) fabricated. Fabricated cages are used for higher ratings and special application machines where possible failure events occur on bars and end-ring segments. Cast rotors are almost impossible to repair after bar breakage or cracks. In the event of cracked bar, current in the rotor bars adjacent to the faulty bar increases up to 50% of rated current. An accurate detection of rotor faults may lead to a complete diagnosis process. Motor current signature analysis (MCSA) has been extensively used to detect broken rotor bars and end-ring faults in induction machines. The detection of rotor bar failures relies on the analysis of current demanded by the machine. This is a non-invasive way (i.e. without interfering with the normal operation of the machine) and the equipment needed for its registration and processing is rather simple. The rotating field theory states any rotor asymmetry generates a component (1-2s) f in the stator current spectrum when it rotates at a constant speed and infinite inertia. Against, the aforesaid conditions, a component at (1+2s) f appears in the current spectrum. These components are usually spaced around the fundamental frequency and are called as sideband components given by (8)

$$f_{sh} = (1 \pm 2.s).f \qquad (8)$$

Where, s = slip.

This conventional approach though robust, has important limitations, reported by several authors [34]. To overcome these drawbacks, some authors have proposed, analysis of current demanded by the machine during transient operation (Transient motor current signature analysis). In this regard, methods based on stator start-up current have been recently introduced.

4. MONITORING TECHNIQUES

Different research papers published in the last ten years, define various techniques used to monitor faults in an induction motor [15]. These techniques can be classified into the following categories using different parameters.

a. Temperature:

Allowing for unobstructed ventilation, the effect of temperature on stator winding can be estimated, by using temperature sensors mounted on the stator winding or embedded in the insulation. It has been shown that as the stator winding ages; it gives rise to formation of space charges. These space charges can be monitored using the thermal step method (TSM). Also owing to temperature, the winding are subjected to thermally stimulated discharge currents (TSDC) which can be helpful in monitoring the energy levels of the traps. Thus by combining TSM and TSDC, stator insulation lifetime can be predicted

b. Magnetic flux:

Abnormal harmonics which appear in the stator current are functions of a number of variables due to magnetomotive force (MMF) distribution and permeance-wave representation of the air-gap. Hence any distortion in the air-gap flux density due to stator defect sets up an axial flux in the shaft. Stator winding short-circuit is the most dangerous types of faults which can render the machine useless, hence to detect the fault and identify the location of shorted turns, search coils are utilised. It has been shown that by using a minimum of four search coils located axisymmetrically to the drive shaft, the location of shorted turns can be found out.

c. *Vibration:*

Industries still rely on measurement of vibration to diagnose faults in an induction motor, because it is the only reliable method. Vibration is seen as an acceleration which varies as the square of frequency. Therefore any changes in the vibration of the machine can be utilised as a tool for different signatures. It has been shown that stator frame vibration is generated due to interterm winding faults, unbalance in supply voltage and single phasing

d. *Power:*

The use of instantaneous power as a detection parameter has more advantages in comparison to current. The use of instantaneous power enhances the reliability of diagnosis of an induction motor. This monitoring technique is independent of the synchronous speed of motor and it generates a characteristic spectral component of power directly at the frequency of disturbance.

e. *Current:*

Motor current signature analysis (MCSA) is a powerful method used for diagnosis of an induction motor. MCSA utilizes the result of the spectral analysis of the stator current to indicate an existing or incipient failure of the motor or of the drive-system. Though MCSA is the most powerful tool, it has some shortcomings that degrade performance and accuracy of motor diagnosis. First MCSA requires a high precision of slip frequency information to guarantee the reliability of diagnosis results. Second stator current data should be sampled after motor arrives at the steady state. The variation of motor speed during the sampling operation invalidates the sampled data. Variable speed drive applications are common in aerospace, appliance, railway and automotive industries and also in electric generators for wind turbines. Therefore advanced signal and data processing algorithms are required to achieve MCSA for diagnosing motors efficiently. Hence some researchers suggest the use of Transient motor current signature analysis (TMCSA).

f. *Induced voltage:*

The shaft voltage induced owing to stator core or winding degradation has not yet proved to be a useful parameter for diagnosis of an induction motor, as the measurement is not reliable. Also, it has been shown that in order to obtain a significant variation in shaft voltage the damage to shaft core or winding should be substantial

g. *Instantaneous Angular speed:*

Utilizing instantaneous angular speed (IAS), asymmetry faults in the induction motor can be detected by monitoring the stator core vibration. In case of unbalanced supply or stator winding fault, the vibration signal contains a component with twice the supply frequency.

h. *Air-Gap Torque:*

For a healthy motor, the air-gap harmonic represents a zero frequency. Any unbalance created in the air-gap torque due to faults or even due to unbalanced voltages, produces a harmonic torque whose frequency = $-2\omega s$. The air-gap torque is produced by the flux linkage and the currents of a rotating machine. Double fundamental frequency torque indicates a gap in the stator winding and/or voltage.

i. *Partial discharge:*

The grade of insulating material plays a vital role in stator winding failure. Using online partial discharge (PD) test the effectiveness of stator winding maintenance can be easily monitored Insulation imperfections give rise to a small electric discharge, owing to delaminations within the ground wall insulation, resulting from overheating or poor manufacturing, due to which voids or air pockets are formed in the insulating material, resulting in a discharge. A deteriorated winding has a higher PD activity than a winding in good condition. Techniques have been developed where PD can be monitored using specialized sensors.

j. *Surge current:*

In the surge test two identical high voltages, high frequency pulses are simultaneously imposed on two phases of the motor winding with third phase grounded. The reflected pulses are compared on an oscilloscope to indicate the insulation faults between windings, coils, and group of coils. This is a predictive field method to show the turn-turn insulation weakness before the turn-turn short-circuits occurs.

k. *Gas analysis:*

The degradation of electrical insulation within a motor produces carbon monoxide gas which can be detected by an infrared absorption technique.

l. *Motor circuit analysis:*

In Motor circuit analysis (MCA), a low amount of energy with amplified responses is applied. The responses help in evaluating the condition of both the rotor and the windings through comparative readings.

5. SIGNAL PROCESSING TECHNIQUES

Papers published in the recent years classify diagnosis procedure for an induction motor into three classes [4]: 1) model based; 2) signal based; 3) data based.

Model based diagnosis defines an asymmetrical induction motor whose model is used to predict failure fault signatures. The difference between measured and simulated signatures is used as a fault detector. Signal based diagnosis relies on advances in digital technology. It looks for known fault signatures in quantities sampled from the actual machine. The signatures are then monitored by suitable signal processors. Signal processing can be used to enhance SNR and to normalize data in order to isolate the fault from other phenomena and decrease sensitivity to operating conditions. Data based diagnosis does not require any knowledge of machine parameters and model. It relies only on signal processing and on clustering techniques.

Signal processing can be further classed into three main subclasses: spectral estimation techniques, time-domain techniques and time-frequency estimation:

A. *Spectral Estimation:*

Spectral estimation techniques are widely adopted in machine diagnosis. Non-parametric, parametric and high resolution methods can be utilized for spectral estimation. Non-parametric methods are based on conventional Fourier analysis, optimal band pass filtering analysis. Non-parametric methods do not solve *the* limits of the frequency resolution of the classical Fourier analysis. Parametric methods are based of estimation of a linear time invariant system from noise by autoregressive moving average model. Parametric methods have improved performance though they are affected by SNR level. High resolution methods can detect frequencies with low SNR. They have been recently introduced in the area of induction machine diagnosis by the application of multiple signal classification (MUSIC) method. MUSIC and zooming Methods are conjugated to improve the diagnosis by detecting a large number of frequencies in a given bandwidth.

B. Time-Domain analysis:

Time-domain analysis is a powerful tool for a three-phase squirrel cage induction motor. In the oscillation of the electric power in time domain becomes mapped in a discrete waveform in an angular domain. Data clustering techniques are used to extract an averaged pattern that serves as the mechanical imbalance indicator. Time-domain technique can track the fundamental frequency and slip of the machine and then compute a diagnosis index without any spectrum analysis.

C. Time-Frequency analysis:

Time-frequency analysis consists of a 3-D time, frequency and amplitude representation of the signal which is inherently suited to indicate transient events in the signal.

5. CONCLUSION

Fault diagnosis of an induction motor is a still a challenging task for researchers and academicians. Motor current signature analysis is still an open topic of research. As reported by included references, a large majority of research was oriented to induction machines, often with constant speed. Attempts are being made to design artificial intelligence systems using fuzzy logic, neural networks, and genetic algorithm. Making use of digital signal processors for effective monitoring and diagnosis have given appreciable results, but still a lot of work has to be done in the near future to deal with induction motors with adjustable speed drives. The papers published in the past years reflect experimental results obtained from lab set-up using small induction machines. But dealing with large induction machines in field still produces new challenges. Eventually in the near future the reliability and efficiency of diagnostic techniques will improve and may lead to the design of fault tolerant drives.

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