Spectral Analysis for Faults Diagnosis of Induction Machines

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Abstract—The condition monitoring of the electrical machines can significantly reduce the costs of maintenance by allowing the early detection of faults, which could be expensive to repair. In this paper, some common faults of induction motor such as stator winding faults, eccentricity faults are experimentally diagnosed with help of motor current signature analysis (MCAS). This method utilizes the results of spectral analysis of the stator current. All experiments are conducted on 0.5 hp, 415V induction motor. To obtain the current spectrum of motor, Virtual instruments (VIs) was developed with help of programming in software LabVIEW8.2. The experimental results show the significant presence of sideband frequencies in current spectrum of motor which clearly indicates the faults of the induction machine.

Keywords- condition monitoring, fault detection, motor current signature analysis (MCAS), virtual instrument (VI).

I. INTRODUCTION

The induction machine is essential in many industrial applications. It is therefore desirable to reduce downtime by employing methods of machine condition monitoring. A widely used method of induction machine condition monitoring utilizes the steady-state spectral components of stator quantities. These spectral components can be used to detect broken rotor bars, bearing failures, air gap eccentricity etc. Traditionally, these techniques have focused on the detection of faults during steady-state machine operation. [1-2]. There are many condition monitoring methods, including vibration monitoring, temperature monitoring, chemical monitoring, acoustic emission monitoring, current monitoring, etc [3]. Except for current monitoring, all these monitoring methods require expensive sensors or specialized tools and are usually intrusive. In current monitoring, no additional sensors are necessary. This is because the basic electrical quantities associated with electromechanical plants such as currents and voltages are readily measured by tapping into the existing voltage and current transformers that are always installed as part of the protection system. As a result, current monitoring is non-intrusive and may even be implemented in the motor control center remotely from the motors being monitored. Therefore, current monitoring offers significant implementation and economic benefits.

Another advantage of current monitoring is that an overall electric machine condition monitoring package is possible, given the fact that the detection of other machine faults and the estimation of machine speed and efficiency have been well achieved via stator current. Thus, Current monitoring techniques are most effective for detecting faults of induction motor. But it is fact that very limited numbers of current monitoring techniques are used in the industry because it is very difficult to assess the severity of fault based on current signature [4]. In this research work, Motor Current Signature Analysis is applied to diagnose the common faults of induction 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.

II. FAULTS EFFECTS ON STATOR CURRENT SPECTRUM

Broken rotor bar fault, short winding fault, bearing fault, air gap eccentricity fault and load fault are common faults of induction motor. This paper is focused on diagnosis of short winding fault and air gap eccentricity fault with help of current signature analysis therefore this section briefly describes the effects of these faults on stator current.

A. Stator winding faults

A motor failure can result in the shutdown of a generating unit or production line. One major cause of the failures is breakdown of the winding insulation leading to puncture of ground wall. Early detection of inter shorts during motor operation would eliminate consequently damage to adjacent coils and stator core reducing repair cost and motor outage time. In addition to the benefits gained from early detection of winding insulation breakdown, significant advantages would accrue by locating the faulted coil within the stator winding.

The most common kind of faults related to stator winding of induction motors are: phase-to-ground, phase-to-phase and short-circuit of coils of the same or different phase. The last kind of fault is also called turn to turn fault. [5-7]. The inter short circuit of the stator winding is the starting point of winding faults such as turn loss of phase winding. The short circuit current flows in the inter-turn short circuit windings. This initiates a negative MMF, which reduces net MMF of the motor phase. Therefore, the waveform of air gap flux, which is changed by the distortion of the net MMF, induces harmonic frequencies in a stator winding current. The frequencies which appear in the spectrum showing the presence of a short-circuit fault are given by the following equation [5,8,9]:

\[ f = \frac{n}{P} \times f_s \]

where:
- \( f \) = frequency of the spectral component
- \( n \) = number of short-circuit windings
- \( P \) = number of poles
- \( f_s \) = fundamental frequency of the supply
\[ f_s = f_1 \left\{ k \pm \frac{n}{p} (1-s) \right\}, \quad \ldots(1) \]

where

- p - pole pairs
- s - rotor slip
- \( f_1 \) - fundamental frequency (Hz)
- \( f_{sc} \) - short-circuit related frequency (Hz)
- \( k=1,2,3,... \) order of the frequency harmonic
- \( n= \text{integer } 1,2,3,4,... \)

The frequencies revealing the presence of short-circuit of winding are in some cases very close to frequencies related to other kinds of defect, as for example eccentricities. For a correct diagnosis, it is very important to be able to distinguish one from the other.

**B. Air gap eccentricity fault**

Air gap eccentricity may be detected by identifying the characteristics current signature pattern being indicative of abnormal levels of air gap eccentricity and then that signature. Air-gap eccentricity in electrical machines can occur as static or dynamic eccentricity. The effects of air-gap eccentricity produce unique spectral patterns and can be identified in the current spectrum. The analysis is based on the rotating wave approach whereby the magnetic flux waves in the air-gap are taken as the product of permeance and magnetomotive force (MMF) waves. The frequency equation for determining air-gap characteristics [10-13] is as follows:

\[ f_{ag} = \left\{ n_{rt} R \pm n_d \right\} \left( \frac{1-s}{p} \right) \pm n_{ws} f_1 \quad \ldots(2) \]

where

- \( f_{ag} \) = frequency components in a current spectrum due to rotor slotting and air gap eccentricity, Hz
- \( n_{rt} \) = any integer, 0, 1, 2, 3,...\( R \) = number of rotor bars
- \( n_d \) = eccentricity order number; any integer, 0, 1, 2, 3,...\( n_d = 0 \) for static eccentricity (principal slot harmonics)
- \( n_d = 1, 2, 3,... \) for dynamic eccentricity
- \( s = \text{nondimensional slip ratio} \)
- \( p = \text{pole-pairs, which is half the number of poles (P), i.e. } p = P/2 \)
- \( n_{ws} \) = order number of stator MMF time harmonic or stator current time harmonic; odd integer, 1, 3, 5,...
- \( f_1 = \text{supply line frequency, Hz} \)

In general, this equation can be used to predict the frequency content for the current signal. There are three \( n \)'s in the equation and, therefore, three sets of harmonics: \( n_{rt} \) is rotor related, \( n_{ws} \) stator related and \( n_d \) eccentricity related. For static eccentricity variations \( n_d = 0 \) and for dynamic eccentricity variations \( n_d = 1, 2, 3,... \).

**III. DEVELOPED SYSTEM FOR DIAGNOSIS OF MOTOR FAULTS**

A system for fault detection was developed and implemented based on Motor Current Signature Analysis (MCSA). The stator current is first sampled in the time domain and in the sequence; the frequency spectrum is calculated and analyzed aiming to detect specific frequency components related to incipient faults. For each motor fault, there is an associated frequency that can be identified in the spectrum. The faults are detected comparing the amplitude of specific frequencies with that for the same machine considered as healthy. Based on the amplitude in dB, it is also possible to determine the degree of faulty condition. In the described system, data acquisition board was used to acquire the current samples from the motor operating under different load conditions. The current signals are then transformed to the frequency domain using a Fast Fourier Transform (FFT). The figure 1 shows the fault detection and diagnosis system for induction motor.

![Figure 1: Motor fault detection and Diagnosis system](image1)

**IV. EXPERIMENTAL SET UP AND DATA ACQUISITION FOR DETECTION OF MOTOR FAULTS**

In order to make several measurements with healthy and faulty squirrel-cage induction motors a modern laboratory test bench was set up as shown in figure 2. It consists of an electrical machine coupled with rope brake dynamometer. The speed of the motor is measured by digital tachometer. The virtual instrument (VIs) was built up with programming in LabVIEW 8.2. This VIs was used both for controlling the test measurements and data acquisition, and for the data processing. A data acquisition card and acquisition board ELVIS are used to acquire the current samples from the motor under load.

![Figure 2: Experimental set up](image2)
Stator current was measured from the one phases with current transformer whose transformation rate is 5/1. The induction motor current was digitalized with a National instrument’s data acquisition card PCI-6251. The 6200 family devices are low cost, multifunction I/O devices with up to 100 kS/s, 4 differential analogue inputs. The proposed LabVIEW program takes a signal in and perform signal processing module’s algorithm and record this knowledge in the computer environment.

V. DETECTION OF SHORT WINDING FAULT

This section experimentally investigates short winding faults in stator winding of induction motor and their effect on the motor current spectrums. Faults are detected comparing the harmonic amplitude of specific frequencies with the harmonic amplitude of the same machine considered as healthy. Short winding fault is replicated in a laboratory. The experiment was performed on three phase 0.5 hp, 4 poles, 50 Hz motor. Several measurements were made, in which the stator current waveform was acquired for a given number of short-circuited coils. Current measurements were performed for a healthy stator winding and also for the same machine with different number of shortened coils in the same phase. The data was sent to a PC through an acquisition board (ELVIS) of National Instruments. The sample frequency used for the measurement is about 25 kHz. In this way, frequencies up to 12500 Hz can be included in the analysis. After the reading, the current signal is decomposed by a Power spectrum algorithm. All the signal processing is performed using LabVIEW’s Advance Signal processing module to generate the frequency spectrum. First, motor was tested in the absence of fault. Afterwards, several experiments were performed on motor under no load condition and with load coupled to shaft. Initially, the motor was damaged with 5% short circuit of winding. Then, severity of fault was increased to 15% and 30%. Using the data acquisition system, following experiments were performed on 0.5 hp, 415V motor:

1) 15% shortened, load uncoupled
2) 30% shortened, load uncoupled
3) 15% shortened, load coupled
4) 30% shortened, load coupled

A. Experimental results

The Laboratory experiments were performed on motor using the system described in previous section for healthy working condition and for winding short circuits of 5%, 15% and 30%. Here, test result of one phase is presented because the results of other two phases are very similar. During the test, the motor was coupled with rope brake dynamometer. The slip was 0.01 and 0.08 at no load and full load respectively.

The figure 3 shows the power spectrum for the healthy condition. The motor was operating at 0.7 amp, corresponding to no load. As can seen from figure 3, the spectrum is completely free of any current components around main supply frequency and consequently, the frequency range in which current components due to stator winding faults are expected, are empty.

![Figure 3: Power spectrum of Healthy motor under no load condition](image1)

![Figure 4: Power spectrum of faulty with 15% shortened under no load condition](image2)

![Figure 5: Power spectrum of faulty with 30% shortened under no load condition](image3)

![Figure 6: Power spectrum of faulty motor (15% shortened) with load coupled to shaft](image4)
The motor thus shows no sign of stator winding faults. Figure 3 to 5 show the test results obtained with no load coupled to the shaft and for short circuit in the phase winding ranging from 15% to 30%. The speed of motor was 1485 rpm at no load. Virtual instrument predicted the current components due to stator winding faults at position 25 Hz and 75 Hz. The components are distributed symmetrically around fundamental frequency as expected, different magnitude from main supply frequency. The components are sign of stator winding fault. Figure 6 and 7 shows the test results obtained with shaft load coupled to the load and for short circuit in phase winding. The full load speed is 1380 yielding a frequency interval of 27 Hz to 73 Hz for detection of short winding fault. It can be seen that the magnitude of short circuit related frequencies increases with the severity of short-circuit. The magnitudes of the short circuit frequencies are termed as FF (Fault Frequencies).

VI. DETECTION OF AIR GAP ECCENTRICITY DETECTION

This section of research paper is focused on air gap eccentricity faults. In practice, all three-phase induction motors contain inherent static and dynamic eccentricity. Air gap eccentricity causes a ripple torque, which further leads to speed pulsations, vibrations, acoustic noise, and even an abrasion between the stator and rotor. Therefore, it is critical to detect air gap eccentricity as early as possible. To replicate the eccentricity fault in laboratory, special methods were used. The effects of eccentricity faults under different load condition are studied to get the fault signature information.

Same type of motor has been used throughout analysis. In this experiment, static eccentricity was created in motor. The normal air gap between the stator and rotor in the experimental induction motors was very small. It was 0.4 mm. The small air gap makes it very difficult to implement rotor eccentricity. To solve this problem, the rotor has to be uniformly machined 0.4mm to increase the air gap up to 0.8mm mm. The static eccentricity is created by first machining the bearing housing of one end bell eccentrically, and then inserting a 0.2 mm offset shim between the housing and the bearing. In this way, 25% static eccentricity is created as shown in figure 8.

Several measurements were made in which the stator current waveform was acquired for diagnosis of air gap eccentricity. Current measurements were performed for healthy motor and for faulty motor with static eccentricity. The current was read with sensing rate of 25000 samples/sec. The data was sent to PC through ELVIS (acquisition board) from National Instrument PCI-6251. The sample frequency used for the measurement was about 1 kHz. Reading was taken at no load and full load for static air gap eccentricity. After taking the reading, the current signal is decomposed by a Power Spectrum algorithm. The bearing housing is machined again to increase the static eccentricity up to 50%. Then test was also again at no load and full load for identifying the magnitude of current components. The parts of an induction motor are shown in figure 9.

A. Experimental results

To detect the air gap eccentricity, the current was analyzed to identify the current components between the frequencies 750 Hz to 950 Hz. The slip was 0.01, and 0.08 at no load and full load respectively. Figure 10 shows a power spectrum between 900 Hz to 1000 Hz to accurately determine the frequency components for 25% static eccentricity at no load. Virtual Instrument (VI) predicted current components (941 Hz) due to abnormal level of static eccentricity for no load conditions. The results show that the components predicted by equations (2) are present. Figure 11 shows the current spectra from motor after its housing was machined and installed again with 50% air gap setting at no load. This figure shows the increased level of fault frequency at 941 Hz.
At full load condition, the motor was operating at 1.05 amp. The full load speed was 1380 rpm yielding a frequency at 778 and 878 Hz for detection of air gap eccentricity. Figure 12 shows the Power spectrum of faulty motor with 25% static eccentricity under full load. The fault frequency (FF) at 878 Hz can be seen in this spectrum which is result of abnormal level of air gap eccentricity.

![Power spectrum of faulty motor with 25% static eccentricity under full load](image1)

**Figure 10:** Power spectrum of faulty motor with 25% Static eccentricity under no load condition

![Power spectrum of faulty motor with 50% static eccentricity under no Load condition](image2)

**Figure 11:** Power spectrum of faulty motor with 50% static eccentricity under no Load condition

![Power spectrum of faulty motor with 25% static eccentricity under full load](image3)

**Figure 12:** Power spectrum of faulty motor with 25% static eccentricity under full load

Similarly, figure 13 shows the power spectrum to determine the frequency components for 50% static eccentricity at full load. Here, fault frequency (878 Hz) is appeared with increased magnitude. Comparing the various air gap eccentricity cases (Fig.10 to 13), it can be seen that magnitude of static eccentricity related frequencies increases with severity of air gap eccentricity fault.

![Power spectrum of faulty motor with 50% eccentricity under full load](image4)

**Figure 13:** Power spectrum of faulty motor with 50% eccentricity under full load

**VII. CONCLUSION**

The Spectral analysis for faults Diagnosis of Induction machines is discussed in this paper. The non invasive approach based on the computer aided monitoring of stator current; Fast Fourier Transform (FFT) is implemented here. The experimental test presented in this paper confirm motor faults such as short winding faults and air gap eccentricity can be detected by current monitoring using FFT based power spectrum. Experiments show that under no load condition, it is difficult to detect short winding faults because the associate frequency is very close to the fundamental. Results also show all expected bands which are the due to short winding fault. In the experiment, severity of fault was increased 15% to 30%. It can be seen that the magnitude of short circuit related frequencies increases with increase the severity of short-circuit.

The subject of on-line detection of air-gap eccentricity in three phase induction motor is also discussed in this paper. Experimental results obtained by using a special fault producing test rig, demonstrate the effectiveness of the proposed technique, for detecting presence of air gap eccentricity in operating three phase induction machine. Experimental results show that it is possible to detect the presence of air-gap eccentricity in operating three phase induction motor, by computer aided monitoring of stator current. In conclusion, it appear that spectral analysis using signal processing techniques may be adequate to indicate the presence of faults in induction motors. This may be achieved at a relatively low cost, eliminating need for expensive spectrum analyzers.
REFERENCES


