Detection of Stator Winding Inter-turn Short Circuit In Induction Motor Using Vibration Specified Harmonic Amplitude

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Abstract

Vibration analysis is one of the most common tools in condition monitoring and detecting faults in electrical machines. There are several standards to monitor the machines condition and discern unusual situation in electrical machines by this technique. Current standards that are being used for fault diagnosis in electrical machines by vibration analysis mostly deal with increases in overall vibration amplitude in faulty conditions. As Inter-turn in motor or generator stator fault doesn’t affect overall vibration and just increase several frequencies that will be introduced in this paper, these standards cannot detect stator inter-turn. The author suggests that Pursuing of special frequencies is best way to detect inter-turn in machines by vibration technique instead of using current standards for detecting the mentioned fault. Finally will be shown vibration spectrum in an asynchronous motor in both healthy and stator winding inter-turned situation and compared the amplitude of introduced frequencies in that experimental object.

Keywords: Condition monitoring, Vibration, Standard, Inter-turn, Fault diagnosis.

1. Introduction

Induction motors are vital components in many industrial applications. Although they carry some important advantages such as robustness, reliability and simplicity of structure, they do occasionally fail, which may be inherent in the machine itself or caused by operating conditions [1]. Despite the fact that induction machines are reliable, they are subjected to some undesirable stresses, causing them some faults resulting in failures [2], [3], [4].

Induction motor is subjected to many different types of faults [5]. A recent reliability paper [6] described and listed the distribution of IM faults as follows: bearing (69%), stator windings (21%), rotor bar (7%), and shaft/coupling (3%). According to this static distribution, the importance of stator faults had inspired several academic and industrial researches. The times passed between the appearances of an inter-turn short-circuit and the final breakdown of the motor is available.
Studies demonstrated that a faulty motor can tolerate several start up and stop cycles with rated load operation. However, other cases exist where the complete breakdown occurs almost immediately the inter-turn short circuit is detected [7]. Many techniques have been proposed to detect the stator inter-turn faults over the last three decades. Techniques based on the time domain analysis of induction motor currents and voltages basically analyze their sequence components [8].

Vibration analysis is one of the most common techniques for electrical machinery. There are several standards in vibration method. VDI 2056 & ISO 10816 families are well known in industry [9], [10]. Commonly they measure overall amplitude of several parts of electrical machinery.

2. Cause of Stresses in Stator

The stator is subjected to various stresses such as thermal, electrical, mechanical, and environmental [11], [12], [13], [14], [15], [16], [17] which severely affects the stator condition leading to faults [4]. Deterioration of winding insulation usually begins as an inter-turn fault involving a few turns of the winding. The fault current, which is the order of twice locked-rotor current, causes severe localized heating and the fault rapidly spreads to a larger section of the winding [18].

The majority of these faults are caused because of a combination of various stresses acting on the stator, which can be classified as follows [19]:

2.1 Thermal Stresses

These stresses might occur due to thermal aging and thermal overloading. As a thumb rule, for every 10°C increase in temperature, the insulation life gets halved due to thermal aging. Unless the operating temperature is extremely high, the normal effect of thermal aging is to render the insulation system vulnerable to other influencing factors or stresses that actually cause the failure [11]. If the insulation system loses its physical integrity, it fails to resist the other dielectric, mechanical, and environmental stresses. The winding failure will occur irrespective of the degree of thermal aging, if any of the above mentioned stresses becomes severe. Thermal overloading can occur due to the applied voltage variations, unbalanced phase voltage, cycling overloading, obstructed ventilation, higher ambient temperature, etc. As a thumb rule, for every 3.5% voltage unbalance per phase, the winding temperature increases by 25% in the phase with the highest current [11].

2.2 Electrical Stresses

The electrical stresses leading to winding failures can be classified into dielectric, tracking, corona, and transient voltage conditions. The definite relationship between insulation life and the voltage stresses applied to the insulating materials has to be taken into consideration during selecting the materials and establishing the coil designs for adequate design life. These stresses can be classified into: 1) phase-to-phase, 2) turn-to-turn, and 3) turn-to-ground.
2.3 Mechanical Stresses

These stresses might be produced from coil movement and rotor striking the stator. The force on the coils due to the stator winding current is maximum during the starting cycle and causing the coils to vibrate at twice the line frequency with movement both in the radial and tangential directions. This coil movement can cause damage to the coil insulation, loosen the top sticks, and cause damage to the copper conductors. The rotor can strike the stator due to a number of reasons like bearing failures, shaft deflection, rotor-to-stator misalignment, etc.

2.4 Environmental Stresses/Contamination:

The presence of foreign material could cause various ill effects on the functioning of the motor such as reduction in heat dissipation (which will increase operating temperature thereby reducing insulation life), premature bearing failure because of high-localized stresses, and breakdown of the insulation system (causing shorts and grounds). [5]

The inter turns short circuit (ITSC) fault in a stator winding is one of the stator faults which had recently attracted considerable research and great industrial interest, since its early and efficient diagnosis paves the way to avoiding more severe stator faults. In fact, if a short circuit of a few turns is undetected the fault will be spreading out causing critical insulation breakdown (by the increase of the temperature) and finally leading to phase-ground or phase-phase faults in a short time and thus conducts to the permanent damage of the motor. [20]

There are many ways to detect mechanical and electrical problems in induction motors, either directly or indirectly, such as vibration analysis [2], [21], motor current signature analysis (MCSA) [11], [12], [22], [23], electromagnetic field monitoring [13], chemical analysis, temperature measurability, infrared measurement, acoustic noise analysis [24], and partial discharge measurement. Among these methods, vibration analysis and current analysis are the most popular ones due to their easy measurability, high accuracy and reliability.

This paper will introduce diagnosis of inter-turn fault in stator of induction motors by analyzing stator frame vibration spectrum.

3. The Air-gap Magnetic Field Analysis

According to the fundamental of the electro-mechanics, the rotating magnetic field of asynchronous motor is rotating at the synchronizing speed

\[ n_0 = \frac{60f_0}{p} \]

so the alternating frequency of magnetic is the same as the frequency of electric network. The magnetic poles always become to appear coupled, this makes the rotor of asynchronous motor in one rotating period bear the electromagnetic force which has double frequency of rotating magnetic field. Note that, electromagnetic force changes \( p \) times (\( p \) is number of pole pairs) when the electromagnetic pulling force rotating around, which is produced by the magnetic poles. At spatial location, the electromagnetic vibration and rotating magnetic field are synchronous; the frequency of stator electromagnetic vibration is \( 2f_0 \) which is the product of the rotating magnetic field frequency \( \left( \frac{f_0}{p} \right) \) and the number of pole-pairs of electromotor \( (2p) \), and is double of the power supply frequency.

The electromagnetic vibration arouse by stator abnormality.

There are many different forces and interactions as a result of the power source and the interactions between the stator and rotor. The power source is a sinusoidal voltage that varies from positive to negative peak voltage in each cycle. Many different problems either electrical or mechanical in nature can cause vibration at the same or similar frequencies. One must look closely to differentiate between the true sources of vibration. A power supply produces an electromagnetic attracting force between the stator and rotor which is at a maximum when the magnetizing current flowing in the stator is at a maximum either positive or negative at that instant in time.
Consequently there will be 2 peak forces during each cycle of the voltage or current wave reducing to zero at the time when the current and fundamental flux wave pass through.[13] This will result in a frequency of vibration twice the power source frequency (twice line frequency vibration). This particular vibration is extremely sensitive to the motor's foot flatness, frame and base stiffness and how consistent the air gap is between the stator and rotor, around the stator bore. It is also influenced by the eccentricity of the rotor. On 2 pole motors, the twice line frequency vibration level will appear to modulate over time due to its close relationship with 2 times rotational vibration [13].

When stator winding inter-turn short circuit fault has happened, the additional circulating current would be produced in this loop, and it will generate a MMF distribution across the air-gap, this MMF is in addition to the normal MMF. The normal MMF is rotating at synchronous speed in the direction of rotor revolution. But the MMF produced by the inter-turn fault is centered on the axis of the faulted coil, it is stationary in space, and its amplitude will be pulsated sinusoidal in time at the rated frequency. Neglecting the high order harmonics, the air-gap MMF on stator winding inter-turn short circuit fault can be represented approximately as [26]:

\[
f(\alpha, t) = F_{s+} \cos(\omega t - p\alpha) + F_{s-} \cos(\omega t + p\alpha) + F_{3} \cos(3\omega t - p\alpha) + F_{Y2} \cos \left(\omega t - p\alpha + \frac{\pi}{2}\right) + F_{Y2} \cos \left(\omega t - p\alpha + \psi + \frac{\pi}{2}\right) \cos(2\omega t)
\]  

Where: \(p\) is the pair of poles number. \(\omega = 2\pi f = p\omega_s = 2\pi pf_r\), \(\omega\) is electrical angular frequency, \(f\) is electrical frequency, \(\omega_r\) is the rotor mechanical angular frequency, \(f_r\) is the rotor mechanical frequency. \(\alpha\) is the stator mechanical space angle. \(\psi\) is generator internal active power angle.

Where the first terms in (1) will produce positive-sequence armature MMF with electric angular frequency \(\omega\), and pulsation frequency is \(f\). The second terms in (1) will produce negative-sequence armature MMF, which electric angular frequency is \(\omega\), and pulsation frequency is \(f\). The third terms in (1) will produce positive sequence armature MMF that its electric angular frequency is \(3\omega\), and pulsation frequency is \(3f\).

Through the above mentioned analysis, the faulty characteristic information of stator electromagnetic vibration can be obtained by [25]. According to the last equation:

1) The frequency of vibration is double of the power supply frequency;
2) Cut off power supply, the electromagnetic vibration disappears immediately; the vibration can be measured in stator frame and stator shaft bearing;
3) Vibration the rigidity of frame has relations with motor load.

4. Experimental Test

To verify the accuracy of the analysis of vibration theory which is mentioned above, this paper chooses asynchronous motor which model number is Y2-100LZ-4 to do a series of experimental tests in the special machines & drive laboratory at Iran University of Science & Technology. The following parts of this paper will priority study the influence of faulty rotor windings causes of vibration to motor. Through the experiment, the time-domain vibration signal of motor’s frame is measured when motor is at the normal condition state, two inter-turn short circuited and five inter-turn short circuited then analysis about the transformation of frequency domain is carry out also the changing regulation of vibration signal while having fault is discussed.

During the period of testing, the motor is fixed on the working table and operating with nominal voltage. The basic parameters of motor are shown in table 1. Motor with connection turn to turn is shown in Figure 2. By connecting two or more wires extracted from the stator we can have 2 or more inter-turn circuit where the multi-channel vibration signal collecting and processing equipment is Easy Viber which is manufactured by VMI Company as the data signal collecting system.
**Table 1.** Motor Basic Parameters

<table>
<thead>
<tr>
<th>Rated Voltage (v)</th>
<th>Rated Power (hp)</th>
<th>Frequency (Hz)</th>
<th>Rated speed (rpm)</th>
<th>Number of phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>380</td>
<td>4</td>
<td>50</td>
<td>1430</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Number of Pole-pairs</th>
<th>Type</th>
<th>R_s (Ω)</th>
<th>R_r (Ω)</th>
<th>Weight (Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Y2-100LZ-4</td>
<td>2.3</td>
<td>2.2</td>
<td>38</td>
</tr>
</tbody>
</table>

**Table 2.** (a) Typical zone boundary limits (ISO 10816-1) [9]

<table>
<thead>
<tr>
<th>R.m.s. vibration velocity (mm/s)</th>
<th>Class I</th>
<th>Class II</th>
<th>Class III</th>
<th>Class IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>0.48</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>0.7</td>
<td>D</td>
<td>D</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.12</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
</tr>
<tr>
<td>1.8</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
</tr>
<tr>
<td>2.8</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
</tr>
<tr>
<td>4.5</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td>7.1</td>
<td>J</td>
<td>J</td>
<td>J</td>
<td>J</td>
</tr>
<tr>
<td>10.2</td>
<td>K</td>
<td>K</td>
<td>K</td>
<td>K</td>
</tr>
<tr>
<td>18</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>L</td>
</tr>
<tr>
<td>20</td>
<td>M</td>
<td>M</td>
<td>M</td>
<td>M</td>
</tr>
<tr>
<td>45</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
</tbody>
</table>

**Figure 4.** (b) The 2f & its sideband components spectrum chart of motor vibration

**Table 3.** Main component amplitude of motor vibration signal’s spectrum

<table>
<thead>
<tr>
<th>Running state</th>
<th>2f</th>
<th>First sideband</th>
<th>Second sideband</th>
<th>Third sideband</th>
<th>Fourth sideband</th>
<th>Average of sidebands</th>
</tr>
</thead>
<tbody>
<tr>
<td>Healthy</td>
<td>0.018</td>
<td>0.0026</td>
<td>0.0140</td>
<td>0.0016</td>
<td>0.0323</td>
<td>0.0126</td>
</tr>
<tr>
<td>2 ring</td>
<td>0.0325</td>
<td>0.0039</td>
<td>0.0155</td>
<td>0.0029</td>
<td>0.0321</td>
<td>0.0136</td>
</tr>
<tr>
<td>5 ring</td>
<td>0.1002</td>
<td>0.0027</td>
<td>0.0180</td>
<td>0.009</td>
<td>0.0403</td>
<td>0.0175</td>
</tr>
</tbody>
</table>

**Figure 1.** Vibration signal of healthy motor: (a) Frequency domain (b) Time domain
4.1 The vibration experimental and spectrum analysis when the motor is operating at healthy condition

The vibration signal and spectrum chart of no-load operation of healthy motor are shown in Figure 1.

From Figure 1(a) & (b) the vibration signal for healthy motor operation is relatively smooth, and also has $2f$ component and its sidebands components are so. Vibration overall amplitude (RMS) in this situation is 0.3154 mm/s and according to ISO 10816 the motor is healthy and it is true.

4.2 The vibration experimental and spectrum analysis when it has 2 rings inter-torned

The vibration signal and spectrum chart of no-load operation with 2 rings inter-torned are shown in Figure 2(a) & (b).

Comparing the Figure 2(a) & (b) the regulation is that the vibration signal waveform is obviously comparable while motor has 2 rings inter-torned $2f$ component and its sidebands increasing obviously at the faulty condition. Vibration overall amplitude (RMS) in this situation is 0.3209 mm/s and according to ISO 10816 the motor is healthy and it is not true.

4.3 The vibration experimental and spectrum analysis when it has 5 rings inter-torned

The vibration signal and spectrum chart of no-load operation with 5 rings inter-torned are shown in Figure 3(a) & (b).

Comparing Figure 3 to Figure 2 it is shown that when motor is operating with no-load and the number of inter-turns increasing the $2f$ component and its sidebands is increased obviously. Vibration overall amplitude (RMS) in this situation is 0.3518 mm/s and according to ISO 10816 the motor is healthy and it is not true.

It is so important that at faulty condition with inter-turn in stator overall vibration according to ISO 10816 is in good condition and with overall amplitude inter-turn fault cannot be recognized.

\[\text{Figure 2. Vibration signal of motor with 2 ring inter-turn: (a) Frequency domain (b) Time domain}\]

\[\text{Figure 3 Vibration signal of motor with 5 ring inter-turn: (a) Frequency domain (b) Time domain}\]
5. Conclusion

This paper employed asynchronous motor for example and carries out a great deal of experimental tests while studying the situation of changing vibration when motor is working at normal state and the fault conditions of stator windings. The main goal is to measure the vibration signal of motor stator’s frame and to accomplish a series of time-domain analysis and frequency-domain analysis.

Through the analysis, the $2f$ component and its sidebands increased obviously in the motor vibration signal after fault has occurred in stator windings. The $2f$ component value and the average of sidebands have relation with faulty motor vibration signal. Although their overall values according to standard ISO 10816 is in good condition (zone A), as seen in TABLE2. Certainly, the relevant of the relation between the faulty motor windings and vibration character frequency are still need a further research such as the relation between vibration frequency and motor parameters.

6. ACKNOWLEDMENT

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REFERENCES


