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A Method for Indentifying Broken Rotor Bar and Stator Winding Fault in a Low-voltage Squirrel-cage Induction Motor Using Radial Flux Sensor

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Abstract – In this paper, a method for detecting broken rotor bar and stator winding fault in a low voltage squirrel-case induction motor using an air-gap flux variation analysis is proposed to develop a simple and low cost diagnosis technique. To measure the leakage flux in radial direction, a radial flux sensor is designed as a search coil and installed between stator slots. The proposed method is able to identify two kinds of motor faults by calculating load condition of motors and monitoring abnormal signals those are related with motor faults. Experimental results obtained on 7.5kW three-phase squirrel-cage induction motors are discussed to verify the performance of the proposed method.

Keywords: Induction motor, Fault diagnosis, Broken rotor bar, Short-turn stator winding, Air-gap flux

1. Introduction

Induction motors are widely used electrical machines, for their simplicity of construction and reliability. However, they are subject to failures those may be due to production processes or operating conditions. These unexpected failures cause severe damages in industrial processes. Motor reliability working group have announced that percentage failure in induction motors is typically: stator related (38%), rotor related (10%), bearing related (40%), and others (12%) [1]. Recently, many researchers have studied diagnosis techniques to predict motor failures at their incipient stage and decide proper replacement time of induction motors. Most of them are focused on the failure prediction method using abnormal signals of failure patterns of motors from current and vibration signals [2]-[4]. Although vibration and current analysis are the most powerful methods for diagnosing motor faults, their sensors are occasionally difficult to install where the environment of industrial field is in poor condition. In addition to this installation problem, there are many low priced low voltage induction motors in the field. Therefore, the diagnosis technique should be easy to install their sensors and low cost comparing to the price of motors.

This paper proposes a method for detecting broken rotor bar and stator winding fault in a low voltage squirrel-cage induction motor using a radial flux sensor to develop a simple and low cost diagnosis technique. The sensor is designed as a search coil and installed between stator slots during motor production to measure the leakage flux in radial direction at the air-gap. The proposed method consists of a calculating load condition, finding abnormal signals and monitoring those signals related with motor faults to indentify two kinds of motor failures. To demonstrate the performance of the method, experimental results obtained on 7.5kW three-phase squirrel-cage induction motors are discussed.

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2. Diagnosis Algorithm

In order to diagnose motor faults, the method which is proposed in this paper uses flux spectra. This spectra has abnormal harmonics those contain potential information of motor faults.

2.1 Detection of broken rotor bar

In the case of broken rotor bar, the current of the broken bar flows in the two bars those are adjacent to it. This causes an unbalanced air-gap local field. The field pulsates at slip frequency and modulates coil-induced voltage at characteristic frequencies as follows [5].

$$f_{BB\_F} = \frac{f_0}{2p} k\left(1-s\right) \pm sf_0 \tag{1}$$

where f_0 is the electrical supply frequency, p is the number of pole pairs, $k = 1,2,3,...$ and s is the per-unit slip.

2.2 Detection of stator winding fault

A turn to turn failure of stator winding causes large asymmetries in the machine winding currents. The effect of the failure is to remove one or several turns from the stator winding. This will have a small, but finite, effect on the main air-gap flux distribution [6]. The failure can be detected by looking at the family of slot pass frequencies

$$f_{SW\_F} = \left(Rf_r - f_0\right) \pm 2nf_0 \tag{2}$$

where R represents the number of rotor slots, f_r is the rotation frequency and n is the integer.

2.3 Calculation of load condition

Most of induction motors in the industrial field operate at variable load conditions. In addition, all characteristic frequencies mentioned in subsection 2.1 and 2.2 are functions of the slip and rotation frequency. Therefore, a calculation of load condition is necessary to diagnose motor faults. One of the best ways to obtain the information of the slip and the rotation frequency is to use rotor slot harmonics (RSHs) as in [7]. The slip frequency can be expressed as

$$f_{slip} = \frac{p}{R}\left\{\left(\frac{R}{p} + \alpha\right)f_0 - f_{RSH}\right\} \tag{3}$$

where $\alpha = \pm k$ (k positive integer) is the time harmonic order and f_{RSH} is the RSH frequency extracted as

$$f_{RSH} = \frac{R}{p} f_{rotor} + \alpha f_0 \tag{4}$$

where f_{rotor} is the rotor speed expressed in electrical hertz. The slip and the rotation frequency those are related with load condition can be calculated easily using the slip frequency.

2.4 Proposed diagnosis method

The proposed method is made up of a calculating load condition, finding abnormal signals and monitoring the signals to diagnose motors those operate at variable load conditions. Fig. 1 shows the flowchart of the method. The method is designed based on the fact that peculiar changes appear at the characteristic frequencies mentioned in (1) and (2) when two kinds of motor faults occur.

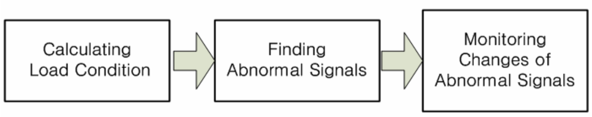


Fig. 1. Proposed diagnosis method flow chart

3. Measurement Environment

A radial flux sensor and a simulator are designed to measure the magnetic flux at the air-gap and to test motors respectively.

3.1 Radial flux sensor

The radial flux sensor is specially designed as shown in Fig. 2. It is designed as a search coil and each search coil is made up of 20 turns (18Ω). The induced voltage at the search coil can be simply expressed by Faraday's law as in (5).

$$e = -N\frac{d\Phi}{dt} \tag{5}$$

where N is the number of coil turns and Φ is the magnetic flux.

Fig. 2. Self-designed search coil

3.2 Induction motor simulator

To investigate the performance of the proposed diagnosis method, an induction motor simulator is designed as shown in Fig. 3. It consists of a test motor, a loaded motor, an inverter which can adjust the load condition of the test motor and a data acquisition system (DAS). The specification of the test motor is given in Table 1 and the radial flux sensor is installed between stator slots in the test motor during motor production as in Fig. 4.

Table 1. Specification of test motor

Specification	Test Motor
Rated Power	7.5 kW
Input Voltages	220/380 V
Input Currents	28.2/16.3 A
Poles	4 P
Frequency	60 Hz
Number of Rotor Bars	28
speed	1760 rpm
Air-gap	0.5 mm

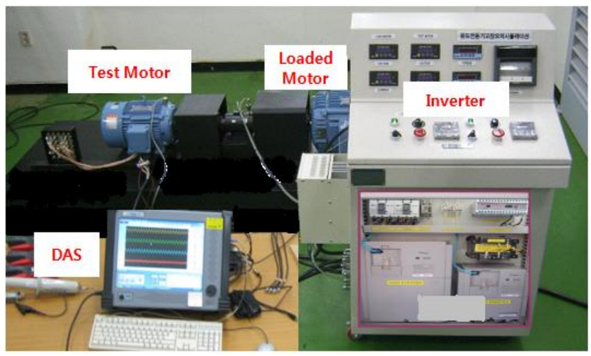


Fig. 3. Induction Motor Simulator

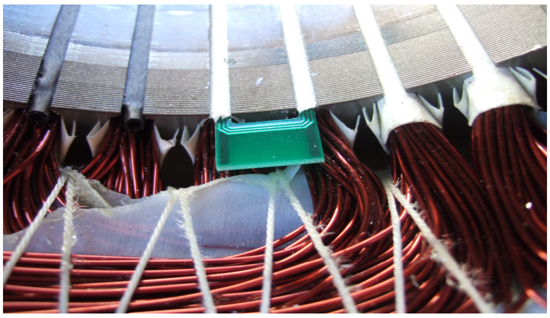


Fig. 4. Installation of radial flux sensor

4. Experimental Results

Stator currents are measured with flux at the same time to verify the performance of the proposed method. All of experimental data are acquired for 10.5 seconds at 100 kS/s with DAS that has 16 bits resolution.

4.1 Experiment of load condition

The power spectrums in Fig. 5 illustrate the RSH amplitudes in different load conditions of a healthy motor where $\alpha = -3$ in (4). Fig. 5(a) and (b) represent spectrums of current and flux respectively. As shown in the figures, the RSHs in the power spectrums of flux are almost same as the current. That means the proposed method can calculate load condition of the test motor like as the current method. In case of load condition 2 where the test motor operates at a speed of 1780 rpm, the RSH frequency is 1011 Hz. Using this frequency the slip and the rotation frequency are easily calculated as 0.0167 and 29.5 Hz respectively.

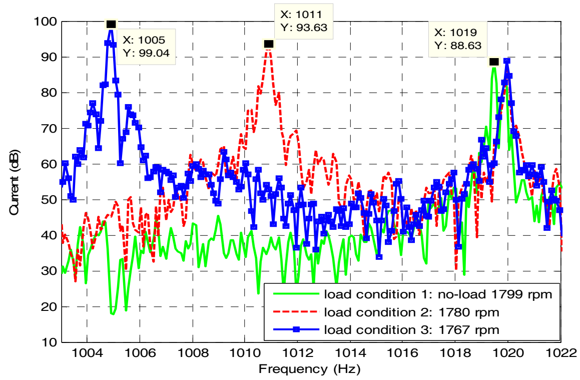
4.2 Experiment of broken rotor bar

Motor current signature analysis (MCSA) has already been used to detect rotor bar faults for several years. It has proved that the waveform of air-gap flux induces following harmonic frequencies of stator current when an induction motor operates with broken rotor bars [2].

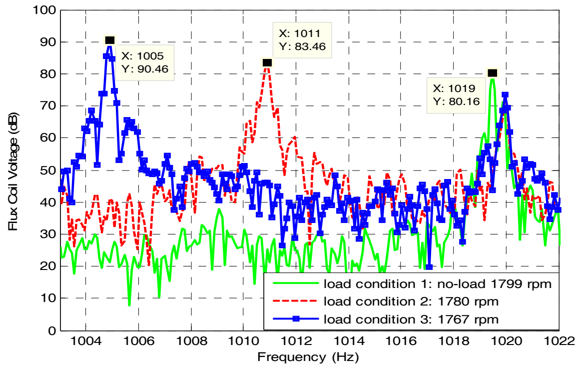
$$f_{BB\_C} = (1 \pm 2ks) f_0 \quad (6)$$

where $k = 1, 2, 3, \ldots$.

To make a comparison between the MCSA and the proposed method, stator currents and flux are measured at the same time. In addition, a healthy motor and rotor bar faulted motors with 2 and 4 broken bars are compared at different load conditions. Fig. 6(a) represents the results of motors at a no-load speed of 1799 rpm. Abnormal signals of the broken rotor bar are difficult to identify because the slip is very small at a no-load operation. However, when the slip becomes large enough such as the case of Fig. 6(b)



(a) current



(b) flux

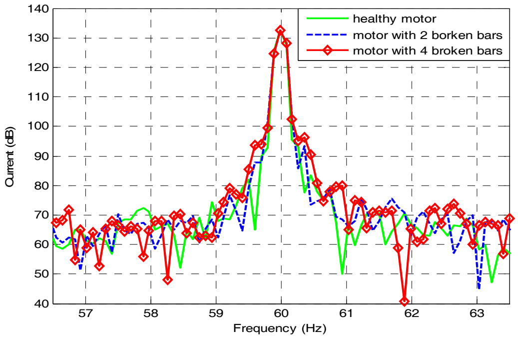
Fig. 5. Healthy motor spectrum

and (c), the abnormal signals are appeared at the characteristic frequencies as in (6). An interesting change is found in this point, the amplitude of the abnormal signals is increased according to the severity of the fault. In Fig. 6(b), the characteristic frequencies of the motor with 4 broken bars are 58.68 and 61.32Hz with a slip $s = 0.011$ and $k = 1$. The abnormal signals of the motor are identified at 57.56 and 62.44 Hz, when the motor operates at a slip $s = 0.02$ as shown in Fig. 6(c).

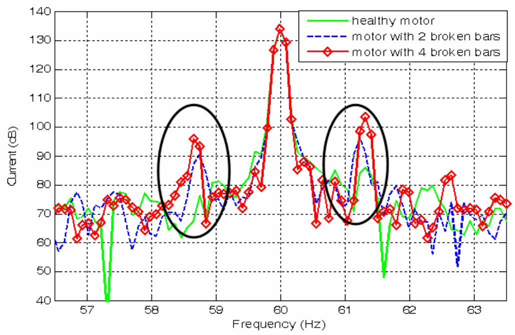
Fig. 7 shows the power spectrums of flux. As in the case of the current method, the abnormal signal of the broken rotor bar is difficult to identify at a no-load operation but appeared at load operations. From (1), the characteristic frequency of the motor with 4 broken rotor bars, as illustrated by Fig. 7(b), is identified at 29.01 Hz with a slip $s = 0.011$ and $k = 1$. In Fig. 7(c), the abnormal signal of the motor operating at a slip $s = 0.02$ appears at 28.2 Hz.

4.3 Experiment of stator winding fault

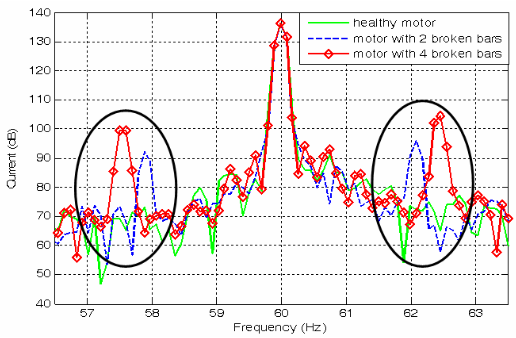
To confirm the ability of the proposed method which can diagnose stator winding fault, two kinds of stator faulted motors are compared with a healthy motor. Even though the abnormal signal of the stator winding fault is not identified at a no-load operation because of the small slip,



(a) no-load: speed of 1799 rpm

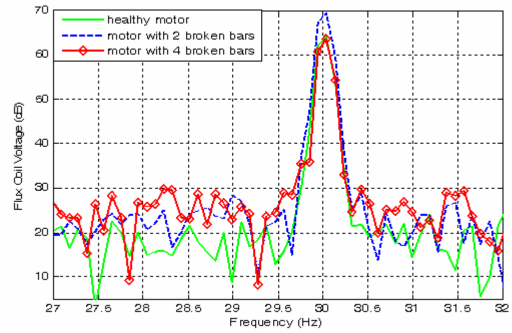


(b) load condition 2: speed of 1780 rpm

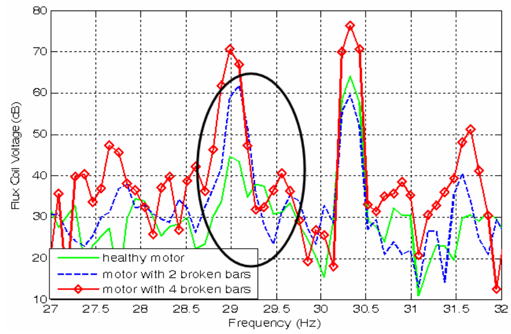


(c) load condition 3: speed of 1767 rpm

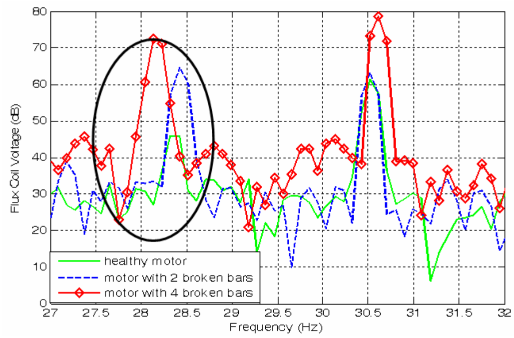
Fig. 6. Broken rotor bar frequency spectrum of current



(a) no-load: speed of 1799 rpm



(b) load condition 2: speed of 1780 rpm



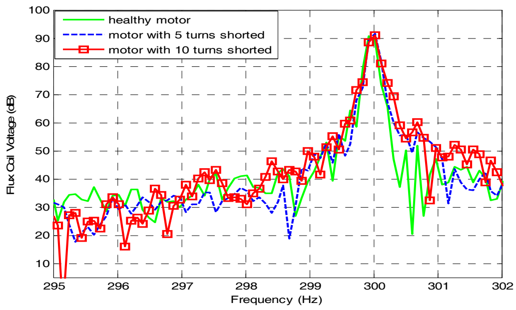
(c) load condition 3: speed of 1767 rpm

Fig. 7. Broken rotor bar frequency spectrum of flux

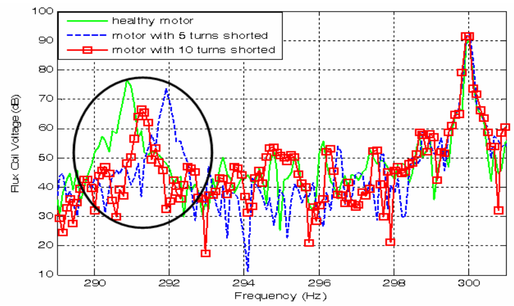
an interesting change which appears at the characteristic frequency is found in load operations as shown in Fig. 7 (b) and (c). The change is that as the severity of the fault increases, the amplitude of the signal decreases. From (2), the characteristic frequencies of the motor with 10 turn short circuited are 291 and 283.9 Hz with a slip 0.011 and 0.02 respectively.

5. Conclusion

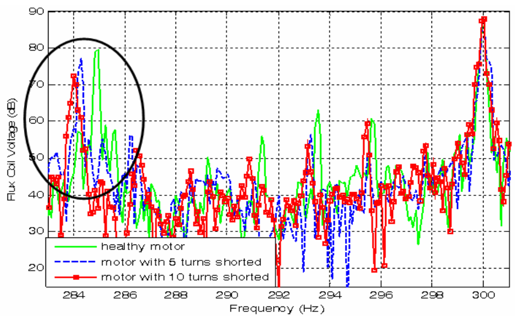
A method for detecting broken rotor bar and stator winding fault in a squirrel-cage induction motor is proposed using the radial flux sensor which can be installed between stator slots during motor production and made at low price comparing to the commercial vibration sensor and current probe. The method is simply composed of a calculating load condition and monitoring abnormal signals those are related with motor faults. The proposed method can calculate the load condition of the motor like as the MCSA method. From the experimental results in broken rotor bar and stator winding fault, there are important changes at the amplitude of abnormal signals those come out at characteristic frequencies. Motor faults such as broken rotor bar and stator winding fault can be identified by looking at the trend of these changes. Therefore, it is convinced that the measurement of the radial magnetic flux at the air-gap is an effective method to discriminate motor conditions among normal, broken rotor bar and stator winding fault.



(a) no-load: speed of 1799 rpm



(b) load condition 2: speed of 1780 rpm



(c) load condition 3: speed of 1767 rpm

Fig. 8. Stator winding fault frequency spectrum of flux

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