A Study on The Broken Rotor Bars in Induction Motor and The Control Characteristics in Inverter

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Abstract-The advantage of the squirrel cage induction motor is the brushless rotor. This advantage for operation and maintenance turns out to be a disadvantage for the detection of the cage rotor bar and endring defects, which means that the detection of cage faults is due to the measurement and analysis of only the stator input signals.
The monitoring task in an inverter drive is complicated mainly because the voltage and current waveforms are nonsinusoidal and the high dv/dt values from fast switching inverterd distort the measurements.
In this paper, we are going to discuss the detection method of broken rotor bar of the inverter fed squirrel cage induction motor by the motor current signature analysis(MCSA) and the opening terminal voltage signal analysis .

1. Introduction

Squirrel-cage induction motor has advantages such as easy maintenance and simple structure type due to not having brush on rotor. However, it is difficult to diagnose directly the fault on the rotor. Therefore, it is referred that the detection of cage faults is due to the measurement and analysis of only the stator input voltage and current signals [1].
Rotor faults of squirrel-cage induction motor are mainly classified as bearing problems, which are caused by misalignment of concentricity and fatigue increase due to overload, and faults on rotor bar & end ring, which are caused by thermal stress, electromagnetic force or the dynamic stresses arising from shaft torque, etc. [2].
On a fault diagnosis, the manufacturers and users of electrical machines initially relied on simple protections for over-voltage and over-current, etc. to ensure safe operation. But this method may be induced to a lot of repair cost and serious danger since the problems are mostly occurred on the breakdown limitation of equipments. Therefore, it has now become very important to diagnose faults at the very inception and there are a lot of publications where the early fault diagnosis on equipments are treated.
The monitoring task in an inverter drive is complicated mainly because the voltage and current waveforms are non-sinusoidal and the high dv/dt values from fast switching inverter distort the measurements [3].
On this paper, we are going to discuss the detection method for broken rotor bar of the inverter fed squirrel cage induction motor by the motor current signature analysis (MCSA) detecting and analyzing the line current spectra on sideband frequency neighboring the fundamental & space harmonics and the opened terminal voltage signal analysis method measuring and analyzing the induced voltage on stator by pure rotor current with opening 3-phase stator power [3] [4].

2. The Fault Analysis Method on Broken Rotor Bar

2.1 Motor Current Signature Analysis [3]

This method is well known to diagnose faults of broken rotor bar on induction motor. This method is to detect and analyze the line current spectrum on sideband frequency neighboring to the fundamental & space harmonics.
Sideband component f_b, which is neighboring to the fundamental frequency of line current spectrum with respect to bar fault, is detected by equation (1).

$$f_b = (1 \pm 2s)f \tag{1}$$

Here, $f_b = (1-2s)f$ is sideband frequency representing broken bars and sideband frequency of $f_b = (1+2s)f$ is due to the consequent speed oscillation.
The actual sideband including harmonics for broken bar is as follows.

$$f_b = (1 \pm 2ks)f, \quad k = 1, 2, 3, \cdots, \tag{2}$$

Inertia for motor load also affects the magnitude of sideband. Other spectra detected on airgap flux for broken bar are as equation (3).

$$f_b = [(\frac{k}{p})(1-s) \pm s]f \quad (k = 1, 2, 3, \cdots,) \tag{3}$$

where p is pole pairs and s is slip [p.u.].
The detectable frequency on current signal of stator coil among sideband frequencies of equation (3) is (k/p = 1,5,7,…,).
When the rotor bar is broken, speed and torque signal are varied with frequency components of 2sf & 4sf.

2.2 Opened terminal voltage signal analysis

Up to this point the fault of bar is detected by analyzing the input current, voltage and power when the motor is supplied by nonideal source. However, this may cause an error because there exists time harmonic of voltage or voltage unbalance.
This method measures and analyzes induced voltage on

stator by pure rotor current with opened 3-phase stator power. This method may not cause above error.
If the input power is cut out during operation, stator current has as much time as rotor time constant and quickly becomes zero. Thus, there is disadvantage that the measuring time is short.
If it is healthy motor, the induced voltage on stator does not include other harmonic components than discontinuous fundamental current distribution of rotor. If rotor bar is broken, rotor MMF waveshape is broken away from normal sinusoidal wave. This phenomenon is detected by performing FFT analysis on line to line voltage of stator.

2.2.1 Induced Frequency Components of Opened Terminal Voltage

After power is cut out, the MMF distribution by rotor bar current of motor is expressed as follows.

$$F_r \cos(npx) \tag{4}$$

where p is the number of pole pairs, n is the harmonic numbers, and x is the angular position with respect to the Rotor.
For healthy motor, there exist fundamental and harmonic components by discontinuous current distribution of rotor bar. Dominant harmonic numbers are given by following equation.

$$n = k\left(\frac{R}{p}\right) \pm 1 \quad (k = 1, 2, 3, \cdots,) \tag{5}$$

where R is the number of rotor bars.
The MMF produces magnetic flux relating to stator, which is given by following equation.

$$\Phi \cos(\ np\ (x + \omega_r t) + \varphi\ ) \tag{6}$$

where ωr is the rotor speed .
Harmonic numbers for integral slot and 3-phase balanced winding is given by *lp*, where

$$l = 6m \pm 1, \ m = 0, 1, 2, 3, \cdots, \tag{7}$$

For healthy motors, it is shown that accorded harmonic numbers of equation (5) and equation (7) is dominant on the line to line voltage spectrum because flux components from (6) have the same pole pair numbers as those of three phase stator winding. However, for faulty motors, the MMF pattern due to broken rotor will be distorted and would contain other harmonic numbers than those given by (5). Therefore, it is possible to perform faulty diagnosis since harmonic numbers of equation (7) out of accordance with those of equation (5) is dominant when rotor bar is broken.

3. Test Result

3.1 Test Model

The specification of test model to diagnose the fault of rotor bar by MCSA is shown on table 1 and the system composition for measurement is shown on figure 1. Test motor with 20kW load is controlled by torque mode inverter with 380V line voltage.

table 1. test model specification

phase/pole	3 / 6	rotor bar no.	38
rating power	75 kW	line voltage	380 V
Inertia	0.475 kgm^3	rating current	144 A
rating speed	3000 rpm	rating torque	238 Nm

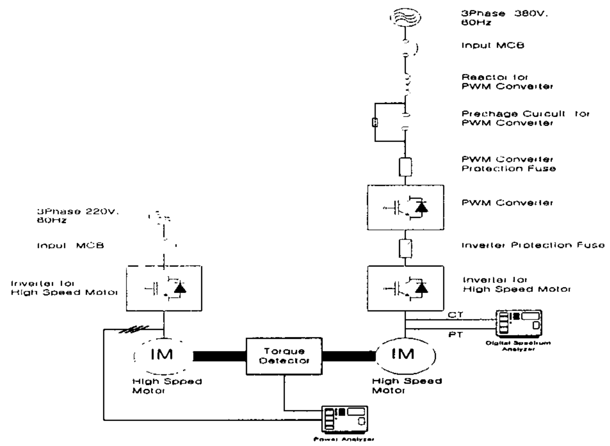


figure 1. measurement system diagram

3.2 Test Results

3.2.1 Results of Current Signal Analysis

Figure 2 shows output current wave of inverter and figure 3 - 4 show line current spectrum for the sideband frequency neighboring to the fundamental and 5th & 7th harmonics.
On figure 3, the sideband frequencies by equation (1) for the fundamental 89.3Hz and slip 0.0375 (p.u.) are 82.6Hz and 96Hz. At 82.6Hz, power density of the motor with broken bar is approximately 4dBV greater than that of healthy motor.
On figure 4, the sideband frequencies for 5th & 7th harmonics 446.5Hz and 625.1Hz are 426 & 433Hz and 598.3 & 605Hz. It is difficult to distinguish the difference of power density on other sideband frequencies than 605Hz of 7th harmonics.
Quadrature component of inverter terminal voltage and current with respect to torque wave variation under 3000rpm & 15kW is shown on figure 5. It is shown on b) that quadrature terminal voltage by broken bar caused wave fluctuation as much as 2 times of slip frequency (2*378.8mHz). It is presumed that wave fluctuation of quadrature voltage is generated by forcing the quadrature current constant.

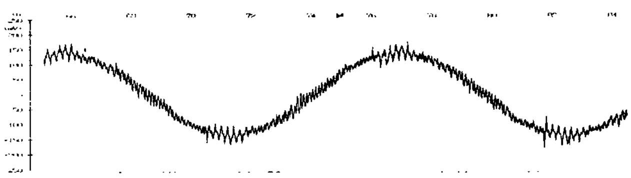
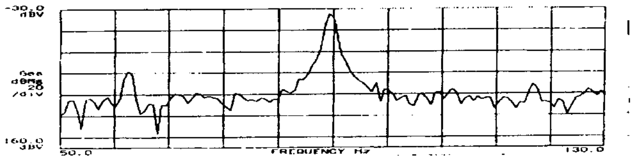
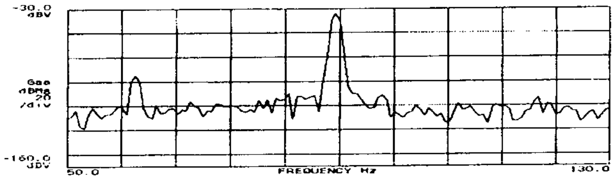


figure 2. inverter output current - 89.3Hz
(x:1ms/300div, y: 0.2V/200A)

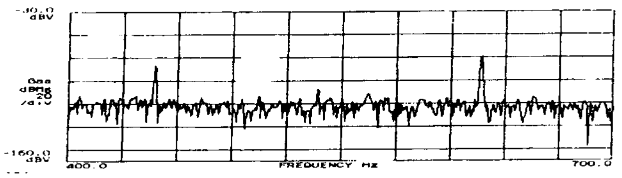


a) healthy

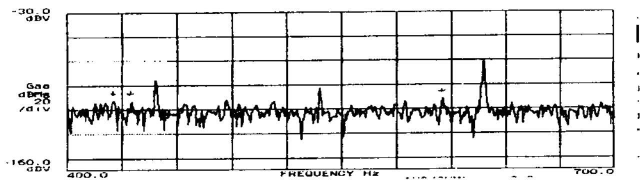


b) faulty

figure 3. line current spectrum around fundamental at 89.3Hz

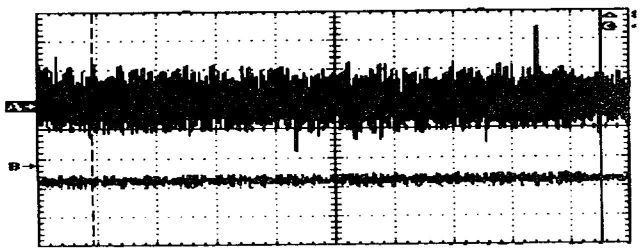


a) healthy

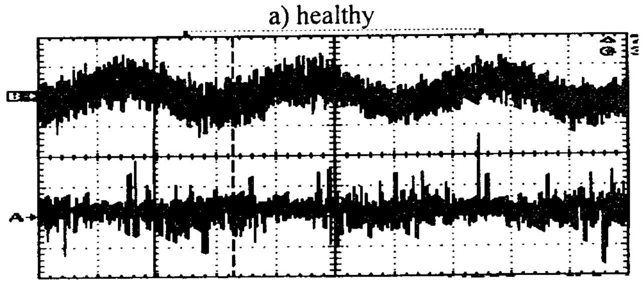


b)faulty

figure 4. line current spectrum around 5,7th harmonics at 89.3Hz



a) healthy



b) faulty

figure 5. quadrature components of inverter voltage and current (15kW -3000rpm)

3.2.2 Result of Opened Terminal Voltage Signal Analysis

This test is operated by inverter under no load and supplied voltage wave is shown on figure6.

The terminal voltage wave after the power is cut out is shown on figure 7. Figure 7-a) represents healthy motor at 87Hz of fundamental frequency and figure 7-b) represents faulty motor at 79.2Hz. The voltage induced to stator by rotor MMF is decreased as much as time constant. Figure 8 shows spectrum of voltage wave on Figure 7. For healthy motor of figure8-a), the accorded 37th harmonic 3.21kHz, which is calculated by equation (5) and (7), is prominent and the other harmonic components than 3.21kHz by equation (7) is latent. However, for faulty motor of figure 8-b) with broken rotor bar, other latent harmonic components than accorded 37th harmonic 2.93kHz by equation (7) is prominent and its magnitude is similar to one another. Therefore, recently this method is widely used since this method clearly diagnoses the broken rotor bar and it is possible to perform the test by simply test procedure and measuring system.

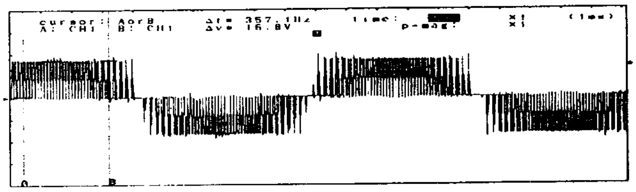
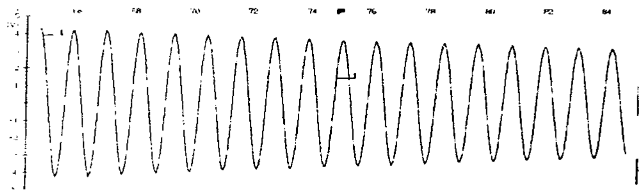
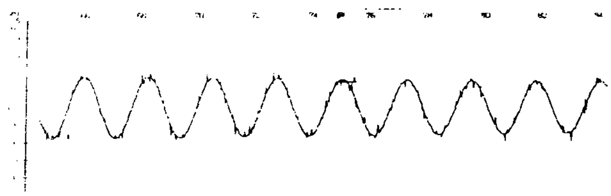


figure 6. inverter PWM supplied voltage wave before opening terminal

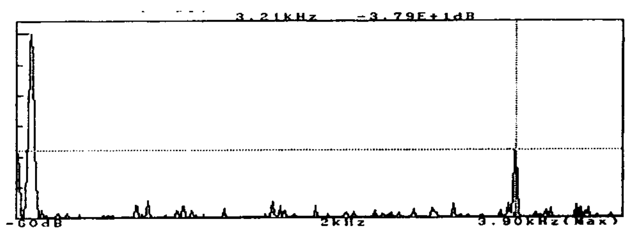


a) healthy (x:10ms/300div, y:10V/400V)

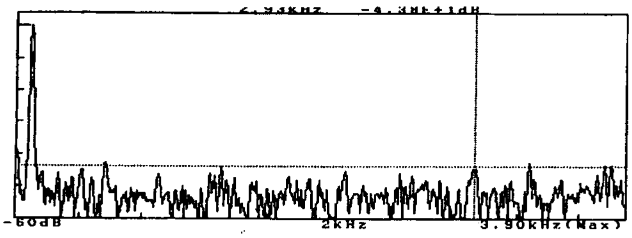


b) faulty (x:5ms/300div, y:10V/400V)

figure 7. terminal voltage wave after power is cut out



a) healthy (Fundamental : 87Hz)



b)faulty (Fundamental : 79.2Hz)
figure 8. Spectrum of after Power is Cut Out

3. Conclusion

On this paper, we clarify the phenomenon of broken bar and verify the reasonability through test by current signal analysis and opened terminal signal analysis method. Current signal analysis method detects and analyzes sideband components neighboring to the fundamental and space harmonic waves existing on line current when rotor bar of squirrel-cage induction motor driven by inverter is broken. Opened terminal signal analysis method measures and analyzes the induced voltage on stator by pure rotor current with opened 3-phase stator power. In a current signal analysis method, it is difficult to take accurate measurement at high speed because of effects of the misaligned shaft coupling and noise during the test. Opened terminal signal analysis method examines closely into the phenomenon of broken bar by simple test procedure and measuring system. However, current signal analysis method is better at on-line motor diagnosis of operating vehicle.

Further study of detect and analysis methodologies on this field will be published with improved results.

[References]

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