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Rotor Fault Detection System for the Inverter Driven Induction Motor using Current Signals

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ABSTRACT

The induction motor rotor fault diagnosis system using current signals, which are measured using an axis-transformation method, is presented in this paper. In inverter-fed motor drives, unlike line-driven motor drives, the stator currents are rich in harmonics; therefore fault diagnosis using stator current is not trivial. The current signals for rotor fault diagnosis need precise and high resolution information, which means the diagnosis system demands additional hardware such as a low pass filter, high resolution ADC, and encoder, etc. The proposed axis-transformation method with encoder and without encoder is expected to contribute to a low cost fault diagnosis system in inverter-fed motor drives without the need for any additional hardware. In order to confirm the validity of the developed algorithms, various experiments for rotor faults are tested and the line current spectrum of each faulty situation using Park transformation is compared with the results obtained from fast Fourier transforms.

Keywords: Fault diagnosis, Induction motor, Rotor fault, Inverter driven system, Current signals

1. Introduction

In recent years, a marked improvement based on the development of the microprocessor and power electronics has been achieved in motor drives. However, motors driven by solid state inverters have undergone a series of voltage stresses because of rapid switch-on and switch-off voltage of semiconductor devices. As a result, condition monitoring and incipient fault detection technology have become an important research area in recent years to prevent systems from sudden shut-downs due to significant motor faults in the industrial manufacturing facilities. In some factories, in order to prevent unexpected motor failures, routine yet very expensive maintenance is performed using high-priced instruments. Therefore, there is a considerable demand to reduce maintenance costs and prevent unscheduled downtime. Over the past several decades substantial research has been done on new condition monitoring techniques for the line-driven and inverter-driven motor drive.

Among these fault diagnosis techniques, analyzing vibration signal with accelerometers, air-gap flux

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measurement with search coil and thermal analysis have provided satisfactory results [1-6]. However these methods usually need extra sensors, hardware and wirings for transmitting the signals, therefore these demands made fault diagnosis techniques very costly. New and promising research horizons in the area of motor fault detection could be explored using the expert systems, artificial neural networks (ANNs), fuzzy systems, genetic algorithms (GAs)[7,8] and adaptive neuron-fuzzy inference systems (ANFIS)[9]. But to extract normal and fault characteristics, these techniques need offline training of a diagnosis algorithm through experimental results. These techniques also need a sophisticated computational procedure.

Therefore a simple and low cost protection, without the use of extra sensors, is always the most attractive method for industrial applications. There is a tendency towards line current signature analysis due to the disadvantage of previous mentioned methods. Motor line current information of inverter fed motors is already available for control and protection purposes. Thus, by using the current sensor feedback and axis-transformation method instead of FFT (Fast Fourier Transform), the new trend for low-cost protection applications is achieved without using any external hardware.

Even though numerous successful line driven motor fault detection methods are reported in the literature, inverter fed driven motor systems still require more attention due to high speed switching noise effects in the line current data and closed loop controller bandwidths [8, 9]. Contrary to the motor line current directly from the utility, the inverted-fed motor line current includes remarkable EMI noise. These EMI noises adversely affect the fault diagnosis due to inherent floor noise which reduces the possibility of true fault pattern recognition using a line current spectrum. Therefore, one should take into consideration as much fault signatures as possible to enhance the reliability of fault diagnosis.

It is well known that adjustable speed motor drives generate sharp-edged waveforms at the output line to line voltage, which cause serious harmonics components. The harmonic contents, which are normally known as a major side effect of an inverter, give rise to extra high frequency signatures and turn out to be amiss in distinguishing faulty current spectrum patterns compared to line driven drives.

Although the rotor faults are a very commonly reported type with an occurrence of 5-10[%][10][11], the diagnosis of these faults are one of the most challenging, even under a line driven motor case when compared to the other faults, because of the low amplitude fault signatures in the current spectrum. However, rotor fault detection of an induction motor fed by an inverter has not been investigated in the literature adequately and there are limited resources on the diagnosis and side effects of current spectrum floor noise that mask small fault related signals.

Thus, in this work, in order to detect broken rotor bar signal clarity using 12-bit ADC, the Park transformation of measured currents (with and without the encoder) are investigated theoretically and experimentally for inverter driven motors. To verify the proposed algorithms, a 2.2 [kW] induction motor and a TMS320C2812 DSP is used.

2. Rotor Fault

Fig. 1 shows the results of motor defection conducted by EPRI, Thorson and IEEE study. The study is carried out on the basis of opinion as reported by the motor manufacturer. In Fig. 1, the reasons for motor faults are classified by bearings fault, stator fault, rotor fault, shaft fault, external device and others, while it shows rotor defection percentage at around 5[%][15].

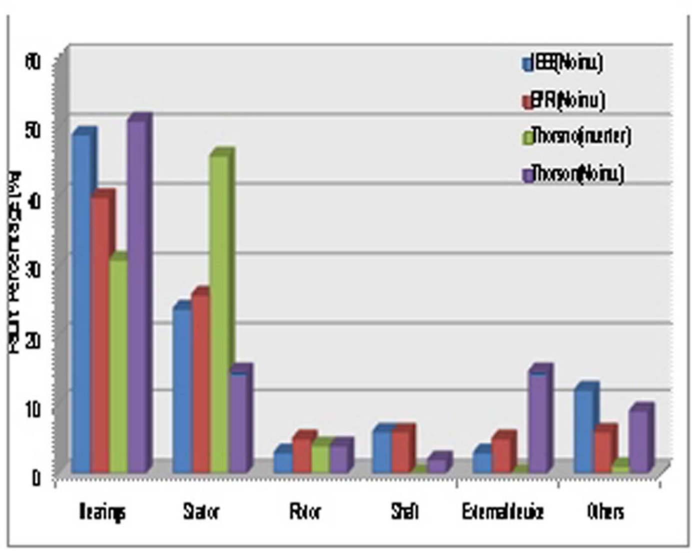


Fig. 1 Results of motor defection

There are several reasons which cause motor defections and are stated below:

- ✓ Thermal stress, hot spot or excessive losses, sparking caused by unbalance and overload
- ✓ Magnetic stress due to electromagnetic forces, unbalanced magnetic pull(UMP), electromagnetic noise and vibration.
- ✓ Residual stress produced by manufacturing problems.
- ✓ Dynamic stress due to shaft torque, centrifugal forces and cyclic stress.
- ✓ Environmental stress caused by abrasion of rotor material or contamination.
- ✓ Mechanical stresses produced by loose lamination, fatigued parts and bearing failure.

For detection rotor bar faults [11], [12], [13] and [14] were using a spectrum analysis of machine line currents, and in these papers, investigate sideband components (f_b) using the proposed algorithm and equation for sideband signals shown below.

$$f_b = (1 \pm 2 \cdot s) f = (1 \pm 2 \cdot k \cdot s) f \quad (1)$$

where, s is slip, f is supply frequency, $k = 1, 2, 3, \cdots$ and f_b is detectable broken rotor bar frequency. While the lower sideband frequency presents the broken rotor bar, the upper sideband frequency is due to consequent speed oscillation.

3. Proposed Algorithms and System Configuration

In order to calculate specific frequency components, generally the FFT (Fast Fourier Transform) method is used, but the FFT method needs considerable calculation time, sophisticated algorithms and much memory. Therefore, axis transformation, Park transformation with and without encoder (a very simple and effective method) is presented and compared to estimate exact sideband current frequency components.

The axis transformation method, which is a Park transformation, makes it possible to convert AC value to DC value. With axis transformation against a specific frequency, the AC and DC components are decoupled, i.e. if axis transformation is employed, the AC component (which is expressed in the stationary reference frame) is transformed into a new rotational reference frame, which rotates together with a selected frequency of components expected to cause a broken rotor bar and AC value noise. Fig. 2 shows the block diagram of the proposed method. Through Park transformation, the AC and DC current components are decoupled, and in order to calculate the exact DC component value expected to cause broken rotor fault estimate mean value for several periods. Based on the previous process, ix_ave and iy_ave are calculated, and by means of classifier status the rotor is determined.

Fig. 3 shows the overall system configuration for rotor fault diagnosis. The inverter control and fault diagnosis system is implemented on the TMS320F2812 digital signal processor board from Texas Instruments. Various blocks used in the rotor bar fault diagnosis package are shown in figure 3. Through the 12-bit on-chip ADC the current signals for motor control and fault diagnosis is collected with 4[kHz] sampling frequency. Using the Clarke transformation and digital filter the raw current signals are transferred. To calculate the fundamental frequency and the specific frequency component (which is an expected fault component caused by the broken rotor bar), the Park transformation, signal conditioning, signal tracking and calculation of the average values the classifier and fault frequency estimation block are used.

3.1 Current Sample

In order to measure phase currents (Ias, Ibs), in this research an on-chip ADC(Analog to digital converter) was used, which has a 4[kHz] sampling frequency (250[us]) while the other phase current, Ics, is estimated using the below equation

$$I_{cs} = -I_{as} - I_{bs} \quad (2)$$

3.2 Clarke Trans. & Digital Filter

Using the measured three-phase currents of the motor and Clarke transformation, real part current, I_α and imaginary part current, I_β , can be calculated. For calculation these current components, eq.(3) and eq.(4) are applied. Also, a digital filter, which is a low pass filter, is used to reduce unwanted noise.

$$I_\alpha = I_{as} \quad (3)$$

$$I_\beta = (I_{as} + 2 \times I_{bs}) / \sqrt{3} \qquad (4)$$

3.3 Park Trans.

This module is used to transfer a specific frequency component, which is expected to cause fault, to a DC value, while the other frequency components remain at a AC value. Equations used for this transformation are (5) and (6).

$$I_x = I_\alpha \times \cos(\theta_{fault}) + I_\beta \times \sin(\theta_{fault}) \qquad (5)$$

$$I_y = -I_\alpha \times \sin(\theta_{fault}) + I_\beta \times \cos(\theta_{fault}) \qquad (6)$$

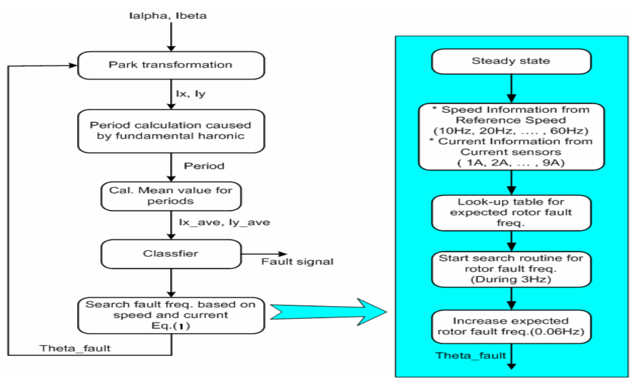


Fig. 2 Block diagram of the proposed method

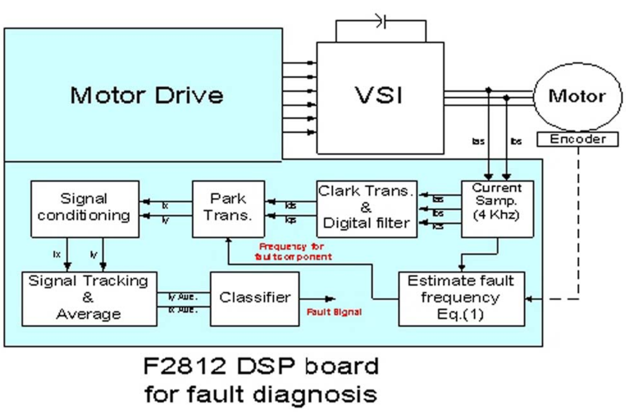


Fig. 3 System configuration

3.4 Signal Conditioning

Park transformed Ix and Iy, which have an AC and DC value simultaneously. So it is necessary to calculate only the DC component. In this module, the period caused by the fundamental component is estimated to remove the AC component.

3.5 Signal Tracking & Average

In this module the average values of Ix and Iy, Ix ave and Iy ave, are calculated for several periods from the Signal conditioning module while the AC component which is contained in Iy, Ix is removed. In other words

If $f_x = f_{ac} + f_{dc}$,

$$\text{Then} \quad \frac{\sum_{n=1}^{k} f_{ac} + f_{dc}}{k} = f_{dc\_ave} \qquad (7)$$

where, k = (period for AC component) / (sampling time).

3.6 Speed Estimation

Fig. 4 demonstrates torque/speed curve for an induction motor. For an induction motor driven by V/F control, feed-forward control and motor speed depends on load torque. A certain load torque is supplied to the running induction motor and the motor speed will vary from ω_1 to ω_2. This region is almost proportional to the stator currents. With this simple idea, speed estimation is performed. According to each frequency speed variation depending on the stator current, amplitudes are measured and a look-up table for speed estimation is built.

Furthermore, in the case of the proposed fault detection, an algorithm it is not necessary to use the exact frequency that is expected to cause rotor fault, because fault detection algorithms are searching for 3[Hz] and analyzing the fault frequency.

4. Experimental Results

The specifications of the IM utilized in this research are listed in Table 1. Fig. 5 shows the experimental system to verify the proposed algorithms.

Table 1 Induction motor parameters

Rated Power	3[Hp]	Rated Speed	1760[rpm]
Rated Voltage	230[V]	Rated Current	7.6[A]

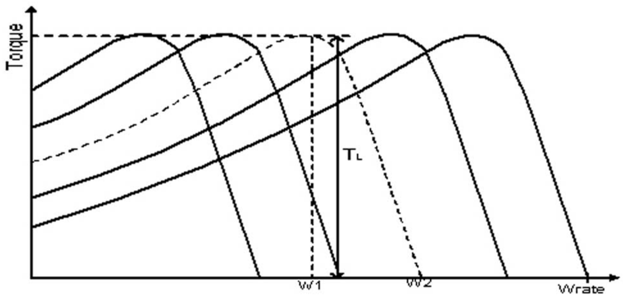


Fig. 4 Induction motor torque/speed curve

(a) Induction motor and load system

(b) Used broken rotor

(c) DSP and Inverter system

Fig. 5 Experimental system

Figure 6(a) represents the current waveform of an induction motor. Figure 6(b) shows the PSD results of a induction motor and the amplitude of a sideband current component is -50[dB] around 26[Hz], which means this induction motor is healthy. Figure 7(a) represents the current waveform of an induction motor. Figure 7(b) shows the PSD results of an induction motor and the amplitude of a sideband current component is -35[dB] around 26[Hz]. As shown in this figure, a rotor faulty component is -35 [dB] which means this induction motor has serious rotor problems. In order to classify rotor defection using a sideband current component, the amplitude of a sideband current component is analyzed. If the sideband component have over -40[dB], it is referred to as a defective motor. From this assumption, the equation below is derived.

$$40[dB] \ge abs\left(20 \cdot \log \frac{\sqrt{I_{de\_ave}^2 + I_{qe\_ave}^2}}{\sqrt{I_{x\_ave}^2 + I_{y\_ave}^2}}\right) \tag{8}$$

Eq.(8) can be rewritten as below:

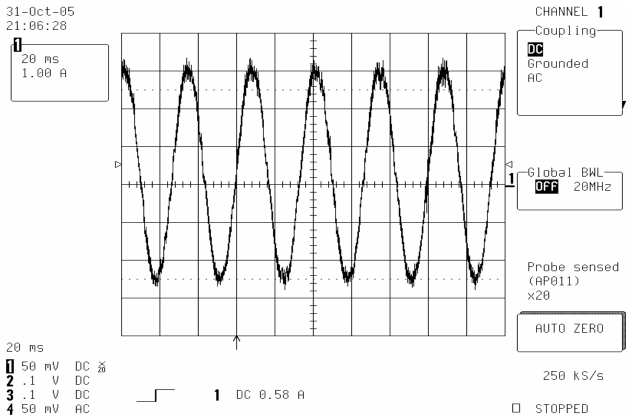
$$I_{x\_ave}^2 + I_{y\_ave}^2 \ge 10^{-4} \cdot (I_{de\_ave}^2 + I_{qe\_ave}^2) \tag{9}$$

Assuming that I_{index} is $10^{-4} \cdot (I_{de\_ave}^2 + I_{qe\_ave}^2)$ and I_{Fault} is $I_{x\_ave}^2 + I_{y\_ave}^2$. And if I_{Fault} is bigger than I_{index} then it means the rotor has a serious defection, if I_{Fault} is smaller than I_{index} then it means the rotor is normal.

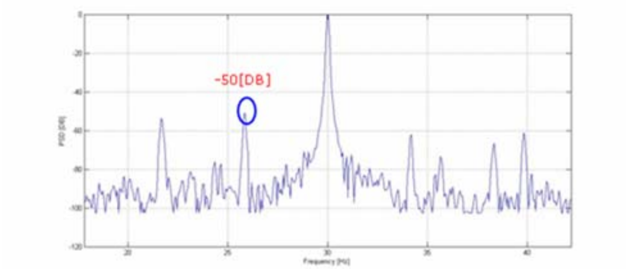
Fig. 8 shows phase current and PSD results. From PSD results, this rotor has a serious defection because it has over -40[dB] around 28[Hz].

Fig. 9 shows the experimental results of Fig.8 with encoder, (a) represents the applied result, I_{index} and I_{Fault} are calculated from eq.(8) and eq.(9), (b) shows frequency, and (c) presents the fault status which indicates the fault to be around 28[Hz](Fault_Index = 1).

Fig. 10 shows the experimental results of fig.(8) without encoder, (a) represents the applied result, I_{index} and I_{Fault} are calculated from eq.(8) and eq.(9), (b) shows frequency, and (c) presents fault status which indicates the fault to be around 28[Hz](Fault_Index = 1).

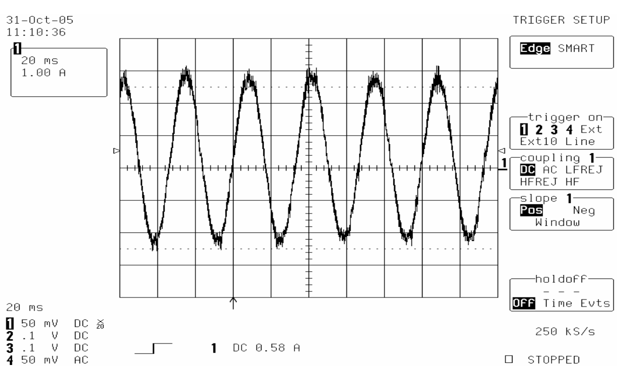


(a) Phase current waveform

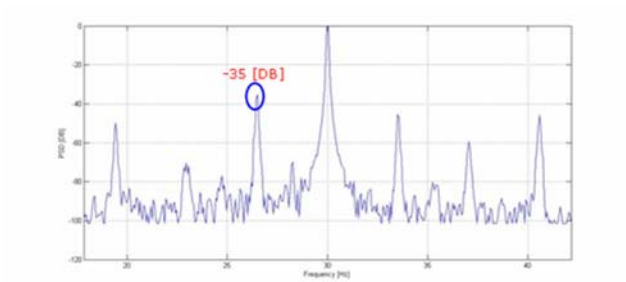


(b) PSD results of phase current

Fig. 6 Experimental results of a healthy induction motor

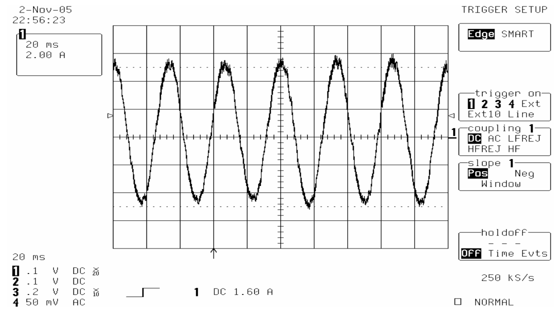


(a) Phase current waveform

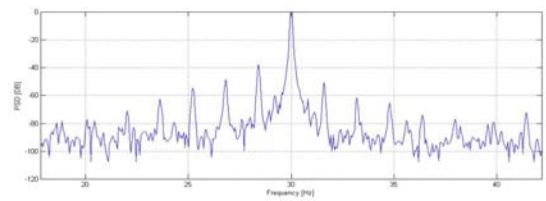


(b) PSD results of phase current

Fig. 7 Experimental results of a faulty induction motor

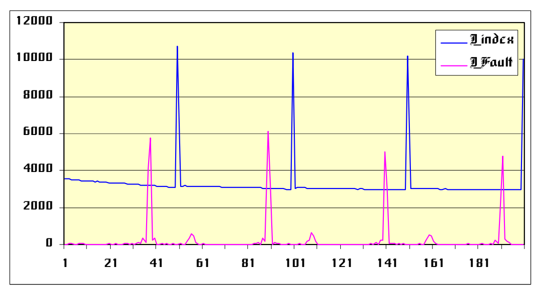


(a) Phase current waveform

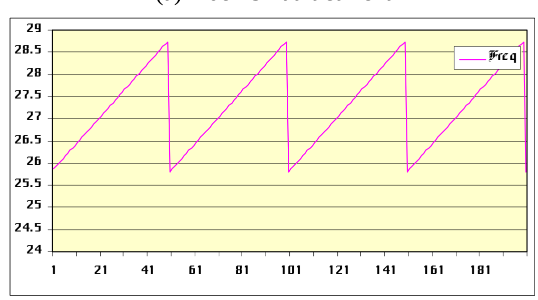


(b) PSD results of phase current

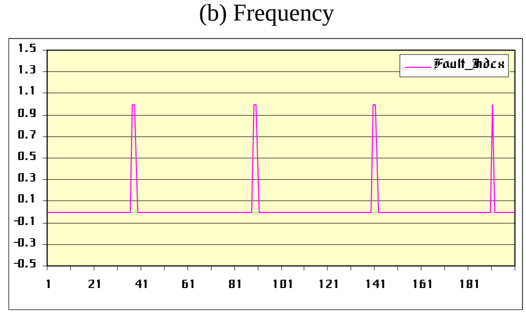
Fig. 8 Experimental result



(a) Index & fault current

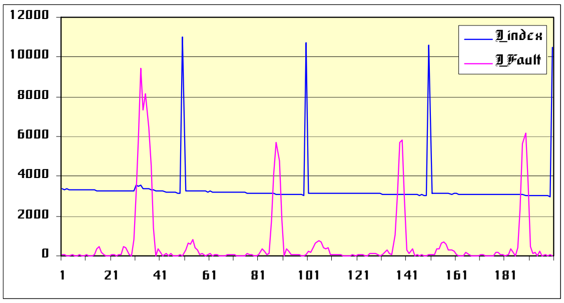


(b) Frequency

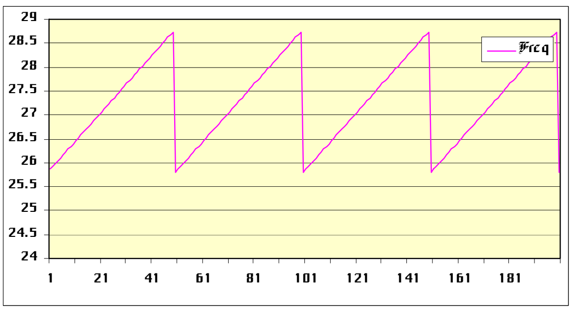


(c) Fault index

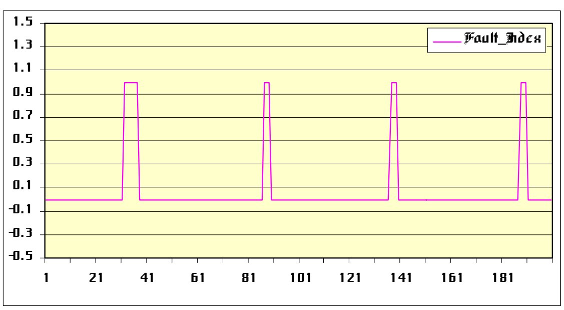
Fig. 9 Results for proposed algorithm with encoder



(a) Index & fault current



(b) Frequency



(c) Fault index

Fig. 10 Results for proposed algorithm without encoder

As shown in these results, the proposed algorithm can detect a rotor defection with and without an encoder.

5. Conclusion

This paper has investigated the feasibility of detecting broken rotor faults using an axis transformation and an average method of current spectrum of an inverter driven induction machine with and without an encoder.

An induction motor defection caused by broken rotor faults produces visible changes in the stator current spectrum at predictable frequencies. However it is very difficult to detect using FFT method because it takes a very long time and needs substantial amounts of data information. However, an axis transformation and average, instead of the FFT method have been proven very effective and cost-efficient through these experimental results.

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