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A new method for early fault detection and diagnosis of broken rotor bars

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ABSTRACT

A new method has been developed for the detection and diagnosis of broken rotor bars faults in three-phase induction motors under no-load conditions. Early detection of faults is made by using a sliding window constructed by Hilbert transforms of one of the phases of the thee-phase currents and the size of a fault is diagnosed by motor current signature analysis (MCSA) of the stored Hilbert transforms of several periods of one-phase current. The information entropy of a symbol tree generated by each sliding window is used as a fault index. The method was tested using healthy and damaged 0.37 kW induction motors under no-load conditions with applied voltages ranging from 220 V to 380 V. One and two broken rotor bars were detected under no-load conditions when supply voltages were 260 V and above. The results indicate that the method yields a high degree of accuracy in fault identification.

1. Introduction

Induction motors are one of the most used electro-mechanical energy conversion devices in industrial applications. Although these motors are robust and reliable, faults can occur due to corrosive and dusty environments. These induction motor faults occur in three components of the motor: the rotor, the stator and the bearings [1]. In recent years, researchers have addressed the problem of early and reliable fault detection in order to minimize process downtime. An ideal fault detection method should require a minimum amount of information obtained from the motor and determine its condition quickly in order to minimize the costs of the detection system and of lost production [2]. Modern industry deals with efficient diagnosis to improve the reliability of system components and to reduce maintenance cost [3].

About 10% of total induction motor faults are broken rotor bars [4]. In recent years, the design and structure quality of stator windings have been improved, but the rotor design has undergone little change. Several monitoring techniques have been developed to detect broken rotor bar faults. These techniques are based on the monitoring of vibration, temperature, motor voltage, and current. The fault detection based on motor current relies on examining the fault-related frequency components in the motor current spectrum. This method, called motor current signature analysis (MCSA), evaluates the magnitude of certain frequency components of the stator current to detect broken rotor bars [1]. Ayhan et al. [4] developed a digital notch filter combined with lower sampling rate and autoregressive spectrum analysis methods for broken rotor bar detection. The lower sampling rate requires less computation and has low cost in the implementation. However, the method was only implemented to detect one broken rotor bar fault. The effects of load and number of broken bars were not demonstrated. A modified MCSA technique was employed to detect broken rotor bar faults under different load conditions [5]. The input signals of MCSA were constructed by using two park vector components. The rotor slip was computed by means of numbers of poles and rotor slots. Bayesian classifier was utilized to distinguish between healthy and faulty condition of an induction motor at steady state. The efficiency of MCSA was also proven by applying the method to stator winding and eccentricity faults [6]. MCSA gives efficient results when the motor is being operated under robust load conditions, but for low load conditions the characteristic sideband components are very close to the line frequency, and the normal spectral leakage can obscure frequency components characteristic of the fault [2]. This problem can be solved by increasing the sampling rate; however, load variations during sampling may decrease the quality of the spectrum [7]. When the motor is operated under a no-load condition, the standard MCSA method fails to detect rotor faults. As a result, MCSA method is dependent on the rotor slip and it has not been applied to broken rotor bar faults under no-load condition. This method also requires high computation effort and present low sensibility for inverter-fed induction motors [8].

Briz et al. [9] and Supangat et al. [10] proposed wavelet transform analysis of the startup current to detect broken rotor bar faults. In two studies, standard wavelet transform were used. A disadvantage of using this wavelet is that there is not any criterion for

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selecting the wavelet function. The transient current based diagnosis also requires the restarting of the motor. In addition, any fault may be occurred when the motor runs at steady state. Tsoumas et al. [11] introduced a novel wavelet-based approach for detection of rotor faults in induction motors. The faults are detected using a stator phase current filtered through a complex wavelet. The extracted features have been used as inputs of support vector machine, and the rotor faults were classified. But, the method requires high computation effort and significant amount of data is needed for the high resolution of fault detection. Jimenez et al. [12] proposed a Hilbert transform based feature extraction for broken rotor bar faults. Their method detects faults by applying the wavelet transform to this feature signal. The modulus of the Hilbert transform reflects the energy variation of the phase current. The energy of the phase current does not vary with time in a healthy machine while this value undergoes an oscillation in a broken rotor bar [13]. The common characteristic of motor current signature analysis and wavelet analysis is that the fault is determined based on rotor frequency. When a motor is operated under very low load or no-load conditions, the transient stator current during startup is used to detect the rotor faults. This method is not appropriate for online condition monitoring. Da silva et al. [14] developed a new fault diagnosis method based on three-phase stator current envelopes using a reconstructed phase space transform. In their method, the signatures of each fault type were extracted from three-phase current envelopes. These signatures were classified using Gaussian mixture models and Bayesian classifiers. Aydin et al. [15] proposed a Hilbert transform based method using a phase space transformation to detect broken rotor bars and broken connector faults. They have used a negative selection method based on a genetic algorithm to detect the faults. For a sensible design to power inverter fed motors, current and virtual flux based approach has been proposed [16]. However, this method requires the measurement current and voltage sensors. In another study, the MCSA method based on a Hilbert transform was used to detect broken rotor bar faults at very low rotor slip conditions [17]. The effectiveness of the method was verified by experimental data on a motor with one broken rotor bar. The performance of the method was not evaluated for different numbers of broken rotor bars. A new method was proposed to detect broken rotor bars faults under no-load conditions [18]. Broken rotor bars faults were detected within very short time at absolute no-load conditions.

The classical signal processing based detection of broken rotor bar faults fails when the motor is operating under very low rotor slip condition. The spectrum leakage of the main line frequency component dominates and obscures the sideband frequency characteristic of the fault. The analysis of faults at low slip is important in industrial applications and would provide the following benefits:

- Improve quality control of new motors.
- Allow no-load analysis of all type of motors.
- Prevent confusion of faults with load-induced current oscillation.
- Reduce the cost of fault analysis.
- Ensure that the motor would not need to be stopped and restarted during production.

Previously reported works detects broken rotor bar faults under a rated load. All of them require the slip computation apart from obtaining the high resolutions of current signals. For no-load and low supply voltage conditions, there is not any study in literature for detection of broken rotor bars using the steady state current signal. In this paper, a new two step algorithm for fault detection and diagnosis in the rotor bars is proposed. The proposed methodology deals with the fault detection problem as a disorder over the Hilbert transform of the determined periods of phase current. The faults are detected by entropy calculation of two consecutive windows. This is the fault detection step of the proposed algorithm. The fault detection stage, differently from former techniques, does not require the slip computation. In addition, this stage needs very little storage of the motor current. A Hilbert transform of ten periods of the current is adequate to generate a fault alarm. The entropy value between two consecutive windows, calculated in the first stage, enables the second stage when this value exceeds a determined threshold. In the second stage, the size of fault is determined by applying MCSA on the Hilbert transform. The main contribution of the approach proposed in this paper is the detection of faults with the entropy based probability distribution of feature signal. The other advantage of the proposed method is related to the usage of less data of the fault detection procedure, combined with a good sensitivity that allows the detection under rather low supply voltages.

In this paper, Section 2 provides the mechanism of the motor current signature analysis. Section 3 presents the symbol sequence statistics and sliding windows method. Section 4 presents the validation of the proposed method using experimental results. Section 5 presents the conclusions, and Section 6 presents the proposed future work on this method.

2. Motor current signature analysis

When a broken rotor bar occurs, no current flows through the broken rotor bar. This factor causes an asymmetry in the rotor magnetic field. In the rotor of a squirrel cage or slip ring induction motor, this asymmetry will cause a side band frequency component in the spectrum of the stator current [19]. MCSA has been extensively used to detect broken rotor bar faults by investigating the sideband components around the supplied current line frequency [2]. The frequencies of sidebands components of current spectrum can be given by:

$$f_b = (1 \pm 2s)f_s \mathrm{Hz} \tag{1}$$

where f_s is the 50 or 60 Hz stator supply frequency and s is rotor slip. The sideband component $(1-2s)f_s$ is called left sideband and $(1+2s)f_s$ is called right sideband. While the left sideband component occurs due to the electrical and magnetic asymmetries in the rotor cage of an induction motor, the right sideband component is due to speed oscillations caused by torque pulsations [20]. The typical method to compute the related harmonic components is the Fourier transform. The Discrete Fourier transform (DFT) is used to obtain the Fourier coefficients of a discrete time signal $x[n]$. This transform can be computed as follows:

$$X[k] = \sum_{n=1}^{N-1} x[n] e^{-j(2\pi/N)kn} \tag{2}$$

where N is the number samples and k is 0, 1, …, $N-1$. The maximum theoretical resolution of DFT is given in (3) [17].

$$\Delta f = \frac{f_{\mathrm{sampling}}}{N} = \frac{1}{NT_{\mathrm{sampling}}} = \frac{1}{t_{\mathrm{observation}}} \tag{3}$$

where f_{sampling} is the sampling rate, T_{sampling} is the sampling period, and $t_{\mathrm{observation}}$ is the observation interval. When the motor is operated at robust load conditions, the motor current signature analysis gives good results. If the load of the motor varies during the sampling time, the locations of sideband frequencies that depend on rotor slip change with speed as shown in Fig. 1.

The changing of sideband frequencies causes the MCSA based diagnosis process to fail because (1) the sideband frequencies caused by speed changes mask the frequencies associated with the broken rotor bars, and (2) the current spectrum hides the