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Mixed eccentricity diagnosis in Inverter-Fed Induction Motors via the Adaptive Slope Transform of transient stator currents

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ABSTRACT

This paper researches the detection of mixed eccentricity in Inverter-Fed Induction Motors. The classic FFT method cannot be applied when the stator current captured is not in steady state, which is very common in these motors. Therefore, a transform able to detect the time–frequency evolutions of the components present in the transient signal captured must be applied. In order to optimize the result, a method to calculate the theoretical time–frequency evolution of the stator current components is presented, using only the captured current. This previously obtained information enables the use of the proposed transform: the Adaptive Slope Transform, based on appropriately choosing the atom slope in each point analyzed. Thanks to its adaptive characteristics, the time–frequency evolution of the main components in a stator transient current is traced precisely and with high detail in the 2D time–frequency plot obtained. As a consequence, the time–frequency plane characteristic patterns produced by the Eccentricity Related Harmonics are easily and clearly identified enabling a reliable diagnosis. Moreover, the problem of quantifying the presence of the fault is solved presenting a simple and easy to apply method. The transform capabilities have been shown successfully diagnosing an Inverter-Fed Induction Motor with mixed eccentricity during a startup, a decrease in the assigned frequency, and a load variation with and without slip compensation.

1. Introduction

According to several studies, eccentricity-related faults amount for a significant percentage among the possible failures in induction motors [1]. Moreover, eccentricities have drawn an important attention during last decades, mainly due to the importance of their possible effects, such as rotor to stator rub [2]. Classical approach for mixed eccentricity diagnosis is based on the Fast Fourier Transform (FFT) analysis of the steady-state current, and the further detection of particular fault-related frequencies (given by the following equation), whose amplitude increases in the spectrum when this fault is present [3]:

$$f_{ecc} = f_1 \cdot \left[1 \pm k \cdot \left(\frac{1-s}{p}\right)\right] \quad k \in \mathbb{N} \tag{1}$$

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Being s the slip, p the number of pole pairs, and f_1 the fundamental supply frequency. In 2-pole-pair machines supplied from a 50 Hz grid, the most relevant harmonics for mixed eccentricity diagnosis are those with frequencies around 25 Hz and 75 Hz in the FFT spectrum of the steady-state current. Higher frequency Eccentricity-Related Harmonics (ERHs) around Principal Slot Harmonics (PSHs) can also be used to perform a diagnosis [4].

Despite its robustness, this classical method has important drawbacks: the FFT spectrum is often corrupted by frequency components due to noises or other phenomena such as load torque fluctuations or supply voltage oscillations. This is the reason why some authors have developed techniques able to diagnose eccentricities in induction machines directly supplied from the grid, which intend to overcome some of the drawbacks of the FFT-based diagnosis, like for example, eliminating arbitrary load effects [5]. Other authors propose analyzing different magnitudes, instead of the stator current, like the stator impedance [6] or the external axial field [7]. Moreover, other signal analysis techniques, like the space transform [8], can be used to detect eccentricities.

The classic FFT method can only be applied to diagnose Induction Motors (IMs) working in steady state. This rarely happens in variable load applications (like in wastewater treatment plants or coal mills, in which the load is continuously varying), and in variable frequency applications (like pumps, conveyors, and machine tool drives). Therefore, in order to detect eccentricity when a steady state current cannot be captured, techniques able to deal with transient currents have been developed. These techniques are usually based on the detection of characteristic time–frequency (*t–f*) evolutions of fault-related components. In [9] the Discrete Wavelet Transform (DWT) has been used to extract the evolution of the ERHs around the fundamental supply frequency. In [10] the Hilbert–Huang Transform has been used for the same purpose. In [11] it is proved the usefulness of tracking the transient evolution of high-order Eccentricity-Related Harmonics using a Wigner–Ville distribution based algorithm. The detection of dynamic eccentricity in Brushless Direct Current Motors is performed in [12] detecting the evolutions of the fault-related components using the Analytic Wavelet Transform (AWT).

Nonetheless, not many works have focused on the diagnosis of this fault in the special case of Inverter-Fed Induction Motors (IFIMs). In [13] the traditional FFT technique is applied to the stator current in order to analyze the influence of the parameters of the inverter on the ERHs appearing on the FFT spectrum. Following with the FFT technique, [14] proposes the eccentricity detection through the specific harmonics created by the inverter. Moreover, in order to improve the FFT technique [15] presents an optimal-slip-estimation, a proper-sample-selection, and a frequency auto search algorithm.

Other techniques instead of the FFT can be used, as the Time-Series Data Mining [16]. In [17] the stator current Wigner–Ville Distributions (WVD) are used to distinguish load torque oscillations and eccentricity faults. Other magnitudes instead of the stator current can be analyzed in order to detect the eccentricity. In [18] the negative and positive sequence Fundamental Components in stator currents and terminal voltages are used to eliminate load oscillation effects. In [19] the zero-sequence-voltage signals are analyzed when the motor is excited with a predefined inverter-switching pattern. In [20] Angular Domain Order Tracking analysis is performed to detect static eccentricity in a closed loop driven motor. In [21], Hilbert and Concordia transforms are applied and compared. In [22] the FFT is applied to the instantaneous power.

On the other hand, the need of a diagnosing tool capable of analyzing transient currents is especially important in the case of IFIMs, which are very common in industry, mainly in applications at variable speed. The analysis of an IFIM with eccentricity, based on Finite Element Methods, is presented in [23]. Ref. [24] proposes a method based on the correlation of a reference signal with the stator current, having the reference signal the same frequency as the fault component frequency. It has been specially designed to deal with noise and to be implemented in a DSP. Finally, [25] proposes the use of an artificial neural network to detect eccentricities in a closed-loop drive-connected IM. Taking into account that the fault components amplitudes change with the load, the neural network is trained to estimate a threshold related to the operating condition.

First, the paper analyses how to theoretically calculate the *t–f* evolutions of the components in the stator current of an IFIM, using a proposed method which obtains the Fundamental Component (FC) evolution only by means of the current captured (Section 2). Thanks to these theoretically obtained evolutions, an adaptive transform can be proposed (Section 3), in which the *t–f* atoms used in each analyzed point are selected according to the signal needs, achieving an optimal result without any iterative process. Then, the problem of quantifying the presence of a certain component evolution is solved (Section 4). In order to test the transform presented, in Section 5 different transient stator currents of the IFIM being diagnosed are analyzed. The corresponding 2D *t–f* plots are obtained, representing the *t–f* evolution of the main components present in the transient current, which enables the diagnosis through the ERHs identification. Finally, in Section 6, the conclusions of the work are presented.

2. Calculating the theoretical time evolution of the components frequencies

Usually, the transforms applied to analyze the components contained in a transient signal have no a priori information about those components and their evolutions. In the present section, a method is proposed to calculate the theoretical time evolution of the main frequencies contained within the stator current of an IFIM. This information enables to apply the optimized *t–f* analysis presented in the next section.

Section 2.1 presents a technique to obtain the time evolution of the FC frequency by means of no other magnitude than the stator current captured. This result is used to obtain the *t–f* evolution of two main groups of components: those appearing for every machine regardless its condition, and those properly related to the fault. A startup current is analyzed as an example, while some considerations about the analysis of other types of transients are given at the end. The figures have