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Induction machine faults detection using stator current parametric spectral estimation

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ABSTRACT

Current spectrum analysis is a proven technique for fault diagnosis in electrical machines. Current spectral estimation is usually performed using classical techniques such as periodogram (FFT) or its extensions. However, these techniques have several drawbacks since their frequency resolution is limited and additional post-processing algorithms are required to extract a relevant fault detection criterion. Therefore, this paper proposes a new parametric spectral estimator that fully exploits the faults sensitive frequencies. The proposed technique is based on the maximum likelihood estimator (MLE) and offers high-resolution capabilities. Based on this approach, a fault criterion is derived for detecting several fault types.

The proposed technique is assessed using simulation signals, issued from a coupled electromagnetic circuits approach-based simulation tool for mechanical unbalance and electrical asymmetry faults detection. It is afterward validated using experiments on a 0.75-kW induction machine test bed for the particular case of bearing faults.

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1. Introduction

Condition monitoring is of high concern in industrial applications since it minimizes the downtime and improves the reliability, availability, safety and productivity of these systems. For electrical motors and generators, faults detection is usually performed by vibration monitoring, temperature measurements, oil monitoring, flux monitoring and current analysis [1,2]. Among these various techniques, current analysis has several advantages since it is a noninvasive technique that avoids the use of extra sensors [3–7]. Moreover, the electrical signals (for instance, the stator current) are usually available and inexpensive to measure.

Stator currents processing-based faults diagnosis of induction machine has received intense research interest for several decades [8–10]. Moreover, the International Standard "ISO FDIS 20958" dealing with "Condition monitoring and diagnostics of machine systems - Electrical signature analysis of three-phase induction motors" sets out guidelines for the online techniques recommended for the purposes of condition monitoring and diagnostics of machines, based on electrical signature analysis. Hence, many studies have shown that fault monitoring could be performed by supervising the current spectrum. In particular, it has been demonstrated that faults introduce additional spectral components in the stator current around the supply frequency [11,12]. For a faulty machine, the frequency location of these components is given by $f_k(\Omega)$,

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Nomenclature

DFT	discrete Fourier transform
FFT	fast Fourier transform
ESPRIT	estimation of signal parameters via rotational invariance techniques
MLE	maximum likelihood estimator
MUSIC	multiple signal classification
DFT	discrete Fourier transform
DSP	digital signal processing
MCMFT	maximum covariance frequency tracking
MDL	minimum description length
PSD	power spectral density
SNR	signal to noise ratio
f_s	stator supply frequency
s	per-unit slip
p	pole pair number

where f_k corresponds to the kth component ($k \in \mathbb{Z}$), and Ω is a set of parameters that must be estimated in order to determine the induction machine health condition. These frequencies are associated with several mechanical and/or electrical faults such as air-gap eccentricity, bearing failures or broken rotor bars. For instance, In the case of broken rotor bars, the fault signature is given by

$$f_k(\Omega) = f_s\left[k\left(\frac{1-s}{p}\right) \pm s\right] \quad (1)$$

where $\Omega = \{s, f_s\}$.

Traditional current-based techniques for fault detection monitor the stator current spectrum and, more precisely, the fault characteristic frequencies [13]. In steady-state conditions, techniques based on conventional PSD estimators have been employed [14]. These techniques can be classified into two categories: non-parametric and parametric methods [15].

Non-parametric methods include the periodogram, which is usually implemented using the FFT, and its extensions. The classical periodogram have been applied for fault detection in [11,12]. The main drawback of this technique relies on its performance. Indeed, even though the FFT is computationally efficient, it suffers from a poor frequency resolution (inversely proportional to the measurement time interval) and leakage effects (the energy of the main lobe leaks into sidelobes) due to windowing. Moreover, frequencies in the Discrete Fourier Transform (DFT) are spaced at intervals of F_s/N where F_s is the sampling frequency and N is the length of the input time series. Attempting to estimate the amplitude of a sinusoid with a frequency that does not correspond to a DFT bin can result in an inaccurate estimate. Therefore, several DFT interpolation techniques have been proposed in order to enhance frequency accuracy such as analytical leakage compensation [16], zero-padding [15], phase interpolation estimator [17] and many others [18–20]. Furthermore, the periodogram method provides reasonably high resolution for sufficiently long data lengths, but it is a poor spectral estimator because its variance is high and does not decrease with increasing data length. In addition of that, it is often advantageous to use a window function other than a rectangular (natural) one and which has a Fourier transform with faster decaying side-lobes than sinc-type function. The multiplication of the data with a particular window function can reduce the sidelobe amplitudes but increases the width of the mainlobe. Common window functions are the Bartlett window, Hamming window, Hanning window, and others [21]. The rectangular window leads to a narrow mainlobe but the highest sidelobes whereas the Hanning window reduces strongly the sidelobe amplitudes but leads to the largest mainlobe [22,23]. Furthermore, the high variance of the periodogram method motivates the development of modified methods that have lower variance, at the cost of reduced resolution. Several modified methods have been introduced such as the Bartlett [24] and the Welch techniques [24,25]. Moreover, the so-called Zoom-FFT (ZFFT) technique [26] has been introduced to improve the frequency accuracy in a specified frequency range without increasing the computational complexity. Nevertheless, the periodogram and its extensions suffer from a low frequency resolution, which is defined as the ability to distinguish two closely spaced frequency components. In [27], demodulation technique based on Hilbert transform was used to improve the frequency resolution of MCSA method for rotor asymmetries detection without concern about the signal nature (multi-component signal).

If an a priori signal model is assumed, parametric methods can be employed to improve the frequency resolution. These techniques are generally called high-resolution methods and include two sub-classes: the linear prediction methods and the subspace techniques. The linear prediction class contains several algorithms like the Prony and Pisarenko methods. The use of these methods for fault detection in electrical drives has been investigated in [28,29]. The subspace class includes the MUSIC and ESPRIT approaches. Applications for induction machine faults diagnosis are available in [2,30–32]. In [33], the MUSIC algorithm and a zooming method were combined to reduce the computational cost of the spectral estimator. However these techniques are generally computationally intensive and lead to suboptimal estimators of the PSD. Moreover, their performance decrease significantly if the noise level increases.

In addition to the aforementioned techniques, many faults detection procedures based on statistical analysis of the current signal have been proposed such as MCMFT [34] and adaptive statistical Time-Frequency Methods [35] without presenting any fault detection criteria for an automatic fault diagnosis.

The above review emphasizes the compromise between frequency accuracy, frequency resolution, statistical performance and computational cost of spectrum analysis techniques for fault detection in induction machine. Furthermore, these previous techniques are general and do not exploit the particular structure of the stator current frequency components

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