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Induction machine bearing faults detection based on a multi-dimensional MUSIC algorithm and maximum likelihood estimation

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ABSTRACT

Condition monitoring of electric drives is of paramount importance since it contributes to enhance the system reliability and availability. Moreover, the knowledge about the fault mode behavior is extremely important in order to improve system protection and fault-tolerant control. Fault detection and diagnosis in squirrel cage induction machines based on motor current signature analysis (MCSA) has been widely investigated. Several high resolution spectral estimation techniques have been developed and used to detect induction machine abnormal operating conditions. This paper focuses on the application of MCSA for the detection of abnormal mechanical conditions that may lead to induction machines failure. In fact, this paper is devoted to the detection of single-point defects in bearings based on parametric spectral estimation. A multi-dimensional MUSIC (MD MUSIC) algorithm has been developed for bearing faults detection based on bearing faults characteristic frequencies. This method has been used to estimate the fundamental frequency and the fault related frequency. Then, an amplitude estimator of the fault characteristic frequencies has been proposed and fault indicator has been derived for fault severity measurement.

The proposed bearing faults detection approach is assessed using simulated stator currents data, issued from a coupled electromagnetic circuits approach for air-gap eccentricity emulating bearing faults. Then, experimental data are used for validation purposes.

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1. Introduction

In a wide variety of industrial applications, an increasing demand exists to improve reliability, availability, and safety of electrical systems. A sudden failure of a system may lead to cost-expensive downtime, damage to surrounding equipment or even danger to humans. Induction machine is omnipresent in these electrical systems. Although it is robust and reliable, the induction machine is subjected to several faults. Common failures that may occur can be roughly classified into stator winding short circuit, broken rotor bar, broken end-ring, rotor eccentricity, bearing faults, shaft misalignment, and load faults [1,2]. In spite of the advances in failures detection, condition monitoring of induction machine is still a challenging task for engineers and researchers [3–5].

A common approach for condition monitoring is vibration monitoring [6–9]. However, this method is expensive since it requires costly additional transducers. A cost-effective alternative is stator currents analysis since currents measurement requires limited number of sensors and is already available for control and protection purposes [10]. In [11] the authors have performed a comparative study of vibration monitoring, stator current analysis and stray flux processing as media for induction machine mechanical unbalance fault detection. A literature survey showed the interest of the approach for mechanical and electrical faults detection [12–19]. A Hilbert–Park transform has been successfully used for mechanical fault diagnosis in induction machines in [20]. Most authors perform induction machine faults detection by monitoring the additional frequency components introduced by the fault. However, no precise stator currents model under fault is given. In various works, numerical machine models accounting for the fault are used without providing analytical stator current expressions [21].

Theoretical analysis has shown that faulty machine frequencies of interest are given by [5,22]

$$f_k = f_s \pm k f_c, \quad k = 0, 1, \ldots, L. \tag{1}$$

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Nomenclature

MD MUSIC	multi-dimensional multiple signal classification
ESPRIT	estimation of signal parameters via rotational invariance techniques
MCSA	motor current signature analysis
MLE	maximum likelihood estimation
PSD	power spectral density
SNR	signal to noise ratio
DFT	discrete fourier transform
MCMFT	maximum covariance frequency tracking
f_s	stator supply frequency
s	per-unit slip
p	pole pairs number

where f_s is the electrical supply frequency, f_c corresponds to the fault characteristic frequency, and $2 \times L$ is the sidebands number. These frequencies are associated with air-gap eccentricity, bearing failures or broken rotor bars faults.

In steady-state condition, f_s and f_c are constants and techniques based on classical spectral estimators (Periodogram and its extensions) have been employed [4,23]. In order to overcome the low frequency resolution of these techniques, high resolution techniques have been proposed such as MUSIC and estimation of signal parameters via rotational invariance techniques (ESPRIT) [24–29]. Moreover, in [30] the authors have proposed a parametric spectral estimation technique based on a maximum likelihood estimation that outperform the conventional techniques such as discrete Fourier transform (DFT) and MUSIC. In non stationary environment, more sophisticated techniques have been investigated such as time–frequency representations [31–35] and time-scale techniques [31,36]. In addition to the aforementioned techniques, many faults detection procedures based on statistical analysis of the current signal have been proposed such as MCMFT [37] and adaptive statistical time–frequency methods [38] without presenting any fault detection criteria for an automatic fault diagnosis.

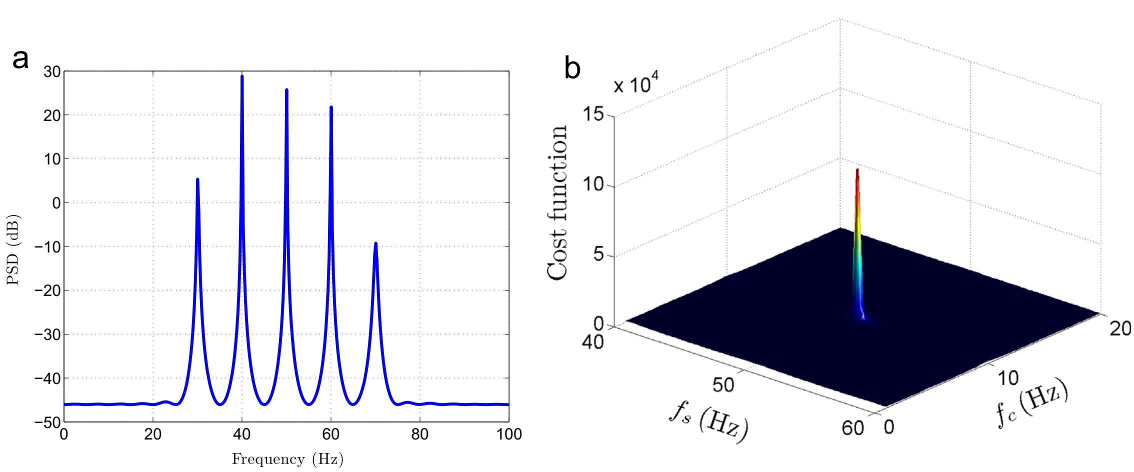
An overview of the existing works emphasizes the compromise between frequency accuracy, frequency resolution, statistical performance and computational cost of spectrum analysis techniques for fault detection in induction machine. Furthermore, it should be mentioned that the classical techniques do not take into account the particularity of electrical signals, such as specific frequency structure of the stator currents under faulty conditions.

In this paper, we propose a stator current signal analytical model that takes into account the particular structure of the fault sensitive frequencies given by (1). A stator current signal model is of great interest since it helps to develop suitable post-processing tools and detection strategies. Then, a high resolution signal processing technique, based on this model, is developed for fault related frequency estimation. Finally, a fault detection criterion is presented.

The major issue addressed in this paper is the development of a condition monitoring strategy that can make an accurate and reliable assessment of the presence of specific induction machine fault conditions, namely the bearing faults. Indeed, this paper focuses on the detection of single-point defects in a rolling element bearing. The proposed fault detection technique is based on three steps. First, the fundamental frequency, the fault characteristic frequency, and the number of sidebands (equivalent to model order selection [39,40]) are estimated based on the MD MUSIC [41]. Then, the maximum likelihood estimator (MLE), which is an optimal technique, is used to estimate the amplitude of the fault characteristic components. Finally, a fault detection criterion is computed using the estimated amplitudes [42]. This criterion allows us to measure the fault severity and then could be used as input for an automatic fault detection procedure.

To illustrate the difference between the classical MUSIC algorithm [43,44] and the proposed technique, Fig. 1 presents the MUSIC pseudo-spectrum and the MD MUSIC for a supply frequency of $f_s = 50$ Hz, a fault characteristic frequency of $f_c = 10$ Hz, and with $SNR = 50$ dB. Fig. 1a shows that the MUSIC pseudo-spectrum exhibits spectral peaks at $f_s \pm kf_c$. In contrast to the classical MUSIC, the proposed technique tracks the supply frequency and the characteristic frequency in a two-dimensional space. Fig. 1b shows that the multi-dimensional cost-function exhibits a single peak at $f_s = 50$ Hz and $f_c = 10$ Hz. Compared to MUSIC, the proposed technique makes the estimation of f_s and f_c (and the subsequent processing) easier. Furthermore, as it exploits more information about the signal (the fault characteristic frequencies are introduced in the faulty induction machine stator current model), the proposed technique is expected to outperform the classical MUSIC algorithm. Finally, the proposed method allows us to measure the fault related frequencies amplitude when the classical MUSIC does not give the true PSD (not the amplitude of the frequency bins).

The major contributions of this paper are threefold:



Pseudo-spectrum estimate via MUSIC. MD MUSIC cost-function

Fig. 1. Cost-function for classical MUSIC and MD MUSIC (cost-function in the case of a synthetic signal with $f_s = 50$ Hz, $f_c = 10$ Hz, $L=2$ and $SNR=50$ dB).

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