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Broken rotor bar diagnosis in induction machines through stationary wavelet packet transform and multiclass wavelet SVM

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ABSTRACT

This paper presents the establishing of intelligent system for broken-rotor-bar (BRB) diagnosis based on a novel combination of both, stationary wavelet packet transform (SWPT) and multiclass wavelet support vector machines (MWSVM). The SWPT is used for feature extraction under lower sampling rate. In fact, it is demonstrated through experimental results that the use of the lower sampling rate does not affect the performance of SWPT to detect BRB, while requiring much less computation and low cost implementation. The multiclass SVM (MSVM) is used to automatically recognize the faults. Different MSVM strategies are compared with various kernel functions in terms of classification accuracy, training and testing complexity. The classification results show that the wavelet kernel function detects the faulty conditions with a higher accuracy.

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1. Introduction

Thanks to its robustness and the convenient power–weight ratio, the induction motor (IM) has dominated the field of electromechanical energy conversion. Nevertheless, in industrial application, IM is subject to unavoidable stress which creates failures in its different parts. Hence, condition monitoring has become necessary to predict the failure and the subsequent interruptions [1–5]. Despite its robustness, the IM presents some faults such as BRB [1–6]. This failure has become an important issue in the field of fault diagnosis. Indeed, operating IM with BRB may not only damage the motor itself, but can also have a catastrophic impact on the related machines [1–4]. The BRB introduces a distortion in the air-gap field that produces sideband component around the fundamental frequency in the current spectrum [4–7]. The frequency fault is given by:

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

where f_b is the sideband frequency associated to the BRB, s is the motor slip per unit and f_s is the fundamental frequency.

The motor current signature analysis (MCSA) is one of the most used techniques in fault detection analysis of IM [1–6]. The main purpose of MCSA is to analyze the stator current and to detect the current harmonics related to the fault. The success of this technique lies on its simplicity and ability to detect all kind of defects: it only needs one current sensor and a straightforward signal processing technique [6–10]. Recently, the wavelet transform in its two variants, namely, discrete wavelet transform (DWT) [11–15] and wavelet packet transform (WPT) [16,17], has become one of the most widely used signal processing technique for IM diagnosis. Particularly, Sadeghian et al. [16] presented an algorithm for the online detection of BRB based on WPT with sampling frequency F_s = 1920 Hz and number of samples N_s = 9984. The extracted features and the slip value are used by a neural network for faults classification. Furthermore, and in order to detect the same fault, Cusidó et al. [12] combined wavelet and power spectral density techniques to give the power detail density as a fault factor with F_s = 6 kHz and N_s = 50,000. In [12,16], the experimental results showed that the proposed methods are able to detect the faulty conditions with high accuracy. However these techniques needed slip estimation which has made the automatic detection very difficult. To overcome this problem Kia et al. [11] applied the DWT to the space–vector magnitude of the stator phase current and computed the coefficient energy associated to the rotor fault with F_s = 10 kHz and N_s = 65,536 samples. This approach was successfully tested to IM under different BRB fault severities without slip estimation. Nevertheless, the use of the space–vector current requires three current sensors which made detection more expensive. Bouzida et al. [13] employed one current

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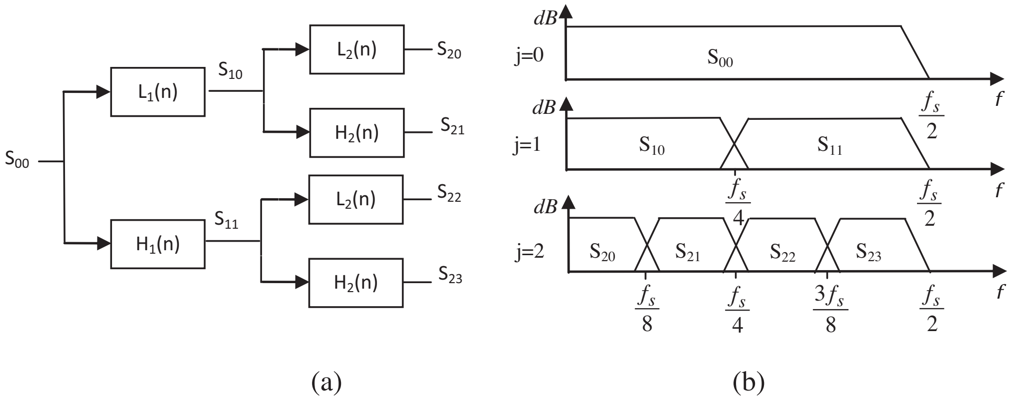

Fig. 1. SWPT: (a) structure decomposition and (b) coefficients frequency range.

sensor and DWT to detect BRB under non-stationary signals with $F_s = 10$ kHz and $N_s = 100{,}000$ samples. Yet, this method required good knowledge of the signals to find the correct F_s, N_s and mother wavelet to improve the detection of faults. As a matter of fact, the sampling rate and number of samples are closely related to the fault detection performance. In addition, the implementation of condition monitoring system is often expensive. Therefore and in order to reduce the cost implementation it is worth mentioning that is necessary to select low sampling rate and a small number of samples while preserving fault detection performance [5].

In this work, it is demonstrated that lower sampling rate of $F_s = 200$ Hz and a reduced number of samples, $N_s = 1024$, can be used for BRB detection.

Unlike previous works where either DWT or WPT is employed to diagnose BRB, in this paper, it is proven that using SWPT comes with great benefits. Indeed, DWT and WPT suffer from lack of shift invariance [18,19]. These shifts can lead to serious problems in the classification, identification, and faults detection [18,19]. The SWPT technique is designed to solve this problem by eliminating the down sampling at each level.

The SWPT is only used to extract the sensitive feature related to the fault but do not allow automatic fault detection. Nowadays, there is a demand to incorporate the learning techniques that can make decisions on the health of the machine automatically and reliably. SVM is relatively a new pattern recognition method based on statistical learning theory introduced by Vapnik [20]. It has been used in many fault diagnosis of IM with good performances [21–26]. The main idea behind SVM is to find the hyper-plane with maximum margin by separating the two-class samples. In the case where data is not linearly separable, SVM can map the input vector into a high dimensional space via a kernel function that satisfies the conditions of Mercer's theorem [27]. Kernel function plays an important role in SVM classification. Many kernel functions can be used: linear, polynomial (Poly), radial basis function (RBF), or sigmoid-shaped function. Recently, some wavelet kernel functions have been successfully applied in many fields of application like classification and nonlinear function estimation [28]. Although, SVM was originally designed to fulfill binary classification [20], several methods have been proposed to construct a MSVM. Among which two approaches are suggested in the literature: one against all (OAA) and one against one (OAO) [29,30]. These methods were mainly evaluated using classical kernel functions especially RBF and Poly [29,30]. Indeed, there is not a particular explanation concerning the use of wavelet kernel.

In this paper and in addition to using lower sampling rate and low number of samples the combination of SWPT and MSVM is used for BRB fault detection. It is demonstrated that under such low sampling rate, DWT and WPT are not suitable for BRB detection. At the classification stage, the accuracy and complexity of both OAO and OAA strategies are compared using three kernel functions, namely RBF, Poly and wavelet.

The reminder of this paper is organized as follows: Section 2 recalls the DWT, WPT, and SWPT techniques. Section 3 introduces the fundamental of the wavelet kernel as well as MSVM. Section 4 describes the experimental setup and motor data specifications. Section 5 outlines the fault-detection schemes together with SWPT feature extraction. Finally, Section 6 summarizes the simulation results and observations. Section 7 concludes the findings of this paper.

2. Stationary wavelet packet transform

DWT is the first discrete implementation of wavelet transform [18,19], it consists on filtering the input signal by a low pass filter (L) and high pass filter (H) leading to two sub-bands called respectively approximations and details, followed by a decimation factor of both. In the next steps, the filter bank is successively applied only to the approximation coefficients. WPT is a generalization of DWT, where the filtering process is applied to decompose both approximations and details sub-bands while still decimating the filters outputs [18,19]. In the DWT and WPT, a fundamental computational step is down-sampling. On the contrary, the SWPT is implemented without down-sampling, keeping all the elements in the coefficients across all the decomposition levels [18,19]. The structure of a two level SWPT is shown in Fig. 1(a). Where S_{00} is the original signal, SWPT coefficients can be computed for each level j by:

$$S_{j+1,2n}(t) = \sqrt{2}\sum_{K} H_{j+1}(k) S_{j,n}(2t-k) \tag{2}$$

$$S_{j+1,2n+1}(t) = \sqrt{2}\sum_{K} L_{j+1}(k) S_{j,n}(2t-k) \tag{3}$$

where n is node number.

The SWPT coefficient frequency ranges are demonstrated in Fig. 1(b). At every level, the SWPT frequency resolution is:

$$f_r = \frac{f_s}{2^{j+1}} \tag{4}$$

The frequency bandwidth of SWPT coefficient is $[nf_s/2^{j+1},\ ((n+1)f_s)/2^{j+1}]$.

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