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Vibration analysis for bearing fault detection and classification using an intelligent filter

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ABSTRACT

This paper proposes an intelligent method based on artificial neural networks (ANNs) to detect bearing defects of induction motors. In this method, the vibration signal passes through removing non-bearing fault component (RNFC) filter, designed by neural networks, in order to remove its non-bearing fault components, and then enters the second neural network that uses pattern recognition techniques for fault classification. Four different categories include; healthy, inner race defect, outer race defect, and double holes in outer race are investigated. Compared to the regular fault detection methods that use frequency-domain features, the proposed method is based on analyzing time-domain features which needs less computational effort. Moreover, machine and bearing parameters, and the vibration signal spectrum distribution are not required in this method. It is shown that better results are achieved when the filtered component of the vibration signal is used for fault classification rather than common methods that use directly vibration signal. Experimental results on three-phase induction motor verify the ability of the proposed method in fault diagnosis despite low quality (noisy) of measured vibration signal.

1. Introduction

Induction motors with many important advantages such as high reliability and performance have a critical role in many industries such as power plants and petrochemical factories. In spite of their reliability, they are subject to some failures. These faults can be detected at early stages by employing suitable condition monitoring techniques. Therefore, researches on fault detection have been widely made in order to prevent sudden failures [1,2].

Fault detection techniques can be classified into three groups of signal-based [3–5], knowledge-based [6,7] and model-based techniques [8,9]. Signal-based fault detection techniques are based on analyzing the spectrum components of measured signals. Model-based techniques need an accurate model of the system to imitate the real process behavior, so it is only used in 10% of real-world applications of induction motors fault detection. To mention a few examples, in [10] a new method for designing robust finite frequency H_∞ filtering of uncertain 2-D roesser models are proposed. In [11] this method is used for linear discrete-time state-delayed systems. Knowledge-based techniques use intelligent methods such as fuzzy systems and neural networks, for instance, to diagnose the faults in induction motors. This paper focuses on knowledge-based techniques that will be explained in detail in the following. Based on the analysis of the origin of induction motor failures, the bearing fault is the major source of most mechanical faults. To show the importance of bearing fault detection, induction motors failures distribution is depicted in Fig. 1 [12,13]. Therefore, the bearing fault detection and troubleshooting in the early stages will decrease the cost of unwanted shutdown [14].

Bearing defects can be categorized as single-point defects and generalized roughness [15]. Single-point defects are usually created off-line in a lab or a workshop, for example, by drilling a hole in either part of the bearing. Generalized roughness are most often generated on-line by the bearing surfaces degradation, but they do not necessarily show distinguishing defects [16,17].

There are many condition monitoring techniques, including; vibration, temperature [18], chemical, and current monitoring [19]. The bearing condition can be monitored very well via machine vibration. This is because bearing faults, whether single-point defects or generalized roughness, will typically produce consecutive and periodic impulse terms in machine vibration caused by passing the ball bearing through the defect points. The period of these terms can be calculated by knowing the rotating velocity, position of faults and bearing dimensions [20].

The simplest frequency-domain analysis method used for bearing fault detection is Fast-Fourier-Transform (FFT) [21]. The impact of vibration generated by a bearing fault has relatively low energy and it is often accompanied by high energy noise and vibration

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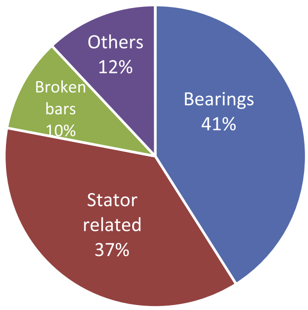

Fig. 1. Pie chart of induction motor failures percentage.

generated by simultaneously-active equipment. Therefore, it is difficult to identify the bearing fault in the spectra using conventional FFT methods. To overcome FFT problems, different advanced signal processing methods have been developed for bearing fault detection such as Short-Time-Fourier-Transform (STFT) [22], Wavelet-Transform (WT), Wavelet Packet Transform (WPT) [23,24] and Park's vector approach [25,26], for instance.

Wavelet packet transform detects the faults on the inner and outer races of bearing. WT shows very attractive features and is suitable for studying non-stationary signals. In contrast to Fourier analysis, which is a frequency-domain transformation, wavelet decomposition localizes features both in time and in frequency. WT is a linear transformation that allows time localization of different frequency components of a given signal. STFT has a limitation of using a fixed width windowing function; however it achieves the same goal. In STFT both frequency and time resolutions of the resulting transform will be fixed.

All these frequency-domain methods need the calculation of characteristic defect frequencies, which rely on bearing parameters such as number of balls and dimension, and also complicated calculations [27]. However, in some studies it was determined that those characteristic defect frequencies are not observable and may not exist at all in the measured signal [16,28].

In 1991, neural network (NN) was first proposed for diagnosing the faults of single-phase motors [29]. In [30] NN was used for diagnosing different types of external faults in three-phase induction motors. In [31] a feed-forward back propagation neural network was designed for bearing, broken bar, stator winding and unbalanced rotor faults detection. Although these researches achieved some success, but used both time- and frequency-domain features with complicated calculation to train the NN. Some of them such as [32] used WPT to pre-process vibration signals before training the NN. In [26] a three stage algorithm is used for fault detection. First, NN is developed to estimate shaft speed, and then dynamic recurrent neural network is used as the pilot model to estimate the residual of current signal. At last, this residual is processed by applying WPT to detect mechanical faults. However, such techniques suffer from high computational effort due to using WPT.

In recent years pattern recognition techniques based on ANN has attracted more attention. In [27] the vibration signal is used as the ANN input to detect bearing faults including; inner race defect and outer race defect, but only artificial defects are investigated. In [33] vibration analysis for bearing fault detection using basis pursuit and NN is proposed. In this paper, basis pursuit is used for feature extraction and then a feedforward NN is trained for classification. However used more than 16 basis pursuit coefficients (as features) with complicated calculation and used NN with two hidden layers are the disadvantages of this paper. In [7] a discrete wavelet transform is used to pre-process current signal before fault classification based on support vector machine. In [34] a fault detection method based on noise cancelation using wiener filter is proposed. In this approach a fault indicator is established based on the output signal of the wiener filter. However, no classification method has been proposed to distinguish the fault localization.

Motivated by this consideration, in current work a non-intrusive detection method for both single-point and generalized-roughness bearing faults in induction motors with particular interest in diagnosing faults at an early stage is proposed. In the proposed method, first healthy components of the vibration signal is estimated by an intelligent filter that is designed based on NN. Note that this network is trained under the normal condition. Therefore, when a measured vibration signal passes through this filter, components that exist in a healthy condition are removed and the filter output contains the components that are relevant to faulty conditions. In the next stage, time-domain features of the filtered signal are extracted to use as inputs of a classifier in order to distinguish fault localization.

It is noting that this approach does not need any bearing parameters for calculation of defect frequencies as it uses only time-domain features to detect the faults. Moreover, unlike previous knowledge-based methods such as [27] which use the vibration signal as the classifier inputs, the proposed method first uses a removing non-bearing fault component (RNFC) filter and then the filter output enters the classifier. This pre-processing enhances the fault detection algorithm in early stages.

This paper is organized as follows; the concept and steps of the designed filter and artificial neural networks discussed in Section 2, experimental results are presented in Section 3, and the paper is concluded in Section 4.

2. Designed method for fault detection based on neural network

The main objective of this section is to design a RNFC filter based on neural networks. Then, a different neural network is designed for the fault classification purpose.

2.1. Intelligent RNFC filter design

Most common methods of bearing fault diagnosis are based on the vibration signal analysis that consists of both healthy and faulty parts. However, analyzing the healthy part of the signal is not beneficial for fault detection.

In order to prevent analyzing the non-bearing fault component (i.e. healthy part), first, the irrelevant part is estimated with an artificial neural network based filter, and then the estimated part is removed from the main sampled vibration signal. The RNFC filter block diagram is shown in Fig. 2 and all variable names are defined in the following:

$\nu(n)$: Motor vibration signal.
$y(n)$: Estimated irrelevant part of the vibration signal (non-bearing fault components).

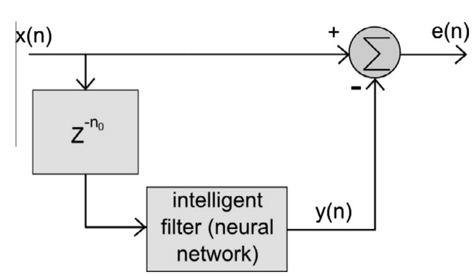

Fig. 2. Removing non-bearing fault component (RNFC) filter.