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Probabilistic frequency-domain discrete wavelet transform for better detection of bearing faults in induction motors ☆

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ABSTRACT

Due to the importance of induction motors' continuous operation, early detection of faults has become a major trend. As reported in an IEEE study, bearing failures include more than half of mechanical faults. To detect existence of this fault, methods such as (short-time) Fourier, (continuous–discrete) wavelet, and Park transforms introduced. Static modeling of fault behavior is determined to be the major deficiency of above-mentioned methods. In other words, using conventional detection techniques, fault is assumed to have deterministic behavior, in which the fault frequencies are constant. As a matter of fact, fault characteristics can be affected under loading or environmental conditions, which makes conventional standing invalid. Authors of this paper have developed their previously introduced technique, frequency-domain discrete wavelet transform (FD-DWT) into a stochastic model. This makes the detection process valid for more variety of fault conditions and leads to earlier detection of fault and less damage to motor compared to other strategies.

1. Introduction

Loss of energy in induction motors due to bearing faults causes vibrations mostly along the inner and outer race [1–3]. An inner race defect has a more severe effect on the output signal of the induction motor versus an outer race fault, because it cracks the motor shaft more severely. Simultaneously, an unaligned shaft along with a bearing defect brings greater losses compared solely to a broken bearing (which happens because of an outer race problem) [4]. Therefore, inner race fault detection is a more time-consuming process [5], because the fault characteristic has a non-deterministic pattern that can be combined with other fault characteristics. In this paper, we try to introduce an efficient probabilistic algorithm that recognizes an outer race fault along with inner race breakdown.

To address the issue of bearing fault diagnosis using wavelets, Yan et al. and Ergin et al. [6,7] mentioned the benefits of the discrete wavelet transform (DWT) over the continuous wavelet transform (CWT) in terms of reduction in computation time and earlier detection of faults with this tool. Kumar et al. and Eren et al. [8,9] studied the performance of DWT analysis for detection of bearing faults using Neural Networks and saw that DWT analysis is extremely useful for de-noising the raw data from an induction motor in a classification process. Eren et al. and Mohammed et al. [10,11] applied wavelet packet decomposition in order to realize characteristics of bearing faults. In these works, the fault characteristics only exist in specific frequencies. These authors have not considered possible parameters affecting the magnitude of a fault, including overloading, or environmental conditions. In the case of a bearing defect, cracks to the shaft can happen, which causes two mechanical fault characteristics combined. Also, environmental conditions such as humidity and outside temperature can change the fault frequencies from the calculated values [12]. As a result, it can be concluded that conventional static methods, such as the Park transform or wavelet decomposition for detection of faults may not be valid in real-world applications, where the above-mentioned parameters can vary widely.

In order to reduce error in finding the location of fault information, some authors have proposed a new probabilistic algorithm that is more reliable under various conditions of operation. In the proposed approach, induction motor behavior under fault situations is modeled using a Gaussian distribution. A Gaussian distribution can be used to stochastically model behavior of any natural phenomenon, such as bearing fault condition, but not much information about this phenomenon is available [13]. This

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distribution is applied to input voltage frequency; in other words, due to the fact that a bearing fault affects the motor with deviations in the input voltage frequency [14], motor performance under a bearing fault condition is modeled by applying a deviation in input voltage frequency. No deviation in the input voltage frequency represents the healthy operation of a motor; but an increase in this deviation will increase the magnitude of the fault (a crack in a bearing system may vary between 1 and 5 mm in depth). This condition can be realized by a Gaussian distribution, in which the mean value represents the healthy condition (no variation) that is most likely to happen, but by getting far from the mean value, the magnitude of a bearing fault increases (the variation increases), which is less likely to happen (because of fast performance of protection systems).

To detect the fault, stator current has been adopted as a detection signal. Therefore, stator current signal in each level of FD-DWT is used for decomposition. Since the system operates as a linear system, if a mechanical fault exists in a motor, the fault frequencies in the stator current can be observed and detected. If the conditional operation of a motor is modeled with a Gaussian distribution, another Gaussian function can be found around the calculated fault frequencies, which are derived from output stator current. The mean of this distribution shows the frequency range in which the fault happens with the highest probability. It will be shown that the mean is close to the calculated fault frequency. As it gets further from the mean of this distribution (fault magnitude increases), it shows the decreasing probability of fault signature existence. By an increase in the number of decomposed levels, the harmonics and additional high-energy components are reduced and output probabilistic distribution looks more like a Gaussian distribution. This approach is extremely useful for detecting low-energy faults, such as bearing faults, and especially an inner race fault that causes more damage to the motor.

This manuscript is structured as follows. In Section 2, a model for an induction motor is developed; bearing faults are tested in this model. In Section 3, the frequency-domain discrete wavelet transform is introduced, which relies on frequency-domain analysis using DWT. In Section 4, the probabilistic approach for detection of a bearing fault using FD-DWT under various conditions of operation is presented, and the results verify the benefits of probabilistic modeling of bearing faults.

2. Bearing defect characteristics

As mentioned in the previous section, bearing faults that occur but are not diagnosed cause catastrophic electrical and mechanical losses. Therefore, it seems necessary to detect the existence of a fault and calculate its severity. In order to acquire knowledge about fault behavior, a model-based prototype was developed. Fig. 1 shows a general scheme for the developed model. Induction motors with parameters shown in Table 1 were fed with three-phase voltages, and the stator current was acquired. By deriving the stator current using a relevant data acquisition system, mathematical analysis of the waveform was applied and fault frequencies were calculated.

Next, a model of bearing faults is considered. Fig. 2 illustrates a general ball-bearing configuration in a rotor. Faults happen in four major areas of the bearing section: inner and outer race, balls, and cage. For each fault, a specific frequency response exists: ball spin frequency f_b, ball pass frequency of the outer race f_o, ball pass frequency of the inner race f_i, and fundamental cage frequency f_c. With several experiments, the following mathematical representations for these faults were derived [15]:

$$f_b = \frac{PD}{BD} f_r \left[- \left(\frac{BD}{PD}\right)^2 \cos^2(\beta) \right] \tag{1}$$

$$f_o = \frac{n}{2} f_r \left[1 - \left(\frac{BD}{PD}\right) \cos(\beta) \right] \tag{2}$$

$$f_i = \frac{n}{2} f_r \left[1 + \left(\frac{BD}{PD}\right) \cos(\beta) \right] \tag{3}$$

$$f_c = \frac{1}{2} f_r \left[1 - \left(\frac{BD}{PD}\right) \cos(\beta) \right] \tag{4}$$

In Eqs. (1)–(4), n is the number of balls, PD is the bearing race diameter, BD is the ball diameter, β is the angle between the balls in the races, as seen in Fig. 2, and f_r is the motor rotational speed in hertz.

Usually, the number of balls in a bearing system varies between six and 12 [15]. In this work, the bearing system contains six balls. Blodt et al. [16] showed that the characteristic frequencies given in

Table 1
Induction motor characteristics

Characteristic	Description
Type	Squirrel Cage
Nominal Speed (rpm)	1430
Nominal Power (kW)	4, 10
Voltage (L–L)	400
Nominal Frequency (Hz)	50
Stator Resistance (Ohms)	1.405
Stator Inductance (H)	0.0058
Rotor Resistance (Ohms)	1.395
Rotor Inductance (H)	0.0058
Mutual Inductance (H)	0.1722
Number of Balls in Bearing	6

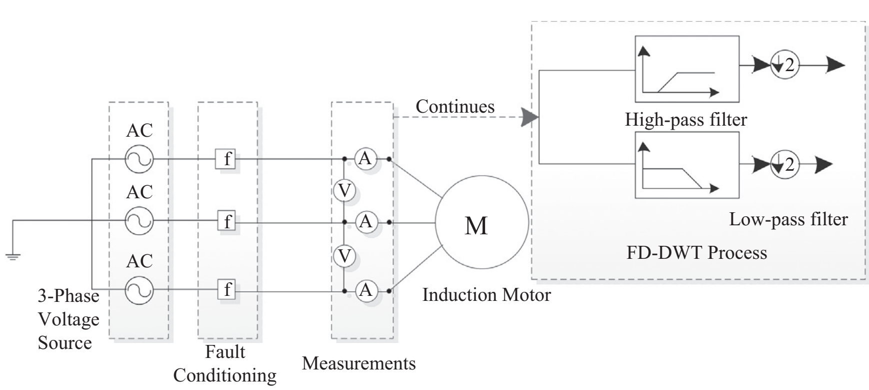

Fig. 1. : Induction motor model developed for fault detection.