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DIAGNOSTICS OF INDUCTION MOTOR BASED ON ANALYSIS OF ACOUSTIC SIGNALS WITH APPLICATION OF FFT AND CLASSIFIER BASED ON WORDS

DIAGNOSTYKA SILNIKA INDUKCYJNEGO OPARTA NA ANALIZIE SYGNAŁÓW AKUSTYCZNYCH Z ZASTOSOWANIEM FFT I KLASYFIKATORA OPARTEGO NA SŁOWACH

Paper presents method of diagnostics of imminent failure conditions of induction motor. This method is based on a study of acoustic signals generated by induction motor. Sound recognition system is based on algorithms of data processing, such as FFT and classifier based on words. Software of sound recognition of induction motor was implemented. Studies were carried out for four imminent failure conditions of induction motor. The results confirm that the system can be useful for protecting the engines and metallurgical equipment. System can be useful in inspection of metallurgical products.
Keywords: Diagnostics, Recognition, Sound, Classifier, Induction motor

Referat opisuje metodę diagnozowania stanów przedawaryjnych silnika indukcyjnego. Metoda ta oparta jest na badaniu sygnałów akustycznych generowanych przez silnik indukcyjny. System rozpoznawania dźwięku oparty jest na algorytmach przetwarzania danych takich jak algorytm FFT i klasyfikator oparty na słowach. Zaimplementowano oprogramowanie rozpoznawania dźwięku silnika indukcyjnego. Przeprowadzono badania dla czterech stanów przedawaryjnych silnika indukcyjnego. Wyniki badań potwierdzają, że system może być przydatny do ochrony silników i sprzętu hutniczego. System może być przydatny do kontroli wyrobów hutniczych.

1. Introduction

There are lots of methods that can be used for the diagnostics of electrical machines and metallurgical equipment. In the literature, popular methods are based on a study of electrical signals [1], [2], [3]. Thermal effects of short-circuit current on winding in transformer oil were investigated [4]. Mechanical and magnetic properties of materials were investigated [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30]. The tribological properties of high speed steel based composites were investigated [31]. Structural and mechanical properties of brazed joints of stainless steel and aluminium were investigated [32]. Influence of the asymmetry of vibrators resistance to motion on the correctness of the vibration distribution on working surfaces of vibratory machines was investigated [33]. Computed Tomography was applied as a non-destructive method of monitoring quality of the castings [34]. Diagnostic methods of technological properties and casting cores quality were developed [35].

In recent years, the methods of sound recognition were developed [36]. Hence the idea to use them for machines. For example electric arc furnace generates sounds. It is possible to study imminent failure conditions of electric arc furnace. Studies concern induction motor that generates acoustic signals. These studies can be used to the diagnostics of electrical machines, mechanical machines, hydraulic machines, pneumatic machines. The paper presents new implementation of the diagnostics of imminent failure conditions of induction motor.

2. Study of information contained in acoustic signal of induction motor

Devices for recording of acoustic signals at frequencies from 100 Hz to 15000 Hz have low price and are available. Therefore research will be conducted in the frequency range from 100 Hz to 15000 Hz.

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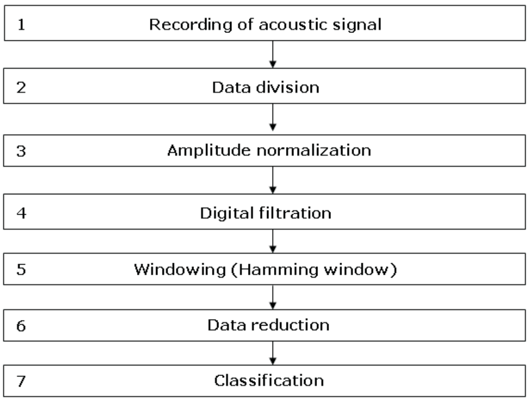

Fig. 1. Plan of study of acoustic signal contains three steps: preprocessing, data reduction, classification

The greatest difficulties arise when the engineer must choose the method of signal processing and analysis of sound. It can be noted that sounds of damaged and undamaged motor are different. Solving of this problem is to find the appropriate choice of signal processing algorithms. This allows to detect small differences in the sound of induction motor. There are many methods for preprocessing, data reduction and classification of acoustic signals [36],[37].

3. Sound recognition process of induction motor

The plan of study of acoustic signal was proposed (Fig. 1). Measurements were made by digital voice recorder WS 200S. This audio file contains following parameters: sampling frequency is 44100 Hz, number of bits is 16, number of channels is 1. Sound recognition process of induction motor contains pattern creation process and identification process (Fig. 2).

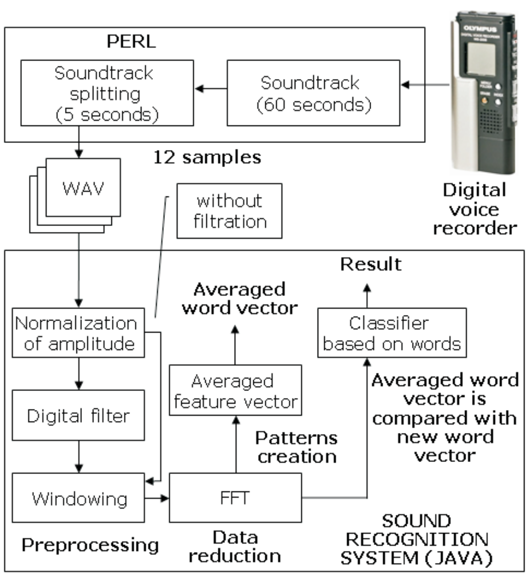

Fig. 2. Sound recognition process with application of FFT and classifier based on words

Soundtrack is recorded and split. At the beginning of pattern creation process signals are normalized and filtrated. Afterwards data are converted through the Hamming window. Next data are converted through the FFT algorithm. FFT algorithm creates feature vectors (80 features). Four averaged feature vectors are created. Next these vectors are converted into four averaged word vectors. Steps of identification process are the same as for pattern creation process. Significant change occurs in the classification. In this step, word vectors are compared with each other (averaged word vector and new word vector).

3.1. Fast Fourier Transform

FFT transforms time domain to frequency domain.

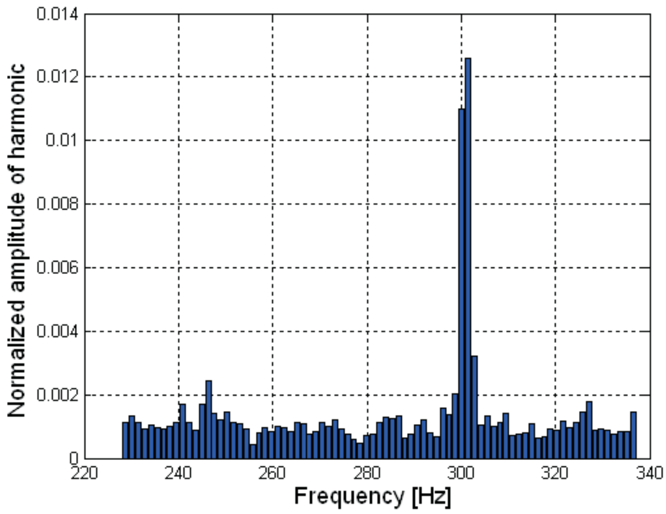

Fig. 3. Frequency spectrum of sound of faultless induction motor with the band-pass filter which passes frequencies 227-337 Hz

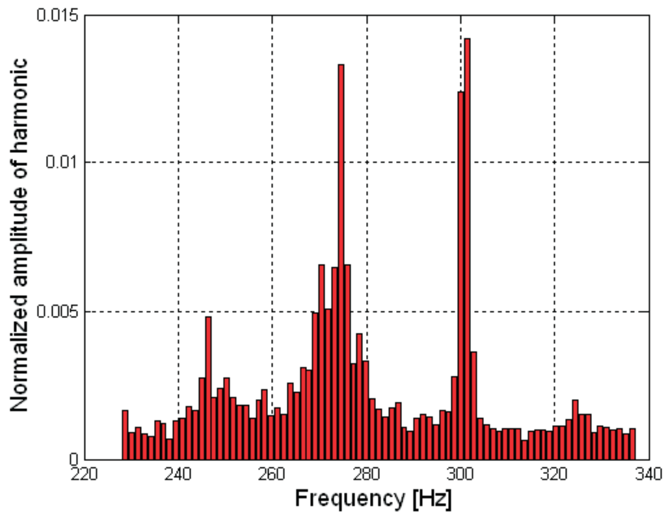

Fig. 4. Frequency spectrum of sound of induction motor with faulty ring of squirrel-cage with the band-pass filter which passes frequencies 227-337 Hz

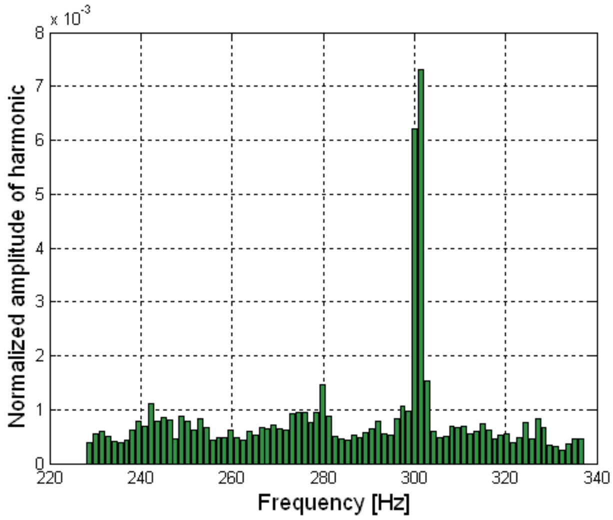

Fig. 5. Frequency spectrum of sound of induction motor with one faulty bar with the band-pass filter which passes frequencies 227-337 Hz

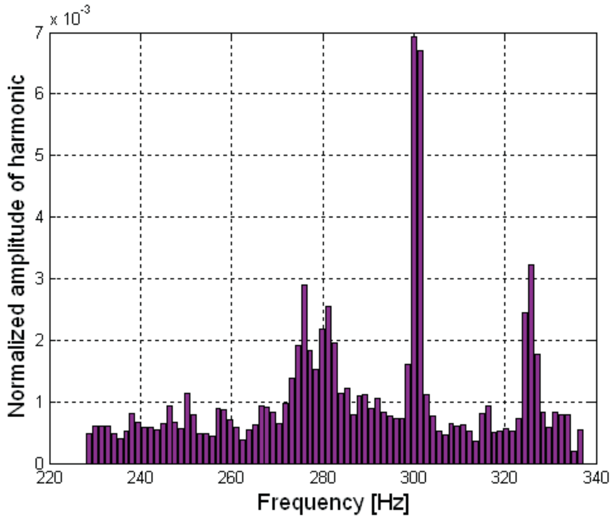

Fig. 6. Frequency spectrum of sound of induction motor with two faulty bars with the band-pass filter which passes frequencies 227-337 Hz

It is applied instead of Discrete Fourier Transform because of shorter time of calculations. It takes a window of size 2^k and returns a complex array of coefficients (harmonics). These coefficients create feature vectors which are used in calculations (Fig. 3, 4, 5, 6).

3.2. Classifier based on words

In the literature there are many methods of classification [38], [39]. Classifier based on words uses word vectors to identify the type of acoustic signal. Pattern is a vector of features $x = [x_1, x_2, \ldots, x_n]$. Classes of patterns are denoted as $w_1, w_2, \ldots w_M$, where M is the index number of the class. Training set is obtained during pattern creation process. Training set contains averaged feature vectors $m_1, m_2, \ldots, m_j$ (1),

$$m_j = \frac{1}{P_j} \sum_{x \in w_j} x_j \tag{1}$$

where P_j is the number of patterns from class w_j.

Averaged feature vector m_j is converted into averaged word vector v_j. Averaged word vector is denoted as: $v_j = [v_1, v_2, \ldots, v_n]$, where $v_1, v_2, \ldots, v_n$ are coordinates (words). Averaged word vector corresponds to the category of recognition.

Each coordinate m_i of averaged feature vector m_j is converted into coordinate of averaged word vector v_j (coordinate is a word which represents a range of values),

$$\begin{gathered} m_i \in < k, 2k) \Rightarrow m_i \rightarrow v_{i1} \\ m_i \in < 2k, 3k) \Rightarrow m_i \rightarrow v_{i2} \ldots \\ m_i \in < kg, kg + k) \Rightarrow m_i \rightarrow v_{ig} \end{gathered} \tag{2}$$

where k is rational number, g is the number of words, v_{ig} denotes word, m_i is coordinate of averaged feature vector.

Classifier based on words uses various ranges containing the coordinates of averaged feature vectors. Classifier uses a limited number of words $v_{i1}, v_{i2}, \ldots, v_{ig}$. Subsequently the parameter k should be chosen so as to obtain high accuracy.

New word vector is denoted as $f = [f_1, f_2, \ldots, f_n]$, where $f_1, f_2, \ldots, f_n$ are coordinates (words). In identification process a new sample is converted into new feature vector x. Next feature vector x is converted into word vector f,

$$x_i \in < k, 2k) \Rightarrow x_i \rightarrow f_{i1} \tag{3}$$

where k is rational number, g is the number of words, f_{ig} denotes word, x_i is coordinate of new feature vector.

Subsequently sample is assigned to the class whose averaged word vector is the closest to the new word vector f. Classifier uses lexicographical comparison. Two strings are compared with each other (coordinate of averaged word vector and coordinate of new word vector).This can be presented as follows:

$$\begin{gathered} f_1 \stackrel{?}{=} v_1 \\ f_2 \stackrel{?}{=} v_2 \\ \ldots \\ f_n \stackrel{?}{=} v_n \end{gathered}$$

The result of each comparison is either true or false. Following formula is presented:

$$U_j = 100\% * U_1/U_2 \tag{4}$$

Where U_1 is the number of correctly compared words, U_2 is the number of all comparisons, U_j is a number representing the percentage of well-recognized words. Finally the following formula is obtained:

$$U_j = \max_i(U_i) \Rightarrow f \to w_j \tag{5}$$

where i=1,2,..., M, j=1,2,..., M, f is word vector, U_i, U_j are numbers representing the percentage of well-recognized words.

The biggest influence on sound recognition results using the classifier based on words will have the data contained in the feature vector and parameter k. Research will be conducted for different parameter k.

4. Results of sound recognition

Research were carried out for four induction motor with power $P_N = 500$W. Categories of sound include: sound of faultless induction motor, sound of induction motor with faulty ring of squirrel-cage, sound of induction motor with one faulty bar, sound of induction motor with two faulty bars.

Moreover, power supply was 220V, $n_N = 1400$ rpm. Pattern creation process was carried out for 25 five-second samples for each category. New samples were used in the identification process. 25 five-second samples, 31 four-second samples, 41 three-second samples, 62 two-second samples, 125 one-second samples were used for each category. The system should determine the state of induction motor. Efficiency of sound recognition is defined as:

$$E = \frac{N_1}{N} \tag{6}$$

where: E – sound recognition efficiency, N_1 – number of correctly identified samples, N – number of all samples.

Efficiency of sound recognition of induction motor depending on length of sample is presented in Fig. 7.

The best recognition results were obtained using the normalization of the amplitude and the digital filter which passed frequencies from 227 Hz to 335 Hz. Parameter k was 0.0015.

Efficiency of sound recognition of faultless induction motor was 85.6-100%. Efficiency of sound recognition of induction motor with faulty ring of squirrel-cage was 60.8-96%. Efficiency of sound recognition of induction motor with one faulty bar was 96.8-100%. Efficiency of sound recognition of induction motor with two faulty bars was 74.19-96%.

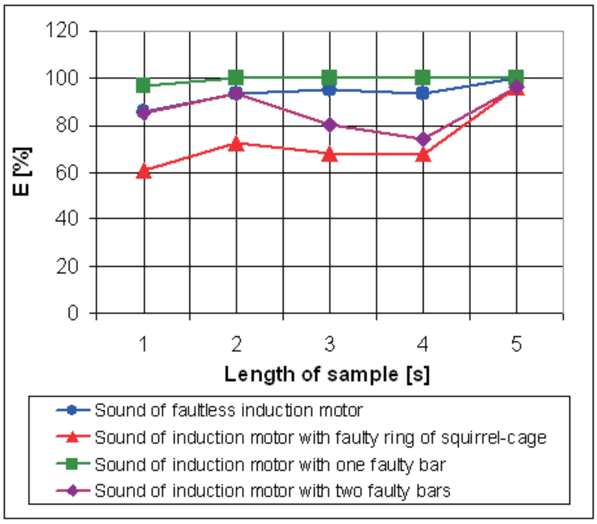

Fig. 7. Efficiency of sound recognition of induction motor with the band-pass filter which passes frequencies 227-337 Hz depending on length of sample

5. Conclusions

Sound recognition system was implemented for induction motor. Results of sound recognition were very good for FFT and classifier based on words. Sound recognition efficiency of induction motor was 96-100% for five-second samples.

Time of performance of identification process of five-second sample was 2.813 s. for Intel Pentium M 730 processor (normalization of amplitude, digital filter, FFT, classifier based on words). Time of performance of identification process of one-second sample was 2.453 s. Sound recognition system can be useful for protecting the engines and metallurgical equipment. System can be useful in inspection of metallurgical products.

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