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DIAGNOSTICS OF DIRECT CURRENT MACHINE BASED ON ANALYSIS OF ACOUSTIC SIGNALS WITH THE USE OF SYMLET WAVELET TRANSFORM AND MODIFIED CLASSIFIER BASED ON WORDS

DIAGNOSTYKA MASZYNY PRĄDU STAŁEGO OPARTA NA ANALIZIE SYGNAŁÓW AKUSTYCZNYCH Z ZASTOSOWANIEM TRANSFORMACJI FALKOWEJ SYMLET I ZMODYFIKOWANEGO KLASYFIKATORA OPARTEGO NA SŁOWACH*

In the paper author proposed an original approach for detection and localization of faults occurring in Direct Current machine. A system for diagnosing DC machines was described. The system performed an analysis of the acoustic signals of DC machine. Researches were conducted for two states of Direct Current machines. The studies were conducted for the algorithms of data processing: Symlet wavelet transform and modified classifier based on words. A pattern creation process has been carried out for the 10 sound samples. An identification process has been carried out for the 40 sound samples. The described implementation of the system may be useful for protecting machines. Moreover, this approach will reduce the cost of maintenance and the number of damaged machines.

Keywords: *Maintenance, recognition, acoustic signals, Direct Current machine, wavelet.*

W pracy autor zaproponował oryginalne podejście do wykrywania, lokalizacji usterek występujących w maszynie prądu stałego. Opisano implementację systemu do diagnostyki maszyn prądu stałego. System przeprowadzał analizę sygnałów akustycznych maszyny prądu stałego. Przeprowadzono badania dla dwóch stanów maszyny prądu stałego. Badania zostały przeprowadzone dla algorytmów przetwarzania danych: Transformacji falkowej Symlet i zmodyfikowanego klasyfikatora opartego na słowach. Proces tworzenia wzorca do rozpoznawania został przeprowadzony dla 10 próbek dźwięku. Proces identyfikacji został przeprowadzony dla 40 próbek dźwięku. Opisana implementacja systemu może być przydatna do ochrony maszyn. Ponadto podejście takie pozwoli zmniejszyć koszty utrzymania i liczbę uszkodzonych maszyn.

Słowa kluczowe: *Eksploatacja, rozpoznawanie, sygnały akustyczne, maszyna prądu stałego, falka.*

1. Introduction

The analysis of electrical machines is important in terms of the cost of maintenance. The recognition of faults of electric machines is important for diagnosis. The design of electrical machines becomes complex because the fast progress being made in technology. Early fault condition monitoring must become more advanced in order to cope with new problems. Sometimes faults do occur and the machine fails in service. In this case the result is the loss of production and revenue. In other case accidents for the industrial process are very dangerous to the operators. The problems of early fault condition monitoring are following: ageing machines, high-reliability requirements, cost competitiveness [29].

Mechanical, electrical and magnetic properties of materials were described in the literature [1, 11, 14, 15, 21, 23, 26, 34, 37, 39, 40]. Researches of properties of materials are very important for the diagnostics because operators can predict how long the machine will be operating. Diagnostics is particularly important for metallurgy, mining, and processing industry.

Diagnostics of machines deals with finding faults arising in machines. It is used for rotating machines. These machines are often used in industry for example in power plants. To identify the most probable faults, many methods using different diagnostic signals. The main methods of early fault diagnostics of machines are based on the study of: magnetic field, ultrasounds, electric signals, acoustic signals, vibroacoustic signals.

In the literature, popular methods are based on a study of electrical, and acoustic signals [6–10, 12–14, 22, 28, 41]. In this paper, research focuses on acoustic signals of DC machine. The results of these studies can be used to improve diagnostics of various electrical machines. Proposed approach will reduce costs of maintenance and the number of faulty motors.

2. The process of sound recognition of Direct Current machine

The process of sound recognition of DC machine contains the pattern creation process and the identification process. The pattern creation process starts with recording of acoustic signals. After that data contained in the soundtrack are divided.

Next obtained data are normalized. Afterwards digital signals are converted through the Wavelet Transform. This transform uses a symmetric wavelet – Symlet. This method decomposes original time series into a number of different sub-series (depending on level of decomposition). In the pattern creation process two words vectors are created (Fig. 1).

Steps of the identification process are very similar to steps of the pattern creation process. The difference is in the classification step. The words vector of specific class is compared with the new words vector. Analyzed sample of sound is assigned to the class whose words vector is the closest to the new words vector.

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl***

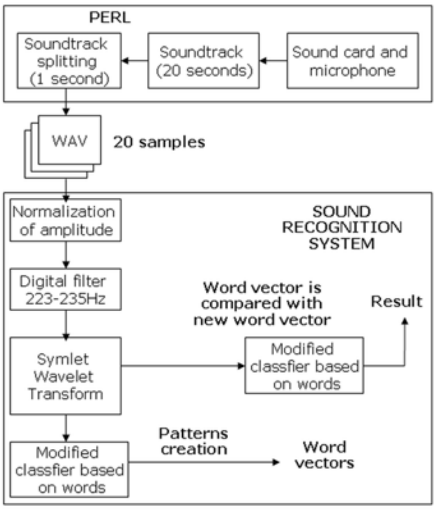

Fig. 1. The process of sound recognition of DC machine with the use of Symlet Wavelet Transform and modified classifier based on words

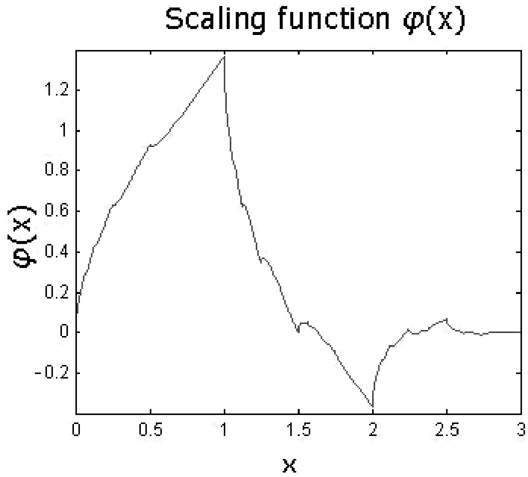

Fig. 2. Scaling function of Symlet Wavelet (sym2)

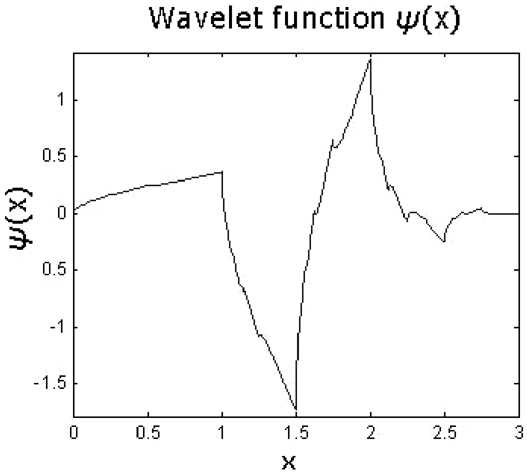

Fig. 3. Wavelet function of Symlet Wavelet (sym2)

2.1. Symlet Wavelet Transform

The Daubechies family of wavelets is one of the orthogonal wavelet families. It was formulated by the Belgian mathematician Ingrid Daubechies in 1988. The wavelet "Daubechies 1" is the same as Haar wavelet. The construction of Symlets wavelet bases is similar to the construction of Daubechies wavelet bases. Symlets wavelets are symmetric. The Daubechies wavelets have maximal phase, whereas the Symlets have minimal phase [36].

Symlet wavelet (sym2) has been applied for sound recognition system (Fig. 2, 3). The filters coefficients corresponding to this wavelet type are shown in Tables 1 and 2.

Table 1. Decomposition filters of Sym2 wavelet

Decomposition Low-pass filter	Decomposition High-pass filter
-0.1294	-0.4830
0.2241	0.8365
0.8365	-0.2241
0.4830	-0.1294

Table 2. Reconstruction filters of Sym2 wavelet

Reconstruction Low-pass filter	Reconstruction High-pass filter
0.4830	-0.1294
0.8365	-0.2241
0.2241	0.8365
-0.1294	-0.4830

The wavelet transform of an acoustic signal is calculated by passing it through a series of filters: low-pass filter and high-pass filter [20, 25]. Sound recognition system obtains detail coefficients ($\mathbf{d_1}$, $\mathbf{d_2}$, $\mathbf{d_3}$,…, $\mathbf{d_n}$) from the high-pass filter and approximation coefficients ($\mathbf{a_1}$, $\mathbf{a_2}$, $\mathbf{a_3}$,…, $\mathbf{a_n}$) from the low-pass, where n is the level of decomposition (Fig. 4).

The vectors $\mathbf{d_1}$,…, $\mathbf{d_n}$ are essential in the process of sound recognition of DC machine (Fig. 5, 6). The absolute values of the coordinates of the vectors $\mathbf{d_1}$,…, $\mathbf{d_n}$ are used in the classification.

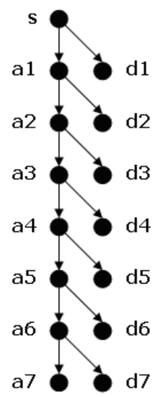

Fig. 4. Detail coefficients and approximation coefficients of 7-th level of decomposition

2.2. Modified classifier based on words

In the literature, a large number of classification methods were described [2–5, 16–19, 24, 27, 30–33, 35, 38]. Modified classifier based on words uses words vectors to identify the type of acoustic signal. Normal classifier based on words is similar to the Nearest Mean classifier. Modified classifier based on words is similar to the Nearest Neighbor classifier. This similarity is that the feature vectors and the words vectors are compared with each other in the same way. Coordinates x_1, x_2,…, x_n of feature vector $\mathbf{x}$ create a pattern. Classes of

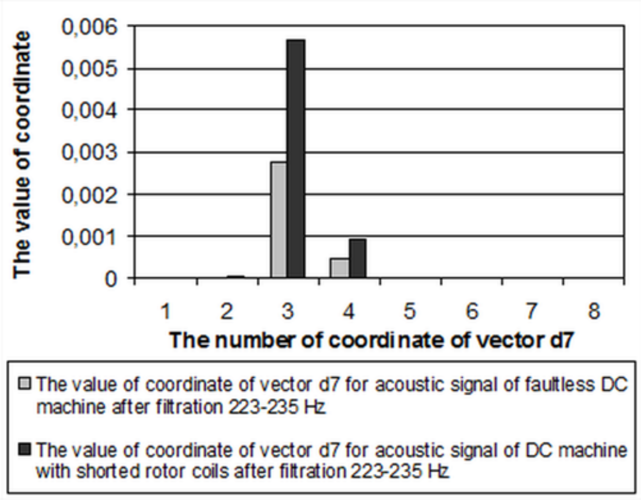

Fig. 5. Detail coefficients of DC machine after filtration 223-235 Hz (sym2 wavelet)

patterns $w_1, w_2, \ldots, w_j$ are related with feature vectors **x**. Training set is used in the pattern creation process. Training set contains processed sound samples - feature vectors $\mathbf{x_1}, \mathbf{x_2}, \ldots, \mathbf{x_j}$. Next, each feature vector $\mathbf{x_j}$ is converted into the words vector $\mathbf{v_j}$. The words vector can be defined as follows: $\mathbf{v_j}=[v_1, v_2, \ldots, v_n]$, where $v_1, v_2, \ldots, v_n$ are words. Each class of patterns is represented by words vectors. The number of patterns is equal to the number of words vectors in the pattern creation process. Coordinates $x_1 \ldots x_i$ of the feature vector $\mathbf{x_j}$ are converted into coordinates $v_{i1} \ldots v_{ig}$ of the words vector $\mathbf{v_j}$. A range of values is represented by a word,

$$\begin{cases} x_i \in [k, 2k) \Rightarrow x_i \to v_{i1} \\ x_i \in [2k, 3k) \Rightarrow x_i \to v_{i2} \\ \ldots \\ x_i \in [kg, kg+k) \Rightarrow x_i \to v_{ig} \end{cases} \tag{1}$$

where g is the number of words, k is rational number, x_i is coordinate of the feature vector, $v_{i1} \ldots v_{ig}$ denote words.

Modified classifier based on words uses selected ranges of values. Next it uses the values of coordinates of the feature vectors. Proposed classifier is based on 260 words, because this number of words is sufficient enough for recognition. After that the parameter k is selected. A new words vector can be defined as $\mathbf{f}=[f_1, f_2, \ldots, f_n]$, where $f_1, f_2, \ldots, f_n$ are words. The identification process uses a new test sample of sound. This sample is converted into the new feature vector **y**. This vector **y** is converted into the words vector **f**,

$$\begin{cases} y_i \in [k, 2k) \Rightarrow y_i \to v_{i1} \\ y_i \in [2k, 3k) \Rightarrow y_i \to v_{i2} \\ \ldots \\ y_i \in [kg, kg+k) \Rightarrow y_i \to v_{ig} \end{cases} \tag{2}$$

where g is the number of words, k is rational number, y_i is coordinate of the new feature vector, $v_{i1} \ldots v_{ig}$ denote words.

After that the test sample is assigned to the class whose words vector is the closest to the words vector of analyzed sample. Lexicographical comparison is used to compare two strings of words. The first string contains coordinates of the words vector of specific class. The second string contains coordinates of the new words vector of the analyzed sample. This can be presented as follows: $f_1=v_1; f_2=v_2; \ldots; f_n=v_n$. The result of comparison is binary (*true* or *false*). The final binary result is used in following equation:

$$U_j = \frac{U_1}{U_2} \cdot 100\%, \tag{3}$$

$$\max(U_j) \Rightarrow \mathbf{f} \to w_j \qquad j = 1, 2, \ldots, \mathrm{M}, \tag{4}$$

where U_j is the percentage number of well-recognized words, U_1 is the number of *true* results, U_2 is the number of all comparisons, **f** is the new words vector of the analyzed sample.

Sound recognition results depends on the data contained in the feature vector. These results also depends on parameter k. This parameter will be selected in the researches.

3. The results of sound recognition

The OLYMPUS TP-7 microphone and Realtek sound card were used to record acoustic signals. Parameters of audio file were: sampling frequency – 44100 Hz, the number of bits – 16, the number of channels – 1, format – WAVE PCM. Operation parameters of DC machine were following: P_N = 13 kW, U_N = 75 V, I_N = 200 A, U_{fN} = 220 V, I_{fN} = 4 A, n_N = 700 rpm. Each group of three loops rotor coils was shorted with the help of resistance R_{bz} = 7.7 mΩ. This resistance was external resistance. It was connected with DC machine. It was used to avoid damage of rotor windings. Investigations were carried out for two acoustic signals of Direct Current machines: acoustic signal of faultless DC machine and acoustic signal of DC machine with shorted rotor coils (Fig. 6).

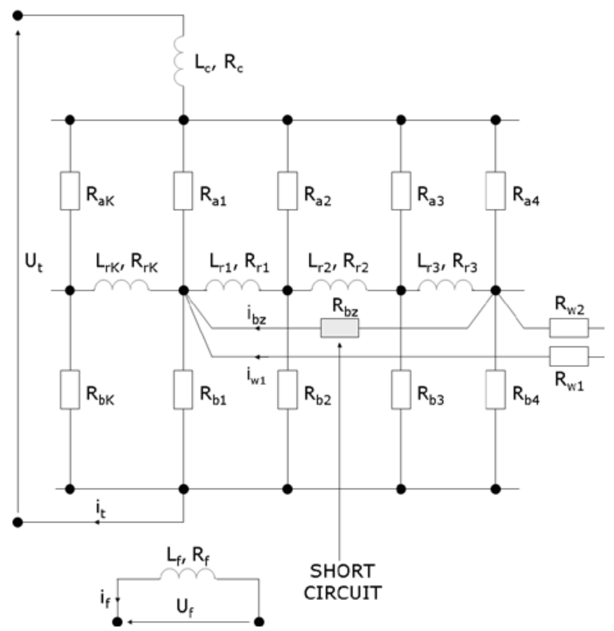

Fig. 6. Scheme of rotor winding of DC machine with shorted coils

10 training samples with a duration of one second were used in the pattern creation process for each type of signal. 40 test samples with a duration of one second were used in the identification process. Efficiency of sound recognition was expressed by following formula:

$$E = \frac{NCRTS}{NATS} 100\% \tag{5}$$

where: *NCRTS* – number of correctly recognized test samples, *NATS* – number of all test samples, *E* – efficiency of sound recognition.

The best recognition results were obtained using the normalization of the amplitude and the digital filter which passed frequencies from 223 Hz to 235 Hz. This frequency was associated with the rotation of the rotor $f_c=4Xn_N$ Hz, where X is a multiple of the frequency. When X=5, the frequency f_c=(20)(700/60) =233.33 Hz was contained in the frequency range from 223 Hz to 235 Hz. Lower limit of the filter 223 Hz was selected for the case of decreasing of the rotor speed. Efficiency of sound recognition of faultless DC machine was 55-95%. Efficiency of sound recognition of DC machine with shorted rotor coils was 65-85%. Efficiency of sound recognition of DC machine depending on parameter *k* was shown in the figure 7. The results were the best when parameter *k* was equal to 0.0004.

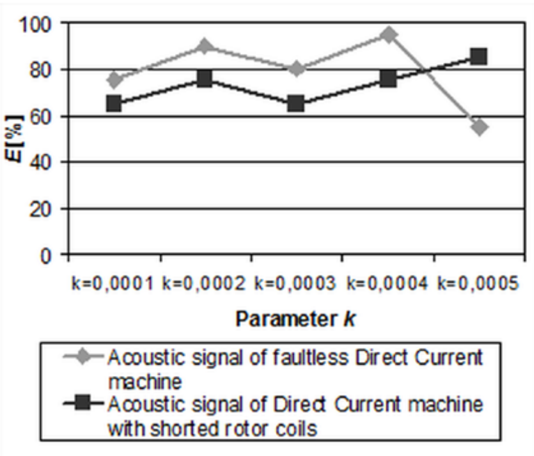

Fig. 7. Efficiency of sound recognition of DC machine depending on parameter k

4. Conclusions

In the paper author proposed an original approach for detection and localization of faults occurring in Direct Current machine. The implementation of diagnostic system for Direct Current machine was described. Acoustic signals were analyzed by the sound recognition system. Algorithms of data processing were investigated for DC machine. The results of sound recognition were good for Symlet wavelet transform and modified classifier based on words. Efficiency of sound recognition of DC machine was 55–95%. The described implementation of the system can be profitable for protection of the machines.

Diagnostics can be more efficient when various techniques of diagnostics will work together, such as recognition of thermal images, acoustic signals, electric signals of machines. Moreover, this approach will reduce costs of maintenance and the number of damaged machines.

Acknowledgments

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