Rev. Roum. Sci. Techn.– Électrotechn. et Énerg.
Vol. **68**, *4*, pp. 357–362, Bucarest, 2023

USING DISCRETE WAVELET ANALYSIS OF VIBRATION SIGNAL FOR DETECTION OF ELECTRICAL MACHINES' DEFECTS

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Keywords: Technical condition; Diagnostics; Electric machine; Defect; Wavelet transform.

The paper proposes a method for establishing the presence of several of the most common defects of rotating electric machines of alternating current using discrete wavelet transform of their vibration signal. It is shown that discrete wavelet transform is one of the most effective methods of pre-processing vibration signals formed from the operation of rotating electric machines. The choice of optimal maternal wavelet functions for each of the considered defects according to the sensitivity parameter is theoretically substantiated, and frequency bands are determined, which should be analyzed for their detection analysis of wavelet transform coefficients. The adequacy of the theoretical conclusions is experimentally confirmed.

1. INTRODUCTION

The technical development of industrial production in general, and automated electric drive in particular, leads to a constant expansion of the scope of rotating electric machines. The consequence of this process is an increase in the complexity, cost, and efficiency of technological equipment and, consequently, the growth of potential losses, accompanied by its accidental failure during operation [1].

Another trend in the industrial development of Ukraine and most of the world's industrialized countries is the increase in electrical equipment (primarily high capacity), which has served its nominal service life. In most industrialized countries at the beginning of the 21st century, the share of such equipment operated at nuclear power plants, thermal power plants, hydropower plants, and hydro storage power plants exceeded 50% [2].

Since there is an inversely proportional relationship between the reliability and operating time of rotating electric machines [1,3], a logical and obvious consequence is the growing relevance of building highly efficient systems for diagnosing them. Since the creation of such systems is primarily limited by the lack of highly informative criteria that would establish the presence of typical equipment defects in the early stages of their formation without the need to intervene in the structure of electric machines [1,3], the development of the latter is a relevant new scientific and applied task that has significant practical value.

2. SETTING THE TASK

The work aims to increase the probability of diagnosing rotating electric machines by developing highly informative criteria characterized by high sensitivity to typical defects, including in the early stages of their formation.

According to the specified purpose of work, tasks are solved:

1. Establishment of the type and amount of measuring information necessary to detect the presence of typical defects of the electric machine, theoretical justification of its sufficiency.
2. The choice and theoretical justification of the primary measurement information pre-processing method.
3. Development of highly informative criteria that would have a high sensitivity to the presence of typical defects of rotating electric machines.
4. Experimental confirmation of the adequacy of the theoretical conclusions.

3. ANALYZING THE WAYS TO SOLVE THE PROBLEM

As of today, a steady trend has been established towards constructing systems for technical control and diagnostics of rotating electric machines based on analysis of their vibration characteristics. This is due to their high sensitivity, information content, and ability to measure this parameter directly in the electric machines' operation mode without significant structural intervention [4,5].

However, the informativeness of the radial vibration signal at this stage of the development of its analysis methods remains a factor that limits the maximum probability of detecting defects in rotating electrical machines. Work [6] shows that the theoretical possibility of detecting some defects of electric machines using only a vibration signal does not exceed 30 %, and the possibility of establishing their location is 25 %. Other authors also come to a similar conclusion about limited informativeness [7–9]. This can be confirmed using combined input signals in diagnostic systems developed by leading global manufacturers, like VIMOS (Swedish branch of ABB company), MCM (German Brüel & Kjær Vibro representative office), ZOOM (VibroSystM Inc., Canada), *etc*.

In addition, implementation of such analysis requires the solution of several scientific and applied problems arising from peculiarities of the vibration signal generated during the operation of rotating electrical machines. Such signal contains periodic components of different frequencies and aperiodic (peak) components due to defects of different nature and other periodic and aperiodic disturbing forces [10,11].

Among the existing sufficiently described and studied approaches suitable for analysis of the temporal realization of vibration signal that can be obtained during the operation of the real electric machine, we can distinguish Fourier transformation and Discrete Wavelet Transformation (DWT). It should be noted that Fourier Transformation is mathematically more complex than DWT. Therefore, at the same speed, it will require higher hardware costs without providing the opportunity to study localized perturbations in general [12]. These features make it inefficient for modern systems of analysis of electric machines' vibration signals. While DWT, being primarily adapted to the detection of localized peak disturbances, does not provide for the presence of ready-made tools designed for the separation of periodic and aperiodic components.

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DOI: 10.59277/RRST-EE.2023.68.4.6

According to a statistical study of causes for the failure of asynchronous motors (being the most common type of rotating electric machines), it was found that in 79 % of cases when the latter failed, one of three types of technological parameters' abnormal deviations occurred, and namely: rotor's mechanical imbalance, bearings' damage, or current asymmetry in the stator circuit [13]. That said, the resulting vibration signal at the early stages of defects' development is normally characterized by the imposition of a significant number of equivalent disturbing factors, some of them being aperiodic [10,11,14].

The peculiarity of vibration signals conditioned by these defects lies in their quasi-periodic nature [10,11,14]. This leads to the fact that during standard Wavelet Analysis, the presence of such defects at the early stages of their development does not lead to a local increase in the amplitude of individual DWT ratios and, therefore, will be hardly noticeable in the analysis of transformation results.

One of the main ideas of signals' Wavelet Representation at different levels of signal decomposition is to divide the functions of approximation to signal into two groups: the one that approximates – a rough one, with rather slow temporal dynamics of change, and a detailed one – with local and rapid change dynamics against the background of smooth dynamics followed by their fragmentation and detailization at other levels of signal decomposition. This is possible in both temporal and frequency domains of Wavelet Signals. Such being the case, the baseline wavelet function allows focusing on certain local features of the processes being analyzed. That said, in its essence, the detailization of continuous wavelet transformation (CWT) is nothing more than the definition of the function of the correlation between the parent wavelet function and the studied signal, which follows from the mathematical model of such transformation [12,15]:

$$W(a,\tau) = \int_{-\infty}^{+\infty} f(t) \cdot \psi_{a,\tau}^{*}(t) \mathrm{d}t, \quad (1)$$

where $W(a,\tau)$ is the detailization function (the result of wavelet transformation); a is the scale parameter; τ is the offset parameter; $f(t)$ is the Function being analyzed and is the wavelet function conjugated in a complex manner.

Given that calculations during wavelet transformation are made by changing the scale of the analysis "window", its temporal shift, multiplication by the signal, and integration along the entire time axis [15,16], the geometric content of such transformation may be represented as the search for sections of analyzed function in temporal and frequency domains, which in their form will be correlated with parent wavelet function.

Similar physical content is preserved in DWT, in implementation of which the detailization ratios may be calculated as follows [12, 16]:

$$d_k^j = \sum_{n \in Z} g_{n-2k} \cdot c_n^{j+1}, \quad (2)$$

where is the k-th detailization ratio of the j-th frequency band; g is the ratio of parent Wavelet Function; c^{j+1} is the approximating ratio of the previous frequency band to be calculated as follows:

$$c_k^j = \sum_{n \in Z} h_{n-2k} \cdot c_n^{j+1}, \quad (3)$$

where h is the coefficient of the scaling function; for a higher frequency band, the temporal realization of the studied signal is used as an approximating ratio.

Such being the case, the problem of these defects' recording may be divided into two subtasks: parent wavelet selection, which would be as close as possible to the vibration signal's defect-conditioned component, and development of the criterion that would allow quantifying the impact of defect-induced oscillation on Wavelet Transformation ratios of separate Frequency Bands and would be characterized by a high selectivity towards the same.

The analysis of literary descriptions of vibration signals conditioned by rotor unbalance shows that this defect leads to oscillations containing a harmonic component localized at rotor frequency and its second and third harmonics. That said, the amplitude of oscillations with transition to the second and third harmonic components decreases sharply [10,11]. This fact determines the feasibility of analysis in its search for the frequency range that includes the rotor speed and, to a lesser extent, the Frequency Ranges that correspond to doubled and tripled rotor frequencies. At the same time, the selection of the parent wavelet should be based on the characteristics of a single harmonic oscillation. According to the study of literary sources, the 4th-order Haar wavelet and Daubechies wavelet may be considered the most related to single harmonic oscillation among typical parent Wavelet Functions. It should be noted that each of them has significant differences in terms of its structure [12,16,17].

Besides, given the periodicity of the vibration signal conditioned by the presence of rotor unbalance, as well as the fact that each of the harmonic oscillations was represented as a separate outburst during the study, we should expect periodic alterations in Wavelet Ratios in the time domain within Frequency Bands, as well as its second and third harmonics. That said, the amplitudes of such periodic changes will be directly related to the degree of defect development. Therefore, when realizing the following inequality:

$$t_{cn} >> T_p, \quad (4)$$

where t_{cn} is the duration of temporal realization of the studied signal; T_p is the period of rotation of the electric machine's rotor. Applying the integrated approach to the analysis of Wavelet Transformation ratios is advisable. Therefore, an averaged numerical square value of Wavelet Ratios of studied Frequency Bands within the time interval, the duration of which is much longer than the period of rotor rotation, may be used as a required numerical criterion for this defect's presence. This approach will allow us to consider the presence of both positive and negative maxima of Wavelet Ratios within the studied time interval. It will be characterized by reduced sensitivity to non-informative disturbances caused by aperiodic disturbing forces that may occur during the operation of the electric machine. Based on the above, in mathematical terms, the numerical criterion for assessment of rotor imbalance impact on Wavelet Transformation ratios of the said frequency bands may be represented as follows [18]

$$k_{\partial e б} = \frac{1}{n}\sum_{i=1}^{n} d_i^2 \ \text{ for } t_{cn} \gg T_p, \quad (5)$$

where n is the number of wavelet transformation ratios of the studied frequency band, and d_i is the i-th wavelet transformation ratio.

To confirm the above theoretical considerations, an experimental study was performed using an electric machine in idle mode with rotor inertia of 0.002 kg·m^2, idle speed of 720 rpm/min (12 Hz), and an additional imbalance of 0.002 kg·m. Piezo accelerometer was mounted on the body of the electric machine in such a way that the measuring axis was directed strictly perpendicular to the rotor of the electric machine. The signal sampling frequency was 232 Hz, the length of the studied signal's time realization being 214 values. The block diagram and photo of the experimental workbench are shown in Figs. 1 and 2.

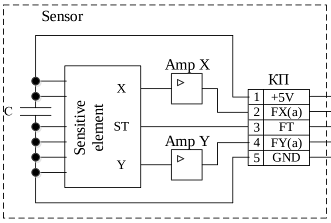

Fig. 1 – Block diagram of the experimental workbench.

Fig. 2 – Photo of the experimental workbench.

The following results were obtained when converting the obtained vibration acceleration signal using the Haar wavelet and subsequent calculation of the proposed numerical criterion for each frequency band with and without unbalance, as shown in Figs. 3 and 4 below.

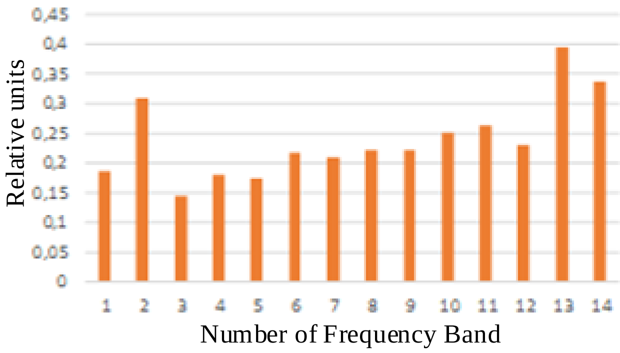

Fig. 3 – Dependence of the mean quadratic wavelet Haar ratios for vibration signal in each frequency band without using the unbalanced.

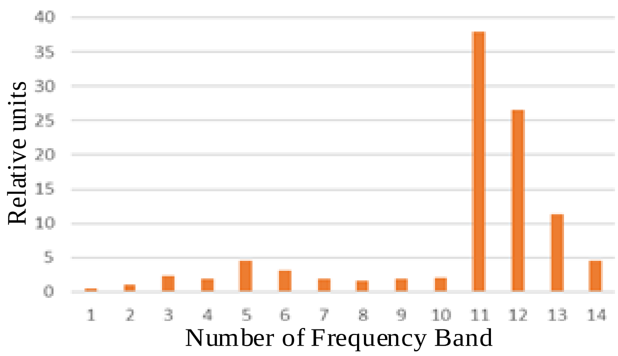

Fig. 4 – Dependence of the mean quadratic wavelet Haar ratios for vibration signal in each frequency band in unbalance.

A similar transformation was also performed using the 4th-order Daubechies wavelet. Calculation results are shown in Figs. 5 and 6.

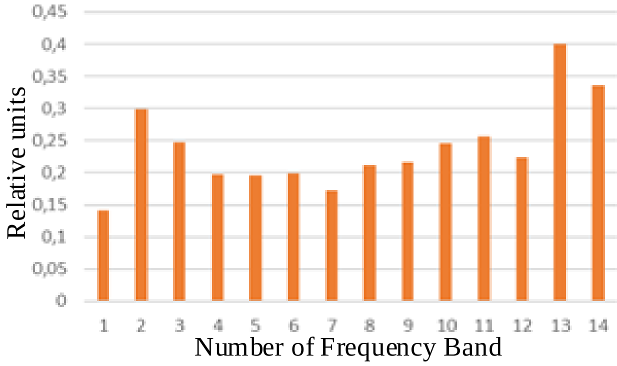

Fig. 5 – Dependence of the 4th order mean quadratic wavelet Daubechies ratios for vibration signal in each frequency band without using unbalance.

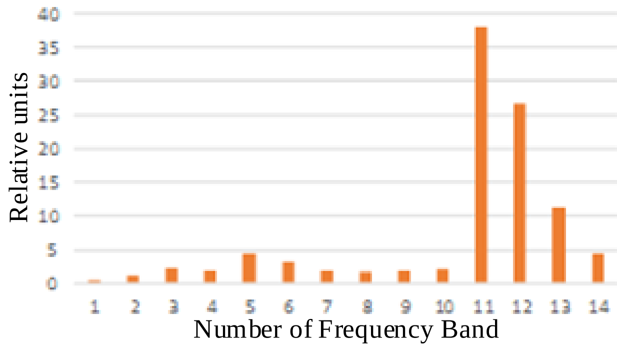

Fig. 6 – Dependence of the 4th-order mean quadratic wavelet Daubechies ratios for vibration signal in each frequency band in the presence of imbalance.

It is clear from Figs. 3 to 6 that the frequency bands corresponding to the electric machine's rotor speed and its second and third harmonics (frequency bands 11, 12, and 13, respectively) are, as expected, the most informative ones for rotor unbalance detection. comparison of the results obtained by decomposition of the signal based on Haar wavelet and Daubechies wavelet of the 4th order showed that both wavelets are characterized by approximately the same, sufficiently high sensitivity to the presence of a studied defect. therefore, given that transformation based on the parent Haar wavelet function is mathematically simpler (requires fewer mathematical operations) [12,16,17], we can conclude that using the latter is more effective for detecting this defect.

Analyzing literary descriptions of vibration signals conditioned by damage to the rotating electric machine's bearings, it was found that this group of defects causes a rather complex quasi-periodic vibration response corresponding to the electric machine's rotor frequency [10,11,14]. Given that vibration response conditioned by bearing damage will be characterized by several peaks within one period, it would be appropriate to use parent wavelet functions of higher order to detect such damage. This may be because its oscillations typically increase with the parent wavelet function order increase. Therefore, expression [12, 15–18] will be valid for the N-th order wavelet function:

$$\int_{-\infty}^{+\infty} t^k \psi(t) \mathrm{d}t = 0, \;\; k = 0,1 \dots N-1. \qquad (6)$$

Since the calculation of ratios of most of the discrete wavelet functions is quite time-consuming [12,16,19], and the form of vibration response in bearing damage is characterized by a rather complex structure that is surely not associated with any known wavelets, the use of Daubechies wavelets is recommended as basic wavelet functions. the main advantage of this wavelet function family lies in the possibility of relatively simple analytical calculation of their ratios for arbitrary order functions [20,21]. Such being the case, the mathematical numerical criterion for estimating bearing defects' effect on frequency bands' wavelet transformation ratios will be like the criterion for rotor unbalance presence (5), provided that these parent wavelet functions are used.

To confirm the above theoretical considerations, an experimental study was conducted using AIM90La6U2.5 asynchronous electric machine with a rated power of 0.75 kW and synchronous rotation speed of 1000 rpm (16.67 Hz) during idle operation. Bearing defect was simulated by using bearings with no oil film. Other parameters of the experiment were completely like those in the study of the rotor unbalance effect described above.

When transforming the obtained vibration acceleration signal using the 4th-order Daubechies wavelet and subsequent calculation of mean-square wavelet ratios for each frequency band during the electric machine's idle operation, the results shown in Figs. 7 and 8 were obtained.

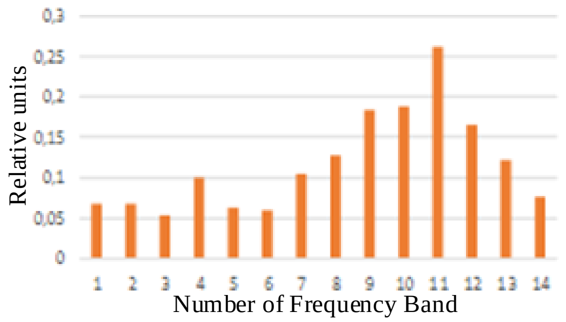

Fig. 7 – Dependence of the 4th order mean quadratic wavelet Daubechies ratios for vibration signal in each frequency band in the presence of oil in the bearing.

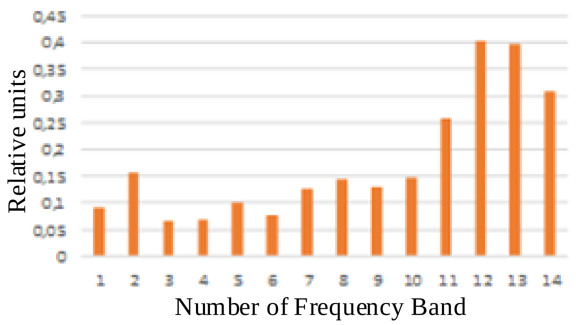

Fig. 8 – Dependence of the 4th order mean quadratic wavelet Daubechies ratios for vibration signal in each frequency band without oil in the bearing.

The obtained vibration signal was transformed similarly using the 6th-order Daubechies wavelet. Calculation results are shown in Figs. 9 and 10.

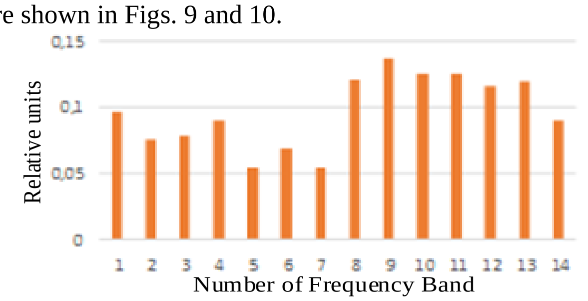

Fig. 9 – Dependence of the 6th order mean quadratic wavelet Daubechies ratios for vibration signal in each frequency band in the presence of oil in the bearing.

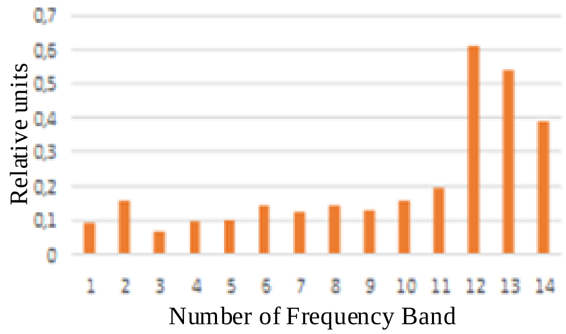

Fig. 10 – Dependence of the 4th order mean quadratic wavelet Daubechies ratios for vibration signal in each frequency band without oil in the bearing.

It is clear from Figs. 7 to 10 that the frequency band corresponds to the rotor speed (frequency band 12), with its second (frequency band 13) and third (frequency band 14) harmonics being, as expected, the most informative ones for bearing defect detection. A comparison of the results obtained during the decomposition of the 4th and 6th-order signal based on Daubechies wavelet showed the validity of previously made assumptions about the feasibility of using higher-order wavelets to detect this defect.

In turn, vibration signals conditioned by a current asymmetry in the stator circuit are characterized by the vibration signal's harmonic component localized at the electrical main's supply voltage frequency [10,11]. This fact justifies the feasibility of analyzing the Frequency Range, which includes supply voltage frequency and using the 4th-order Haar and Daubechies wavelets based on the above considerations. Such being the case, the numerical criterion for estimating the effect of the stator circuit's electromagnetic asymmetry on these frequency bands' wavelet transformation ratios may be represented as follows:

$$k_{\partial в6} = \frac{1}{n}\sum_{i=1}^{n} d_i^2 \quad \text{for } t_{сп} >> T_{жс}, \qquad (7)$$

where $T_{жс}$ is the period of the stator circuit's supply voltage.

To confirm the above theoretical considerations, an experimental study was performed using an asynchronous electric machine described in the previous experiment. Other parameters of the experiment were completely like the study of the rotor unbalance effect described above.

When transforming the obtained vibration acceleration signal using Haar wavelet and subsequent calculation of mean quadratic Wavelet Ratios for each frequency band during the electric machine's operation in normal mode and phase A break, the results shown in Figs. 11 and 12 were obtained.

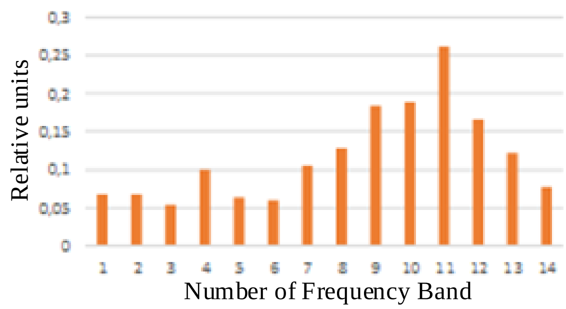

Fig. 11 – Dependence of the mean square wavelet Haar Ratios for each frequency band of the vibration signal when the motor is operating in normal mode.

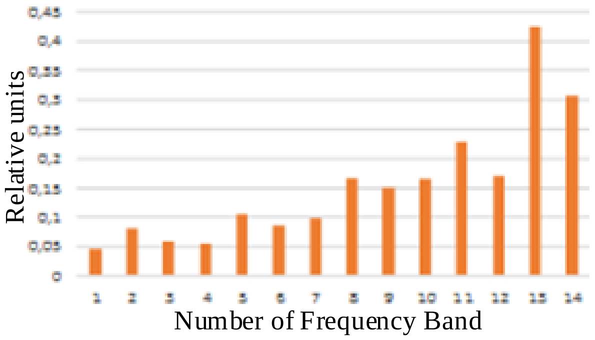

Fig. 12 – Dependence of the mean square wavelet Haar ratios for each frequency band of the vibration signal at phase "A" break.

A similar transformation of the obtained vibration signal was also performed using the 4th-order Daubechies wavelet. Calculation results are shown in Figs. 13 and Fig. 14.

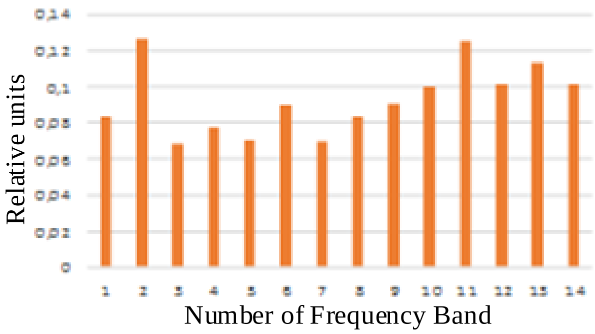

Fig. 13 – Dependence of the mean square 4th-order wavelet Daubechies ratios for each frequency band of the vibration signal when the motor is operating in normal mode.

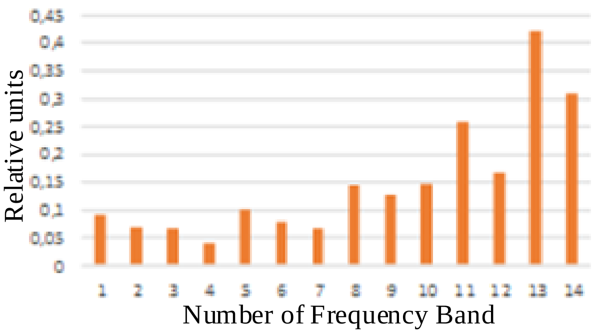

Fig. 14 – Dependence of the mean square 4th-order Wavelet Daubechies Ratios for each Frequency Band of the vibration signal at phase "A" break.

It is clear from Fig. to 14 that the frequency band corresponding to the mains supply voltage frequency of 50 Hz (frequency band 13) is, as expected, the most informative for power asymmetry detection. A comparison of the results obtained by signal decomposition based on the 4th-order Haar wavelet and Daubechies wavelet showed that both wavelets are characterized by approximately the same sufficiently high sensitivity to the presence of the studied defect. Therefore, using Haar wavelet to solve this problem is appropriate based on the above considerations.

4. CONCLUSIONS

1. It has been established that detecting mechanical rotor imbalance and stator current asymmetry using Wavelet transformation of the time-domain realization of the vibroacoustic signal is advisable to perform using the Haar mother wavelet function while bearing defects should be detected using higher-order Daubechies mother wavelet functions.

2. It is shown that when detecting rotor imbalance and bearing defects, it is expedient to analyze the behavior of wavelet coefficients of frequency bands, including rotor frequency and its second and third harmonics. when detecting current asymmetry in the stator–wavelet coefficients of the frequency band, include the frequency of the supply voltage of the electric machine.

3. Numeric criteria for assessing the defects' impact on the wavelet transformation coefficients are proposed as the root mean square value of wavelet coefficients of informative frequency bands when investigating a time interval significantly exceeding the duration of the external influencing factor. it is shown that these criteria have reduced sensitivity to the influence of non-informative single disturbances that may occur during the operation of an electric machine.

Received on 19 February 2023

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