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NON-INVASIVE DIAGNOSTICS OF THE ROTOR THE ASYNCHRONOUS MOTOR WITH USING START UP STATOR CURRENT

NIEINWAZYJNA DIAGNOSTYKA WIRNIKA SILNIKA ASYNCHRONICZNEGO Z WYKORZYSTANIEM PRĄDU ROZRUCHOWEGO STOJANA

A b s t r a c t

This article presents the idea of asynchronous motor's non-stationary stator starting current, filtration methods, in the non-invasive diagnosis of the rotor cage. The mathematical description of the selected analysis forms is omitted in favor of an indication of the practical aspects of the method application and the obtaining of sample analysis results. The object of the study was the single cage induction motor with exchangeable rotors for different faults, machine's load was a generator with field current control system, which was used to control the load torque.

Keywords: *cage damage*, *time-frequency analysis*, *start-up current*

S t r e s z c z e n i e

W artykule przedstawiono ideę metod filtracji niestacjonarnego sygnału prądu rozruchowego stojana zwartego silnika asynchronicznego w bezinwazyjnej diagnostyce klatki wirnika. Pominięto opis matematyczny wybranych form analiz na rzecz wskazania praktycznych aspektów zastosowania danej metody oraz uzyskanych przykładowych wyników analiz. Obiektem badań był silnik jednoklatkowy z wymiennymi wirnikami, o różnym stopniu uszkodzenia klatki wirnika, obciążony prądnicą obcowzbudną, gdzie poprzez zmianę prądu wzbudzenia regulowano moment mechaniczny.

Słowa kluczowe: *uszkodzenie klatki*, *analiza czasowo-częstotliwościowa*, *prąd rozruchowy*

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1. Introduction

The primary diagnostic signal in the assessment of the cage rotor windings of the asynchronous motor, based on the current waveform of the stator, is the so-called first slip component [1, 3, 6], which was established as a result of damage to the rotor cage, which is described by the following relationship:

$$f_0 = f(1-2s) \tag{1}$$

where:

f_0 – frequency of the slip component,
f – frequency of the fundamental component,
s – slip.

In the steady-state, the basic requirement for effective evaluation of the rotor cage is to operate the motor at the rated torque, this condition it is not always possible to meet. Not what otherwise looks like the possibility of diagnosis cage rotor windings based on the signal of start-up current, where the only requirement is to have only minimal motor moment of inertia. Differentiator diagnostic component is its distinctive shape during start-up, which takes the form of an inverted 'V'. At the time of the connection of the machine to the network, the slip component has a frequency equal to that of the network with the approach of the rotor speed to half speed synchronous, diagnostic signal frequency tends to zero, to again after half the frequency of the synchronous speed achieved depends on the value of slip at steady state. This means that at a certain frequency range, the diagnostic signal reaches the same frequency twice. As an indicator of the state of the rotor cage in a steady state, utilizes the difference of network component with a sliding component in decibel scale [11, 12, 14]. Exceeding value 42–45dB, means damage to the rotor windings.

The same relationship can be used to develop the diagnostic indicator in starting the asynchronous motor based on the following equation:

$$K = 20\left(\log_{10}\frac{A_0}{A} - \log_{10}\frac{A}{A}\right) = \log_{10}\left(\frac{A_0}{A}\right)^{20}$$

$$\frac{A_0}{A} = 10^{-\frac{K}{20}} \cdot 100\% \tag{2}$$

where:

A_0 – amplitude of the slip component,
A – amplitude of the fundamental component.

From the above equation, it follows that the ratio of diagnostic signal amplitude to the amplitude of the network component at the same time boot, does not exceed 0.5–0.8%.

Therefore, in the latter section of this article, an ordinate scale was adopted, as the ratio of the maximum diagnostic signal of the input signal after filtration to the network component attributable to a moment of impulse component of a slip. It should also be noted that the number of broken cage bars was not linearly dependent on the assumed rate of damage.

2. Measuring system

The object of measurement tests was the Sg-112M asynchronous motor, loaded by a DC generator. By changing the field current of the DC generator with an auto-transformer and uncontrolled rectifier, the load torque was regulated. In the laboratory, rotors with varying degrees of asymmetry were available – symmetrical and with one, two and three broken cage bars respectively. The motor was supplied with a voltage of reduced amplitude, this was in order to simulate heavy starting conditions.

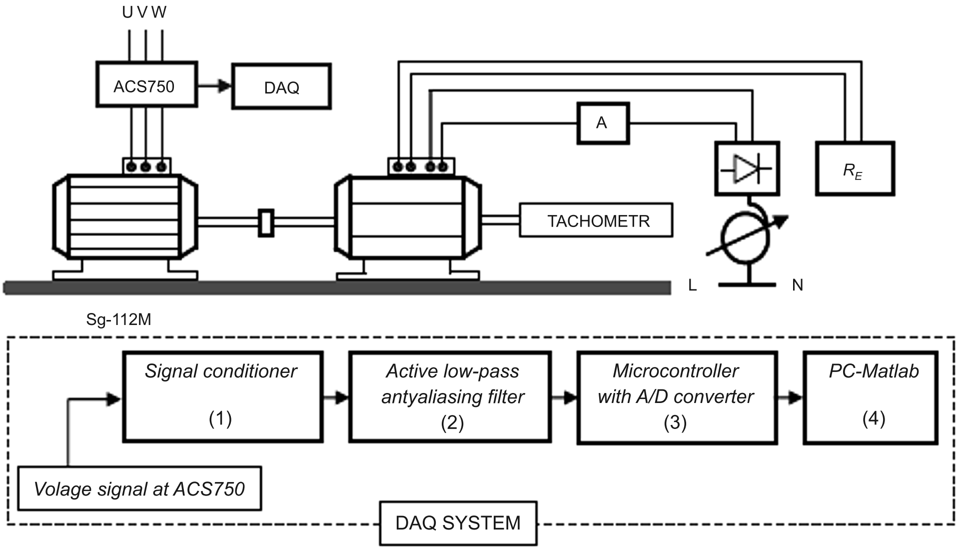

Fig. 1. Diagram of the measurement system

As a data acquisition system, a prototype measuring device was used, consisted of a pre-amplifier, operating as a voltage signal conditioner with current sensors ACS750. Next, with a third-order active filters, of Bessel characteristics, and 2 kHz cut-off frequency and border frequency 19.5 kHz, at sampling level 40 kS/s. As part of the analog-digital processing, a microcontroller with a transmitter A/D with about a 12 bit resolution connected to a PC with Matlab software via the USB port, was used.

3. Methods for diagnosing of the cage rotor damage

3.1. Low-pass filtering

The direct method of low-pass filtering [1, 7, 10, 11] is one of the primary methods of diagnosis of a rotor cage based on the signal of the stator current in transition. In engineering practice, there is a tendency to use the above-mentioned form of digital filtering of the analyzed signal. A digital low-pass filter is required to characterize with mainly small distortion in the passband and a narrow-band transition. These terms and conditions, as a compromise meet the Chebyshev algorithm, high order and distortion in the passband at level –1dB. It is customary to use filters with a cut-off frequency in the range of 10–25 Hz, the reason for this is that the presence of interference of electrodynamic components with frequencies greater than 25 Hz, which lead to the erroneous reading of the diagnostic signal amplitude. Also within this range frequency, it can be seen that the slip component with respect to a network component, maintains a relatively constant value during start-up. Frequencies below 10 Hz read from the slip component cannot be reliable, this is due to the significant increase in the speed of the rotor with the approach of the mid-synchronous speed, thus, capturing two diagnostic pulses may not be possible.

In the following figures, example calculation results using a low-pass filter with a limiting frequency of 15 Hz are presented, and the y-axis is scaled in accordance with the reference information from point 1. In order to compare the results of analyzes for the various methods of the time-frequency filter, in the rest of the work, all waveforms are referenced to the above-mentioned frequencies. It is also worth mentioning that the described electrodynamic phenomena, accompanying diagnostic signal extraction, subject to the same change in time, regardless of the type of filter used and will not be cited in the rest of the article.

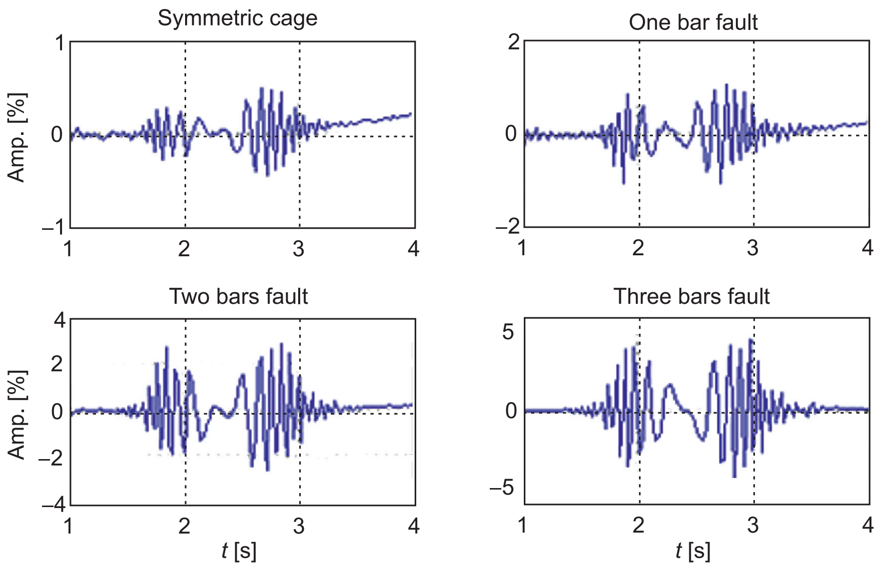

Fig. 2. Low Pass filtering effect

3.2. Short term Fourier transform

Short-Time Fourier Transform [5, 7, 13, 16] is the simplest method of non-stationary signal analysis and is based on dividing the analyzed signal at equal intervals, then in each of the separated portion of the waveform, Fourier transform is carried out. The ultimate result of the STFT is the sum of the modules of the results obtained in each of the compartments. The essential negative effect, on the above-described transformation, is the phenomenon of time-frequency uncertainty, i.e. using short intervals, increase the resolution in the frequency domain is obtained, for long time periods, the results have good resolution in the timeline. In practice, it is preferred to use described transformation with i.e. 'overlapping time windows', where part of the signal is analyzed in the actual window originated from the compartments immediately preceding and following. The method of overlapping windows consequently allows reducing the negative effects of STFT consisting of covering the harmonics with similar frequencies.

Customarily, the result of the application of time-frequency analysis presented in the hardly readable multispectrum form. Therefore, in the results of signal filtering below, the multispectrum is divided into a 2D map of energy in time and frequency domain. In a decibel scale in relation to the network component and the course of the amplitude of the observed frequency in the time domain. The axis ordinate is scaled as the ratio of the observed frequency to the mains frequency, in a time window, in which the maximum diagnostic signal occurred. Examples of the results of calculations, for all transforms, damage was limited to two bars of the rotor cage.

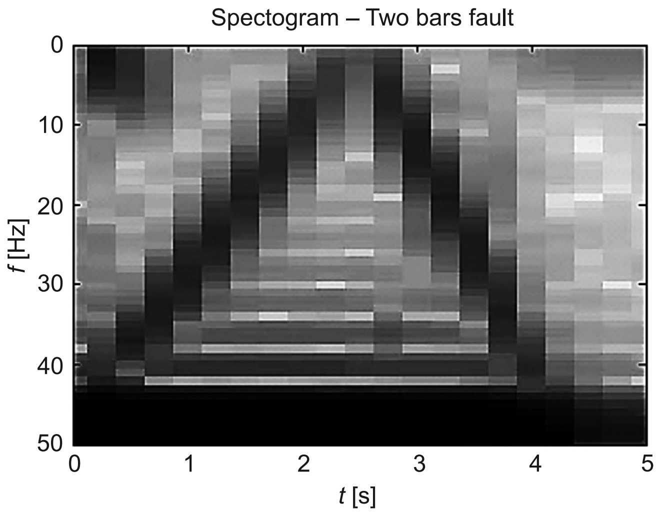

Fig. 3. Spectrogram – Two bars fault

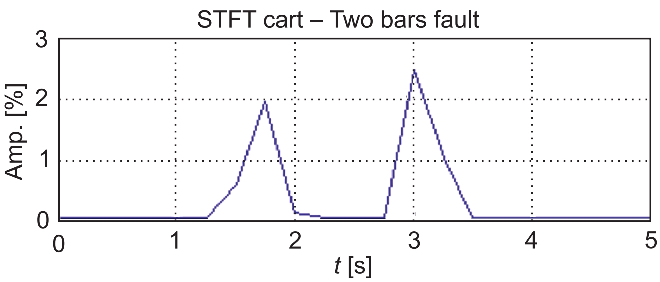

Fig. 4. STFT chart – Two bars fault

3.3. Gabor transform

Gabor transform [7, 13, 16] is a special type of short-time Fourier transform, as STFT is based on the division of analyzed signal, on local compartments by a time window. The difference between the STFT and the classical Gabor transformation, consists of as the time window, Gaussian weighting function. Characteristic feature Gauss function is similarity to the overall function of wavelet, except that the scale factor has a constant value throughout the analysis. In addition, the uncertainty principle, at any desired time interval, always reaches a local minimum, and as a consequence, makes the maximum concentration of energy in the time and frequency domain. The axis ordinate, chart the Gabor transform for the observed frequency, is scaled in the same way as in the case of the transform STFT.

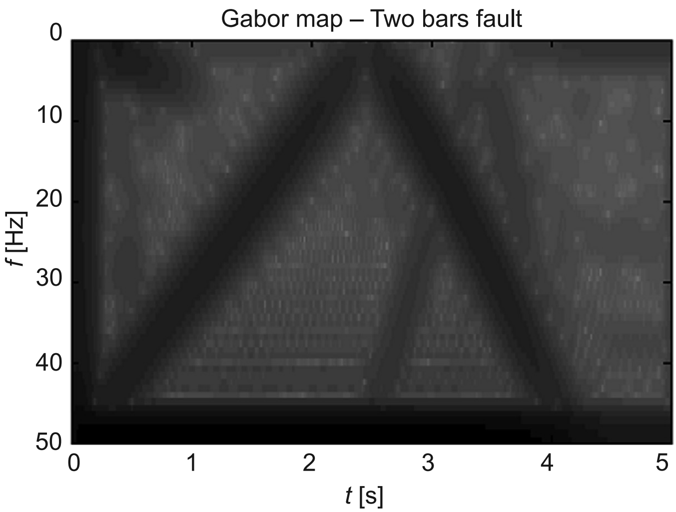

Fig. 5. Gabor map – Two bars fault

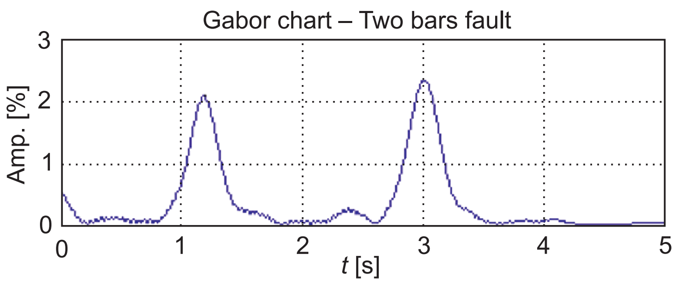

Fig. 6. Gabor chart – Two bars fault

3.4. Wavelet transform

Wavelet Transform [1, 5–7, 10, 13, 16] is a kind of time-frequency transformation of non-stationary signals, involving the matching (comparison) of the selected wavelet function with a specific carrier frequency signal waveform at a given level of decomposition. In the technical diagnostics squirrel-cage induction machines, uses two types of described transformations, respectively as a continuous form (CWT) and discrete form (DWT). The distinguishing feature of CWT is the so-called scale parameter that determines the quality of the results of calculations in the time and frequency, i.e. with increasing the value of the coefficient scale, a better fit of wavelets in the frequency domain is obtained, in the opposite case, in the time domain. Scalogram is a two-dimensional map of highlighted signal energy values for the coordinate system scale-time, wherein, in the event of a perfect fit wavelet to signal, the scale is exactly the inverse of the frequency. In the case of quantized signals, the scale factor can be a description of the following formula:

$$a = \frac{f_s \cdot f_w}{f_0} \tag{3}$$

where:

- a – scale factor,
- f_s – sampling frequency,
- f_w – wavelet frequency,
- f_o – observed frequency.

Formula (3) shows that the sampling frequency 40 kS/s, the network frequency corresponds to the value of scale equal to a = 800, the frequency of 15 Hz corresponds to the scale of the values of a = 2800. This fact is used to scale the y-axis (Fig. 6), dividing the observed frequency scale corresponding to the scale of the network frequency. The main disadvantage of CWT is the phenomenon of redundancy arising from the need to adopt a multivalent series of scale factor to best fit the wavelet function to the processed signal. Eliminating the phenomenon of redundancy, is obtained by applying a discrete form WT, thus dispensed with trying to get the exact result of the calculation. Some substitute the scale factor in discrete transform WT, is finite decomposition of the analyzed signal, consisting in dividing the research signal in the frequency domain, the number of compartments is defined as the level of decomposition, according to the formula:

$$n = \log_2 \frac{f_s}{f_o} - 1 \tag{4}$$

where:

- n – level of decomposition.

In each of the compartments, a low pass filter and a high pass filter should be performed, called respectively detail and approximation. Formula (4) shows that the sampling frequency 40 kS/s, observed frequency corresponds to a value of the decomposition level n = 10. In the case of using CWT, Morlet wavelet was used as a function of analyzing, and for the application of a DWT, DB45 wavelet was used as a function of analyzing.

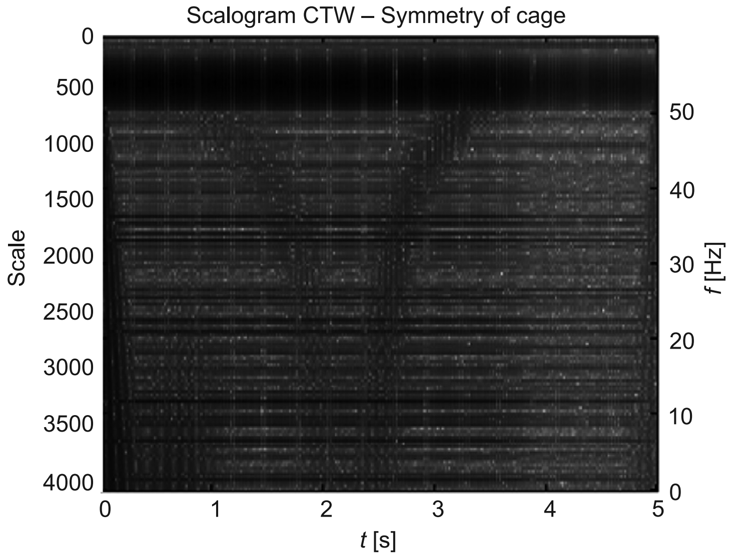

Fig. 7. Scalogram CWT – symmetry of cage

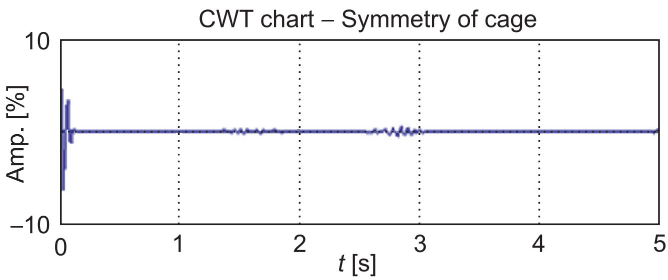

Fig. 8. CWT chart – symmetry of cage

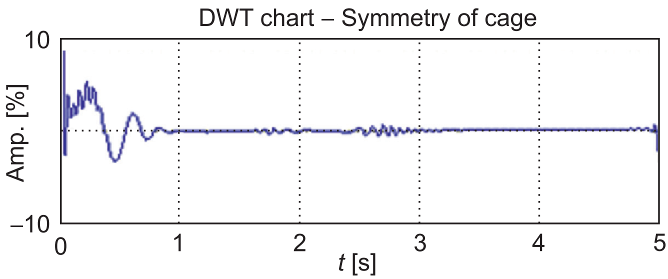

Fig. 9. DWT chart – symmetry of cage

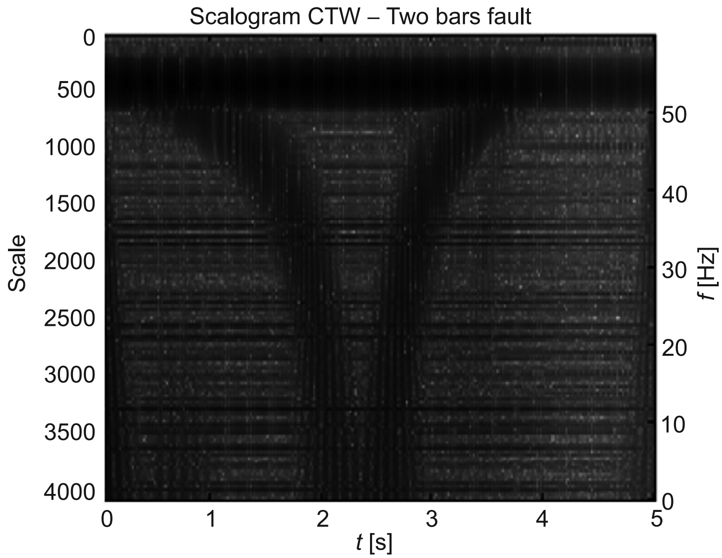

Fig. 10. Scalogram CWT – Two bars fault

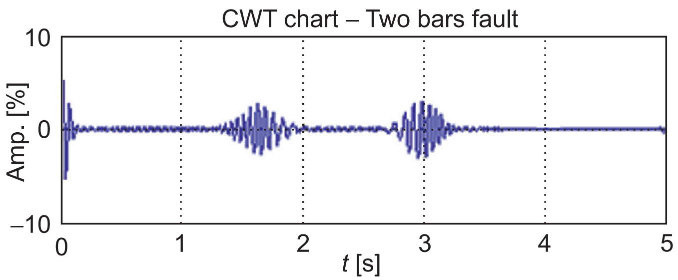

Fig. 11. CWT chart – Two bars fault

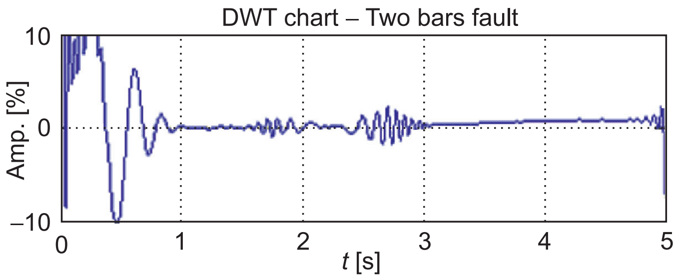

Fig. 12. DWT chart – Two bars fault

3.5. Wigner–Ville transform

The Wigner–Ville transform [15, 16], is characterized by best total resolution in the time and frequency of the above mentioned transformations. The uniqueness of the described transform, involves the use of the analyzed signal, as a function of the time window. It follows that any other time-frequency conversion can be obtained by averaging the transform WV. Although transform described in an ideal way, ideally maps the modulated signals linearly, in the case of nonlinear modulation, the result of the calculation is the sum of the squares of the components of the test signal and an additional factor, complementary solution of the parabolic equation. Commonly an additional member of the aforementioned equation, called parasitic interference, influencing the readability of the instantaneous spectrum.

In order to reduce interference, in practice, so-called pseudo transformation WV is used, which is a compromise between high resolution and decrease the effect of frequency signals generated by the transform itself. As the pseudo transform WV, effectively performed out using FFT, the axis ordinate, is scaled in the same way as in the case of STFT and Gabor transform.

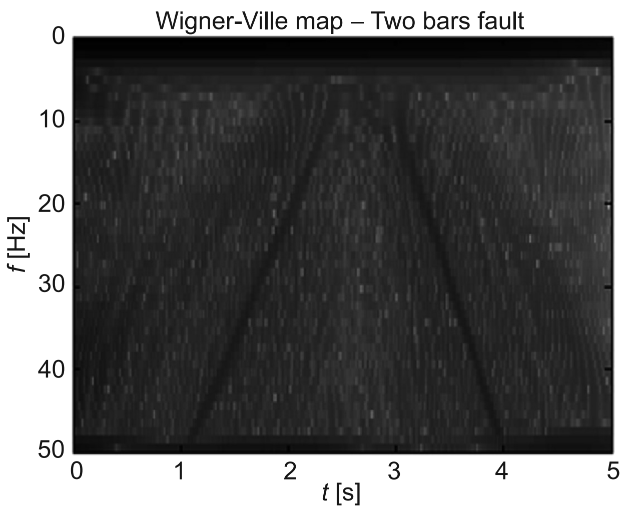

Fig. 13. Wigner–Ville map – Two bars fault

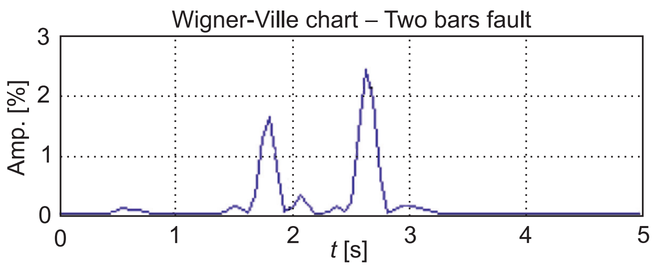

Fig. 14. Wigner–Ville chart – Two bars fault

4. Conclusions

In the presented results, over estimate of condition asynchronous motor winding, on the basis of the stator current waveform in transition, it should be noted that the presented diagnostic signal extraction method, have the advantages of registering only the starting current of one phase of the stator and do not require the measurement of speed. The measurement of speed, for the start of the ongoing over 1.5 s, should be considered as optimal, because of the distinctive mark of the slip component in the band 0–50 Hz. Although the object of the research was an asynchronous motor, it should be noted that the presented methods of analysis can be successfully used to diagnose the winding synchronous motor starter, due to the convergence of electrical phenomena resulting from damage to the rotor. Additionally, irrespective of the form of time-frequency analysis, damage indicator values obtained, did not show significant differences for the same type of defect of the rotor, which directly binds to form the diagnostic signal frequency changes over time, which can be considered as a modulated linearly. Significant differences in quality are noticeable only in the energy distribution of the time-frequency map, readability of which increases with the advancement numerical transform used.

In conclusion, analysis of non-stationary pattern of start-up current, allows for some assessment of the state of the rotor cage without any knowledge of the history of the motor's operation and its design parameters. A serious disadvantage is the limited ability to conduct this type of diagnosis at the start of short duration, where the separation of the time interval in which it can be assumed as a constant rotational speed, is considered to be problematic. The way out of this situation can be used as a pre-filter processing of the measurement signal, adaptive algorithm – this is the subject of ongoing work by the authors of this article.

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