УДК 621.313.333.2

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DECOMPOSITION OF ELECTROMOTIVE FORCE SIGNAL OF STATOR WINDING IN INDUCTION MOTOR AT DIAGNOSTICS OF THE ROTOR BROKEN BARS

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ДЕКОМПОЗИЦІЯ СИГНАЛУ ЕЛЕКТРОРУШІЙНОЇ СИЛИ ОБМОТКИ СТАТОРА АСИНХРОННОГО ДВИГУНА ПРИ ДІАГНОСТИЦІ ПОШКОДЖЕНЬ СТРИЖНІВ РОТОРА

Purpose. To develop a method of decomposition of a signal of electromotive force induced in stator windings in an induction motor with rotor broken bars after disconnection of the motor from the network.

Methodology. Methods of comparative analysis, mathematical modeling and forecasting were used.

Findings. A mathematical model was developed using finite element method for computation of electromagnetic field in cross-section of induction motor with rotor broken bars. It was proposed to use wavelet-transform of winding electromotive force (EMF) signal in order to determine the number and mutual displacement of rotor broken bars. A method for decomposition of electromotive force signal of induction motor stator winding to electromotive force signals of active sides of winding coils was developed using the theory of reverse *z*-transform. This allows one to increase accuracy of induction motors rotor broken bar diagnostics via singling out information features from electromotive force signal of one active side of winding coil We have proposed a method for calculation of electromagnetic field in the cross section of an induction motor with the use of a mathematical model based on the finite element method enabling assessment of broken rotor bars influence on generation of electromotive force in stator windings after disconnection of the motor from the network. The performed analysis of structural features of induction motors allowed us to find out that generation of electromotive force signal in stator winding elements can be influenced by such design factors as the number of pairs of poles, the circuit of connection of coil groups in the winding phase, the type of stator winding. We have proposed to use the theory of reverse z-transform to realize the method of decomposition of the signal of stator winding phase electromotive force.

Originality. For the first time we have developed a method of decomposition of a signal of stator winding phase electromotive force with use of the theory of reverse *z*-transform. This method makes it possible to improve the reliability of diagnostics of induction motor rotor broken bars by means of singling out information features in the signal of electromotive force of one side of the coil.

Practical value. We have developed a software module for automated calculation of electromagnetic field in the cross section of an induction motor.

Keywords*: induction motor, wavelet transform, broken rotor bars, reverse z-transform, electromotive force*

Introduction. Squirrel-cage induction motors (IM) are the most common type of electric machines (EM). As a rule, conditions under which IMs operate are characterized by factors that have negative effect on IM technical state, predetermine untimely aging of the equipment and decrease its life. About 20–25 % of IMs fail annually. According to statistics, about 5 % of IM failures occur due to broken rotor bars.

Analysis of the recent research. There exist different methods of IM broken rotor bars diagnostics [1–7]. Most of them require removing the motor from the technological process and its disassembling. Conventional methods of IM broken rotor bars diagnostics under the operational condition, e.g. the method of current spectral analysis [5], do not take into account mains supply voltage quality influence on the diagnostics results. A number of methods enable taking into consideration the influence of the quality of the mains supply [6] and obtaining more reliable diagnostics results [7]. Besides, the mentioned methods [5–7] do not provide satisfactory results when broken rotor bars are revealed under no-load condition. Moreover, the analysis of the results of the Fourier transform of current signals does not make it possible to determine the damage rate and relative position of broken rotor bars unambiguously.

Paper [8] offers a diagnostic method for broken rotor bars in an induction motor (IM) based on a wavelet analysis of the electromotive force (EMF) signal in the stator phase after disconnecting the motor. In this case EMF conditioned by current attenuation in the windings of turning rotor is induced in stator windings. The form of EMF signal in the winding conductors reflects the character of magnetic induction distribution in the IM air gap. Presence of slots in IM stator and rotor is known to result in tooth spatial harmonics in magnetic field [9]. Tooth kinks, caused by these harmonics and present in the stator winding EMF signal, enable comparison of magnetic field lines and geometric position of the teeth. In their turn, broken rotor bars condition distortions of magnetic field in IM air gap. So it can be supposed that stator winding EMF signal contains information about both magnetic field nonuniformity conditioned by stator and rotor teeth and field distortion caused by presence of broken rotor bars.

Unsolved aspects of the problem. This supposition was confirmed by experimental research for IM with broken rotor bars; test coil was inserted in its stator slots within a pole pitch. The experiments were carried out when the motor was disconnected from the mains. The results of the experiments showed that specific distortions corresponding to broken rotor bars are present in the signal of EMF induced in the test coil (Fig. 1, *b*); there are no distortions in the signal of EMF of the healthy IM (Fig. 1, *a*).

Thus, the signal of EMF induced in the stator windings by attenuating currents of the rotor after disconnection of the motor from the mains can be used as a diagnostic one. However, when analyzing the mentioned diagnostic signal, it is necessary to take into account that such design factors as the number of motor poles pairs, the type of interconnecting coil groups in the winding phase (series, parallel, series-parallel connection), stator winding type can influence the formation of winding phase EMF.

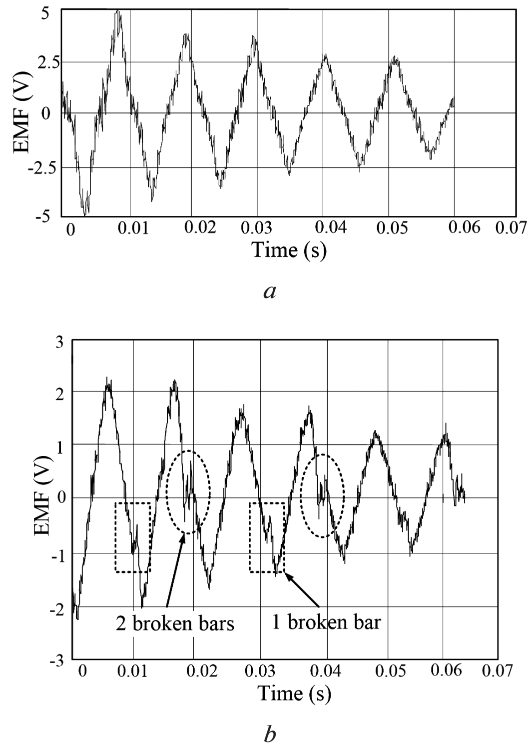


Fig. 1. Experimental signals of EMF in the test coil at the stator of healthy (a) IM and IM with broken rotor bars (b) after disconnection of the motor from the mains

Thus, when stator phase winding EMF signal is analyzed, difficulties connected with reciprocal overlapping of informational features corresponding to breakages of particular rotor bars may occur. It is due to the fact that IM stator winding coils are distributed across its inner surface with a shift by an angle equal to $\gamma = 2\pi/Z_1$, where Z_1 is the number of stator slots and, consequently, stator winding phase EMF is the sum of this winding coils EMFs.

Objectives of the article. The paper proposes to improve the reliability of IM broken rotor bars diagnostics on the basis of the wavelet analysis of EMF signal of one active side of a stator winding coil singled out from the total EMF signal, using inverse *z*-transform [10].

Presentation of the main research. To estimate the influence of the above mentioned factors on formation of the stator winding phase EMF and distortion of informational features, the computer simulation of the magnetic field in the healthy IM cross-section and that of the IM with broken rotor bars was performed using the finite element method (FEM).

The design characteristics of the analyzed IM (P = = 1.5 kW, n = 1395 rev/min, η = 0.77, $\cos\varphi$ = 0.81), were taken into consideration during the simulation. IM winding parameters were: winding type was a one-layer lap winding; number of poles $2p = 4$; number of stator slots $Z_1 = 36$; number of slots per pole and phase $q = 3$; number of winding parallel paths $a = 1$; winding pitch in slots $y = 9$; number of slots between the coils of winding adjacent phases $\lambda = 6$. Each phase of the stator winding consists of two coil groups, each of them, in its turn, contains three coils. A winding phase coil is formed by a group of turns connected in series and inserted in the same slots.

Let us consider formation of IM stator winding phase EMF.

Coil EMF is determined by expression [9]

$$E_c = \omega_c E_t, \tag{1}$$

where ω_c is a number of coil turns; E_t is winding turn EMF.

A coil group contains a number of coils with an equal number of turns situated in adjacent slots. Coils are connected in series and belong to one winding phase (Fig. 2, *a*). Coil group coils are shifted by an electrical angle γ, accordingly, EMFs of these coils are shifted by the same angle (Fig. 2, *b*).

Coil group EMF E_q is equal to the vector sum of EMFs of separate coils of this group (Fig. 2, *c*).

Designations used in Fig. 2 are as follows: B is amplitude of magnetic induction of the fundamental harmonic of the field in the gap; τ is a pole pitch; α is a phase zone angle.

In a general case, the stator winding phase EMF is equal to the vector sum of EMFs of all coil groups making this phase.

For the analyzed IM the winding phase EMF is equal to the sum of EMFs of six coils

$$\dot{E}_{ph} = \sum_{i=1}^{6} \dot{E}_{ci}, \tag{2}$$

where $\dot{E}_{\dot{c}}$ is EMF of the i-th coil; i is a coil number.

As coil EMFs are shifted in relation to each other, as it was stated above, informational features existing in signals of EMF of each separate coil and conditioned by the presence of broken rotor bars, overlap when EMFs are summed up.

To analyze the information value of signals of EMF induced in one active side of a coil, a coil, a coil group and a stator winding phase, it was proposed to develop a mathematical model of 2D magnetic field in IM cross section using the finite element method [8].

Computation of IM magnetic field is made in a batch with the use of a LUA-script. Command set for the LUA-script can be changed in accordance with the problems posed by the computation. The obtained model can be used for research of IM of any required H.P. and different dynamic operation conditions determined only by initial values of currents in the stator and rotor slots. In this case the decrease in the rotor speed after disconnecting the motor from the supply mains is taken into consideration.

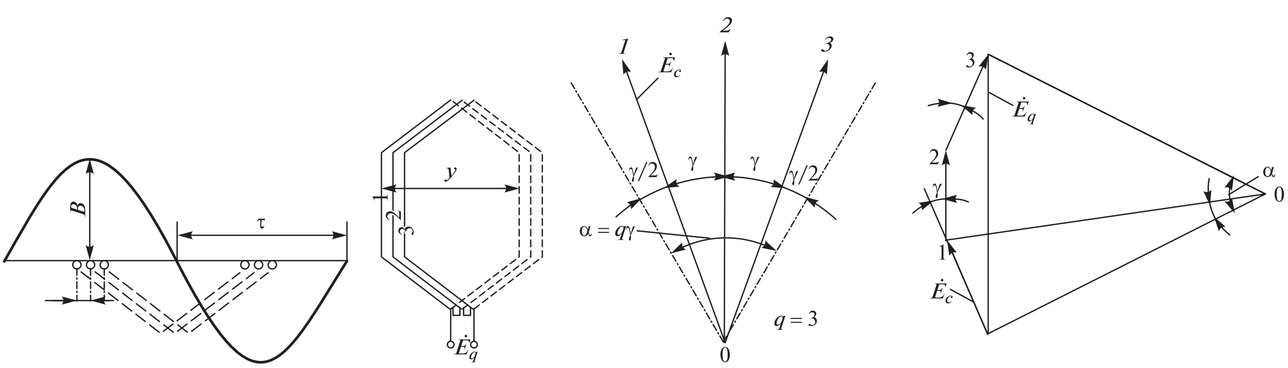
Instantaneous values of the vector magnetic potential (VMP), flux linkage and EMF of one active side of a coil, a coil, a coil group and a stator winding phase were determined as a result of magnetic field calculation.

The IMF signals obtained as a result of field calculation are shown in Fig. 3.

The analysis of the obtained results demonstrated that the signal of EMF of one active side of a coil (Fig. 3, *a*) contains both tooth kinks and distortion of the signal form caused by broken rotor bars. Visual analysis proves that informational features, revealed by distortions of signal form, can be hardly seen in EMF signal of a coil (Fig. 3, *b*), and they are practically absent in the signals of EMF of a coil group and a winding phase (Fig. 3, *c*, *d*).

Thus, the signal of stator winding phase EMF does not contain explicit features typical of the state with broken rotor bars, unlike the signal of EMF of one active side of a coil. To confirm this fact an analysis of the obtained signals was carried out using continuous wavelet transform (Fig. 4). The following designations are used in Fig. 4: C*a* stands for wavelet scale coefficients; *Cb* stands for wavelet shift coefficients.

The analysis of wavelet transform results showed that the wavelet spectrum of the signal of EMF of one active side of a stator winding coil (Fig. 4, *a*) contains specific sections corresponding to the location of broken rotor bars. At the same time these sections are doubled in the coil EMF spectrum (Fig. 4, *b*). It can be explained by summing up of EMFs of two active sides of the coil shifted in the space in relation to each other by the angle equal to $\pi/2$. Therefore, the sections with wavelet coef-



a *b* *c* *d*

Fig. 2. Magnetic induction of coil group (a), coil group in magnetic field (b), coils EMF (c) and vector diagram of determining coil group EMF (d) of IM stator winding

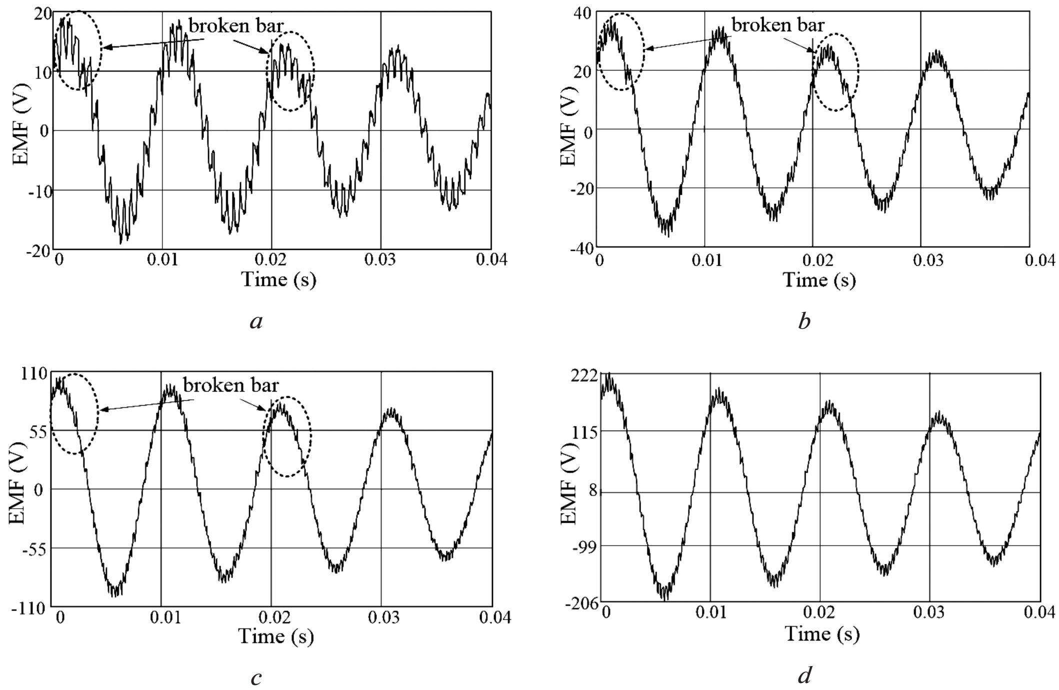


Fig. 3. EMF signals of one active side of a coil (a), a coil (b), a coil group (c) and a stator winding phase (d) of IM with broken rotor bars

ficients characterizing breakages are also shifted in the wavelet spectrum by the same spatial angle.

The analysis of the wavelet spectra of the signals of EMF of the coil group (Fig. 4, *c*) and the winding phase on the whole (Fig. 4, *d*) demonstrated that, due to summing up EMF signals, there occurs a splatter in wavelet spectra of specific sections reflecting rotor bar breakages. Thus, when determining the IM stator winding phase EMF, informational features overlap and make reliable determination of broken rotor bar location more difficult.

Therefore, it is proposed in the paper to analyze the signal of EMF of one active side of the stator winding coil, the signal being singled out from the total signal of the winding phase EMF. In this case the signal of EMF of the winding phase is first divided into the sig-

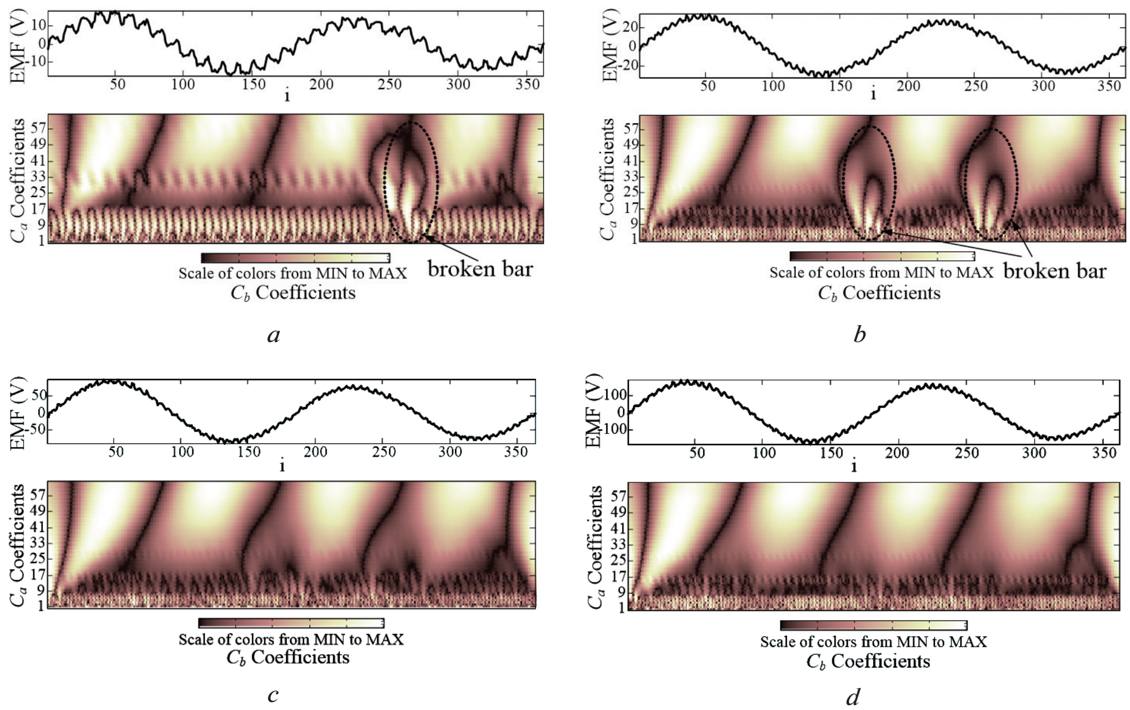


Fig. 4. Signals of EMF of one active side of a coil (a), a coil (b), a coil group (c) and a stator winding phase (d) of IM with broken rotor bars and their wavelet spectra, respectively

nals of EMFs of this winding coil groups. Then the signal of EMF of one of the coil groups, when angles of shear between the coils in the stator slots are known, is divided into the signals of coil EMFs. The signal of EMF of one active side of a coil, which was obtained after division of the signal of winding coil EMF, is the final result. It is proposed to single out the signal of EMF of one active side of a stator winding coil using reverse z-transform [6], whose analytical expression is represented as follows

$$e(k) = Z^{-1}[E(z)], \quad (3)$$

where Z^{-1} is the reverse z-transform operator.

The use of signal delay for n samples allowed one to take into account shear angles between EMF signals in stator windings units.

Thus, for the case of investigated IM one coil group consists of three coils, mutually sheared in the space of stator circle by the value of one slot, or $2\pi/Z_1$ electrical degrees. The EMF of the coil group is formed as a sum of EMF of these three coils. Under the assumption that coils are identical and mutually sheared by previously known and equal angles, using reverse z-transform it is possible to single out an EMF signal of all three coils from the given EMF signal of the coil group.

Fig. 5 contains a block diagram of a mathematical model of singling out a stator winding coil EMF signal from the total signal of EMFs of the winding coil group.

Designations in Fig. 5 are: $E_{c1}(z)$, E_{c2}, $E_{cm}(z)$ are z-images of discrete signals of stator winding coils EMFs; m – number of winding coils; $E_{q1}(z)$ – z-image of discrete signal of stator winding coil group EMFs; k – is a discrete number corresponding to the angle of shear between the coils in the stator slots.

According to the block diagram represented in Fig. 5, one of the EMF signals of coil group $E_{q1}(z)$, derived as a result of decomposition, is splitting into EMF signals of single coils $E_{cm}(z)$ (Fig. 6).

In the analogous way, the signal of EMF of one active side of the winding coil is singled out from the signal of EMF of the coil. Comparison of the initial signal of EMF of one active side of the coil and the one singled out from the total signal of stator winding coil EMF is presented in Fig. 7.

The signals analysis showed that signal of EMF of one active side of the coil, obtained as a result of singling out from the total signal of stator winding phase EMF, corresponds to an analogous EMF signal obtained as a result of magnetic field calculation.

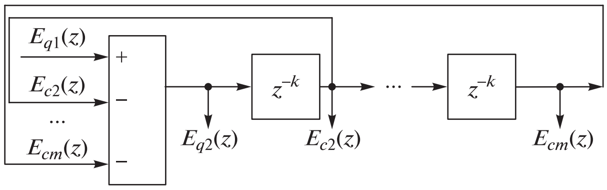


Fig. 5. Block diagram of a mathematical model of singling out stator winding coil EMF signal from the total signal of EMFs of the winding coil group

Thus, the signal of EMF of one active side of the stator winding coil, singled out from the total signal of winding phase EMF, can be used for diagnostics of broken IM rotor bars.

To identify local specific features of the signal of EMF in the stator windings the wavelet analysis of the signal of EMF of one active side of the stator winding coil, singled out from the total signal of stator winding phase EMF, was carried out (Fig. 8).

As it can be seen in the obtained wavelet spectrum, EMF signal distortions, corresponding to the location of broken bars, are also reflected in the wavelet spectrum.

Experimental research. To confirm the results of simulation of the IM magnetic field, considering the broken rotor bars, the experimental research with the use of the developed computerized measuring complex was done. It consists of voltage and current sensors sets, an analog-digital converter and a personal computer for the results analysis. Experimental research was done for a healthy IM and an IM with one, two or three broken rotor bars.

During the experiment IM was off the mains; stator phase voltages were measured by the sensor set. The analysis of the obtained results is demonstrated in Fig. 9, *a*, *b*.

The analysis of the experimental signal of stator winding phase EMF showed that the wavelet spectrum does not contain distinctive sections corresponding to the location of broken rotor bars.

Therefore, in accordance with the proposed method, using reverse z-transform, the EMF signal of one active side of the stator winding coil was singled out from the experimental signal of the winding phase EMF. The obtained EMF signal of one active side of the stator winding coil and its wavelet spectrum are presented in Fig. 10, *a, b, c*.

The obtained results showed that it is possible to determine the location of broken rotor bars on the ba-

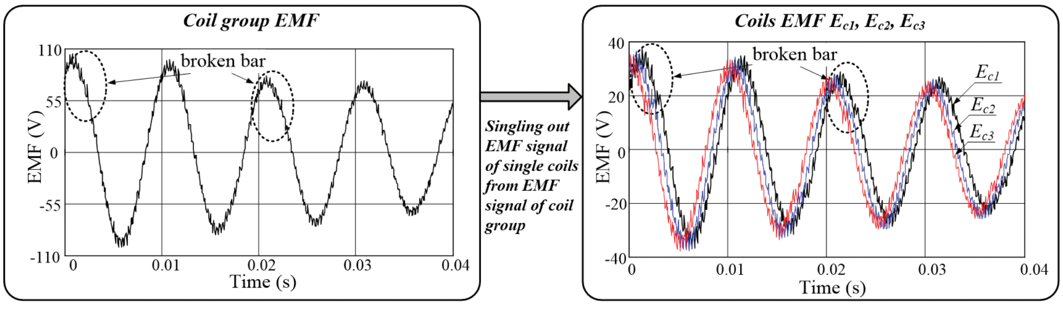


Fig. 6. Singling out EMF signal of single coils from EMF signal of coil group

sis of the analysis of the singled out signal of the EMF of one active side of the coil.

Thus, the experimental research results (Fig. 10, *b*, *c*) correspond to the results of simulation (Fig. 8, *a*, *b*).

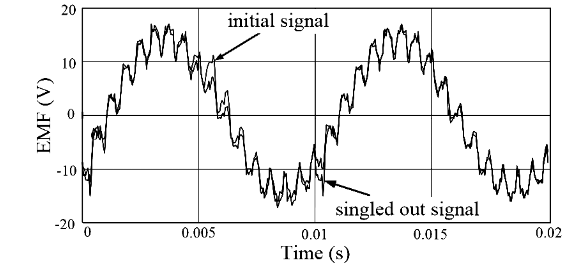


Fig. 7. Initial signal of EMF of one active side of the stator winding coil and the signal singled out from the total signal as a result of z-transform

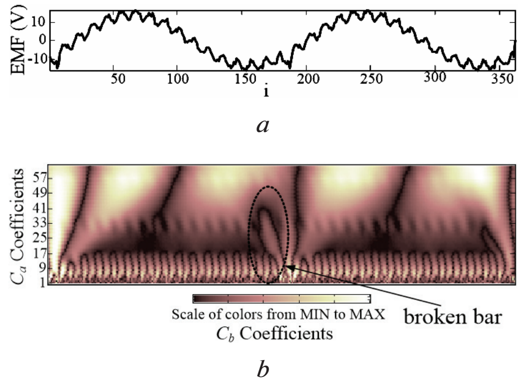


Fig. 8. Signal of EMF of one active side of the coil, singled out from the total signal as a result of z-transform (a), and its wavelet spectrum with broken rotor bars (b)

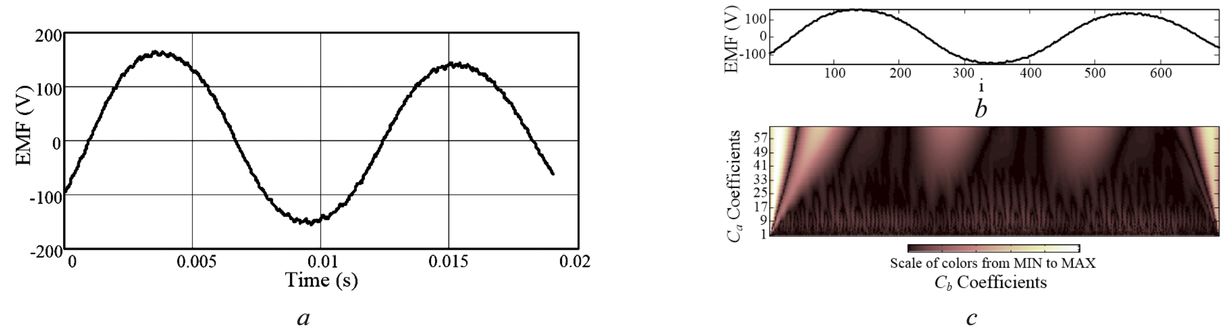


Fig. 9. Experimental signal of stator winding phase EMF of IM with broken rotor bars (a), (b) and its wavelet spectrum (c)

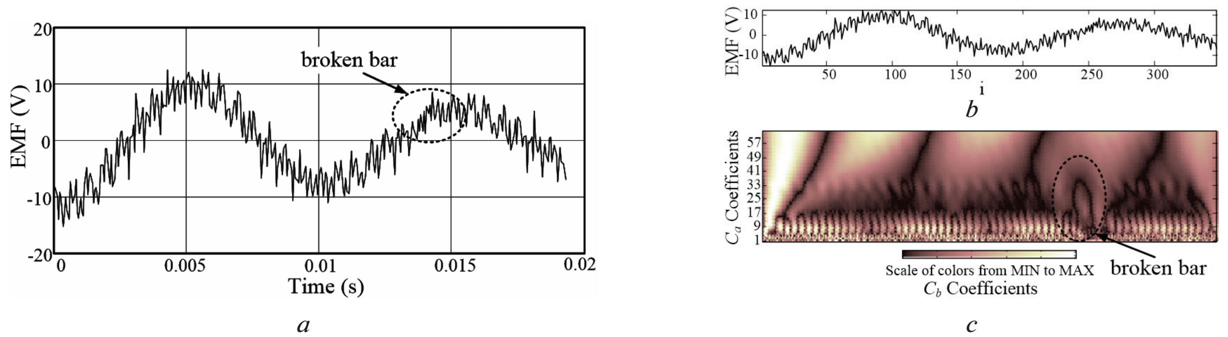


Fig. 10. EMF signal of one active side of the coil singled out, as a result of z-transform, from the experimental signal of stator winding phase EMF, (a), (b) and its wavelet spectrum (c)

Some differences of the singled out signal of the EMF of one active side of the coil, obtained on the basis of experimental data, from the data of simulation are connected with multiple transforms of discrete signals.

Conclusions and recommendations for further research. Use of the wavelet analysis of the signal of electromotive force of one active side of the induction motor stator winding coil, obtained by singling out from the total signal of the winding phase electromotive force, makes it possible to improve the reliability of broken rotor bar diagnostics.

The experimental research, carried out on the developed computerized measuring complex, confirmed the efficiency of the proposed method for IM rotor broken bar diagnostics.

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Мета. Розробка методу декомпозиції сигналу електрорушійної сили (ЕРС), що наводиться в обмотках статора асинхронного двигуна з пошкодженнями стрижнів ротора після відключення двигуна від мережі живлення.

Методика. Застосовані методи порівняльного аналізу, математичне моделювання, прогнозування.

Результати. Розроблена математична модель з використанням методу кінцевих елементів для розрахунку електромагнітного поля в поперечному перерізі асинхронного двигуна з пошкодженнями стрижнів ротора. Запропоноване використання вейвлет-перетворення сигналу електрорушійної сили (ЕРС) обмотки для визначення кількості та взаємного розташування пошкоджених стрижнів ротора. Розроблено метод декомпозиції сигналу ЕРС фази обмотки статора асинхронного двигуна на сигнали ЕРС активних сторін котушок обмотки з використанням теорії зворотного z-перетворення. Це дозволяє підвищити достовірність діагностики пошкоджень стрижнів ротора асинхронних двигунів шляхом виділення інформаційних ознак, присутніх у сигналі ЕРС однієї активної сторони котушки. Запропонована методика розрахунку електромагнітного поля в поперечному перерізі асинхронного двигуна з використанням математичної моделі на основі методу скінченних елементів, що дозволяє оцінити вплив пошкоджень стрижнів ротора на формування ЕРС в обмотках статора після відключення двигуна від мережі живлення. Проведений аналіз конструктивних особливостей асинхронних двигунів дозволив встановити, що на формування сигналу ЕРС в елементах обмотки статора можуть впливати такі конструктивні фактори, як: кількість пар полюсів, схема з'єднання котушкових груп у фазі обмотки, тип обмотки статора. Запропоновано використання теорії зворотного z-перетворення для реалізації методу декомпозиції сигналу ЕРС фази обмотки статора.

Наукова новизна. Уперше розроблено метод декомпозиції сигналу електрорушійної сили фази обмотки статора з використанням теорії зворотного z-перетворення, що дозволяє підвищити достовірність діагностики пошкоджень стрижнів ротора асинхронних двигунів шляхом виділення інформаційних ознак у сигналі електрорушійної сили однієї сторони котушки.

Практична значимість. Розроблено програмний модуль для автоматизованого розрахунку електромагнітного поля в поперечному перерізі асинхронного двигуна.

Ключові слова: *асинхронний двигун, вейвлет-перетворення, пошкодження стрижнів ротора, зворотне z-перетворення, електрорушійна сила*

Цель. Разработка метода декомпозиции сигнала электродвижущей силы, которая наводится в обмотках статора асинхронного двигателя с повреждениями стержней ротора после отключения двигателя от сети.

Методика. Применены методы сравнительного анализа, математическое моделирование, прогнозирование.

Результаты. Разработана математическая модель с использованием метода конечных элементов для расчета электромагнитного поля в поперечном сечении асинхронного двигателя с повреждениями стержней ротора. Предложено использование вейвлет-преобразования сигнала электродвижущей силы (ЭДС) обмотки для определения количества и взаимного расположения поврежденных стержней ротора. Разработан метод декомпозиции сигнала ЭДС фазы обмотки статора асинхронного двигателя на сигналы ЭДС активных сторон катушек обмотки с использованием теории обратного z-преобразования. Это позволяет повысить достоверность диагностики повреждений стержней ротора асинхронных двигателей путем выделения информационных признаков, присутствующих в сигнале ЭДС одной активной стороны катушки. Предложена методика расчета электромагнитного поля в поперечном сечении асинхронного двигателя с использованием математической модели на основании метода конечных элементов, которая позволяет оценить влияние повреждений стержней ротора на формирование ЭДС в обмотках статора после отключения двигателя от сети. Проведенный анализ

конструктивных особенностей асинхронных двигателей позволил установить, что на формирование сигнала ЭДС в элементах обмотки статора могут влиять такие конструктивные факторы, как: количество пар полюсов, схема соединения катушечных групп в фазе обмотки, тип обмотки статора. Предложено использование теории обратного *z*-преобразования для реализации метода декомпозиции сигнала ЭДС фазы обмотки статора.

Научная новизна. Впервые разработан метод декомпозиции сигнала электродвижущей силы фазы обмотки статора с использованием теории обратного *z*-преобразования, который позволяет повысить достоверность диагностики повреждений стержней ротора асинхронных двигателей путем выделения информационных признаков в сигнале электродвижущей силы одной стороны катушки.

Практическая значимость. Разработан программный модуль для автоматизированного расчета электромагнитного поля в поперечном сечении асинхронного двигателя.

Ключевые слова: *асинхронный двигатель, вейвлет-преобразование, повреждения стержней ротора, обратное z-преобразование, электродвижущая сила*

Рекомендовано до публікації докт. техн. наук В. П. Ляшенком. Дата надходження рукопису 26.05.15.