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Development of a diagnostic system for the presence of rotor eccentricity in traction induction motors

The aim of research is to develop a system for functional diagnostics of the presence of rotor eccentricity in traction induction motors of railway rolling stock. To achieve the aim, the following objectives were solved in the work: the Prony's method was adapted to perform the task of diagnosing the eccentricity of the rotor of an induction motor during the operation of the rolling stock; the algorithm of functioning of the system of functional diagnosis of rotor eccentricity based on the adapted Prony's method is proposed; a structural diagram of the rotor eccentricity diagnosis unit based on the adapted Prony's method is proposed; a structural diagram of the system of functional diagnosis of rotor eccentricity is proposed. The most important results are obtaining a mathematical model of the Prony's method, adapted to the task of diagnosing the eccentricity of the rotor of an induction motor during the operation of rolling stock. The adaptation of the Prony's method algorithm is performed by applying the Wiener-Hopf procedure to the analyzed signals. This will make it possible to apply the proposed algorithm in conditions where the process of changing the analyzed signals is stochastic in nature. This will make it possible to determine the eccentricity degree of the AM rotor with greater accuracy and to make a more correct decision regarding the AM operation with the existing eccentricity of the rotor.

Key words: induction motor, diagnosis, eccentricity, rolling stock.

Introduction. The reliable operation of traction motors of rolling stock affects the uninterrupted operation of even the railway. The sudden failure of the elements of traction electric drives during the operation of the rolling stock leads to disruption of logistics and related economic losses. In addition, the violation of established logistical tasks leads to a decrease in the competitiveness of even railway transport. In such conditions, research on the development of methods for controlling the appearance and development of defects in the design elements of traction motors of rolling stock is particularly relevant [1].

A number of damages to traction motors cause the appearance of rotor eccentricity, which is the most common mechanical malfunction of an induction motor (IM). The presence of eccentricity leads to increased wear of bearings. Catching the rotor on the stator can cause structural damage to the rotor and stator or overheating. These factors can cause a breakdown of the damaged layer of insulation in the friction zone. According to research data, eccentricity accounts for 20 to 40% of IM failures [2, 3].

During the IM operation with eccentricity, one-sided magnetic attraction occurs, which causes a decrease in efficiency, and increased heating causes a decrease in starting torque. Therefore, detection

of rotor eccentricity at an early stage of its appearance and development is an important scientific and research task.

The development of algorithms for detecting the presence of rotor eccentricity and the degree of its damage and the construction of functional diagnostic schemes based on them will allow to effectively detect the specified defect during the operation of the traction motor. This will make it possible to increase the reliability and durability of the use of traction IMs in the traction drives of railway rolling stock, which, in turn, will ensure the safety and economy of railway transportation [4].

Analysis of existing technical solutions. The nature of the rotor eccentricity is different, but the negative consequences of this defect are similar. The causes of rotor eccentricity are [5]:

- low-quality manufacturing or repair of motors;
- the influence of operational factors that cause violations of the geometry of the motor design;
- wear of bearings;
- motor shaft deflections, etc.

A characteristic feature of this type of damage is the possibility of continued IM operation without its immediate failure. However, the eccentricity leads to a decrease in the reliability and durability IM indicators, which progress over time and contribute to a decrease in technical and economic and operational indicators.

In studies devoted to the analysis of the causes of rotor eccentricity, two types of eccentricity, static and dynamic, are considered. Static eccentricity is caused by the shift of the axis of rotation of the motor relative to the axis of boring of the stator package, that is, the eccentric position of the rotor in the boring of the stator. The most common causes of static eccentricity are [5]:

- load imbalance;
- vibrations;
- misalignment of shafts;
- sharply changing loads and overloads;
- malfunction of bearings, etc.

Dynamic eccentricity is caused by the displacement of the axis of the outer surface of the rotor with respect to the axis of its rotation and is accompanied by the beating of the rotor, which occurs due to the forces of one-sided magnetic attraction as a result of poor repair or manufacturing defects.

The dynamic eccentricity is usually much smaller than the static eccentricity and for determination during motor operation for the purpose of current diagnostics of the motor condition is not of decisive importance. Therefore, for the diagnosis of damage causing eccentricity in IM, it is advisable to conduct research only on static indicators of eccentricity [5].

The following methods are known from existing studies devoted to diagnosing the occurrence of rotor eccentricity [5]:

- vibrational;
- direct measurement;
- current.

Vibrodiagnostic methods are effective for determining damage to IM elements when diagnosing on the bench, but they have not been widely used in functional diagnostic systems. This fact is explained by the need to use a large number of sensors, the lack of reference values of vibration manifestations of a number of damages and low accuracy during the operation of the mechanism with additional vibration sources [6].

The method of direct measurement of the air gap at several points is used in the repair and maintenance of motors and requires partial disassembly of the IM. This requires stopping the IM for a long time and the conditions of access to the end zone of the magnetic circuit, which excludes the use of the method during the period of operation.

Current methods are the most effective for diagnosing the occurrence of rotor eccentricity. They are based on the analysis of the main electric and magnetic parameters of the motor, namely phase currents, phase voltage, power consumption, flux linkage and magnetic field induction in the air gap during the

operation of the equipment [2]. But for the full use of current methods, a number of separate studies are needed to establish the diagnostic parameters for assessing the type and degree of the motor defect.

Due to the fact that the functional diagnostics system is based on the analysis of the parameters of the stator phase currents of the IM, the construction of such a system requires the determination of diagnostic signs, which will be used to control the presence of eccentricity in the IM. The presence of the rotor eccentricity causes a change in the amplitudes of the characteristic harmonics in the current signals [7]. Such characteristic harmonics include:

- harmonics of passage of rotor grooves;
- side harmonics of the rotor around the power supply frequency;
- harmonics at twice the supply frequency and side harmonics around it.

When diagnosing IM in order to determine the presence of rotor eccentricity, thermal processes in AM should also be taken into account. Thermal processes in IM are "white" Gaussian noise [8]. In addition, the traction drive is affected by various disturbances caused by operational factors of rolling stock [9]. These disturbances have a non-deterministic non-periodic non-Gaussian character [9]. In other words, if the signals of the stator phase currents are affected by non-deterministic non-periodic non-Gaussian influences, the application of Fourier transform algorithms is incorrect. In these cases, it is correct to use correlation analysis methods.

The methods of current IM diagnosis include the following methods:

- method of analysis of motor current signatures [10];
- method of tracking order harmonics [11];
- parametric methods [12];
- methods based on Park vectors [13];
- Prony's method [14];
- methods of artificial intelligence [15].

From the analysis of the listed methods of current IM diagnostics, it was established that the most effective method for solving the problem of diagnosing the presence of rotor eccentricity is the Prony's method. Its advantages are:

- short signal sampling;
- absence of the effect of spectral leakage;
- low sampling frequency.

Despite the listed advantages, the Prony's method has one significant drawback: there are no criteria for choosing the order of the model and the fitting method in conditions where the process of changing the analyzed signal is stochastic.

The analysis of existing technical solutions for the construction of a functional diagnostics system shows that an important stage in the development of the specified system is the adaptation of existing diagnostic information processing methods for continuous control and diagnosis of the presence of rotor eccentricity in traction induction motors.

The aim of this research is to develop a system for functional diagnostics of the presence of rotor eccentricity in traction induction motors of railway rolling stock.

The research contributions of this work are as follows:

- the Prony's method is adapted to perform the task of diagnosing the eccentricity of the IM rotor during the rolling stock operation;
- the algorithm of functioning of the functional diagnostics system of IM rotor eccentricity based on the adapted Prony's method is proposed;
- a structural diagram of the IM rotor eccentricity diagnosis unit based on the adapted Prony's method is proposed;
- a structural diagram of the functional diagnostics system of IM rotor eccentricity is proposed.

Adaptation of the Prony's method to perform the task of diagnosing the IM rotor eccentricity during the rolling stock operation. As a result of the analysis, it was found that the most effective method of processing diagnostic information when building a functional system for diagnosing the IM rotor eccentricity is the Prony's method. Along with such advantages as: short signal sampling; absence

of the effect of spectral leakage; low sampling frequency, it has a significant drawback: there are no criteria for choosing the order of the model and the fitting method in conditions where the process of changing the analyzed signal is stochastic in nature. In this section, an algorithm for adapting the Prony's method is proposed for the purpose of its application when the process of changing the analyzed signals is stochastic in nature.

In the presence of eccentricity in the current signal, the amplitudes of the harmonics change. passage of the rotor grooves. The frequencies of these harmonics are determined by the following expression [16]

$$f_{RSN} = f_s \cdot \left((m \cdot Z_B \pm n_d) \cdot \frac{1-s}{p} \pm \beta_{ws} \right) = f_s \cdot \left(m \cdot Z_B \cdot \frac{1-s}{p} \pm \beta_{ws} \right) \pm f_s \cdot n_d \cdot \frac{1-s}{p}, \quad (1)$$

where $m=1,2,3,\dots$;

n_d - eccentricity order. With static eccentricity $n_d=0$, with dynamic eccentricity $n_d=1,2,3,\dots$;

p – the number of pairs of poles;

β_{ws} – the sequence of time harmonics of the stator of the power source of the induction motor. β_{ws} takes odd values for current signals and axial magnetic flux [17];

Z_B – the number of rotor rods.

In expression (1), the left term is the frequency of passage of the rotor grooves f_r :

$$f_r = f_s \cdot \left(m \cdot Z_B \cdot \frac{1-s}{p} \pm \beta_{ws} \right). \quad (2)$$

The frequencies of the side harmonics f_r around the frequency of passage of the rotor grooves are determined by the right-hand term of equation (1). Harmonics at these frequencies are called subharmonics of the rotor rotation frequency. The frequencies of these subharmonics are determined by the expression [18]:

$$f_r = f_s \cdot \frac{1-s}{p}, \quad (3)$$

The presence of side harmonics of the rotor around the power supply frequency is a sign of dynamic eccentricity [18]. The frequencies of these harmonics are determined according to the following expression:

$$f_{sbr} = f_s \pm k \cdot f_r, \quad (4)$$

where $k=1,2,3,\dots$ – any positive integer.

The analytical expression for the current signal in the presence of eccentricity has the form [18]:

$$I_{ecc}[i] = I_m \cdot \left(1 + \gamma \cdot \cos(2 \cdot \pi \cdot f_r \cdot \Delta t \cdot i + \varphi_0) \right) \cdot \cos(2 \cdot \pi \cdot f_s \cdot \Delta t \cdot i) + \beta[i], \quad (5)$$

where $I_{ecc}[i]$ – value of the IM phase stator currents in the presence of eccentricity;

γ – eccentricity degree.

From the analysis of expressions (1)-(5) it follows that the presence of lateral harmonics f_r around the frequency of passage of the rotor grooves and lateral harmonics of the rotor around the supply frequency in the spectrum of the IM stator phase currents is a sign of the presence of rotor eccentricity.

Spectral analysis methods should be used to determine the presence of harmonics at these frequencies. Subharmonic frequencies are not multiples of the supply voltage frequency (3)-(4). In addition, when diagnosing the presence of eccentricity during the operation of the traction drive, both the power frequency and the rotor speed are constantly changing. This complicates the application of Fourier transform algorithms to determine the specified subharmonics.

Fig. 1 shows a short algorithm of the stages of determining the periodogram, intended for obtaining estimates of the amplitude, attenuation coefficient, frequency, and initial phase by the Prony's method [19].

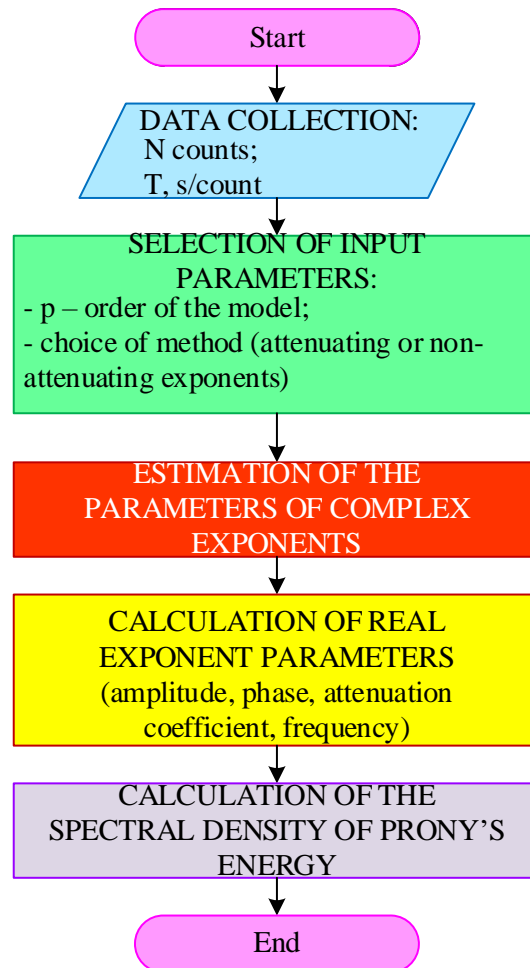


Fig. 1. A short algorithm of the stages of determining the periodogram, intended for obtaining estimates according to the Prony's method

For N readings of complex data $x[1], \dots, x[N]$, the Prony's method allows to estimate $x[n]$ using some p -term complex exponents.

The Prony's procedure for preparing p exponents for $2p$ counts of data can now be represented as the following three steps. At the first stage, the solution of equation [19] is obtained

$$\begin{bmatrix} x[p] & x[p-1] & \dots & x[1] \\ x[p+1] & x[p] & \dots & x[2] \\ \vdots & \vdots & \dots & \vdots \\ x[2p-1] & x[2p-2] & \dots & x[p] \end{bmatrix} \cdot \begin{bmatrix} a[1] \\ a[2] \\ \vdots \\ a[p] \end{bmatrix} = \begin{bmatrix} x[p+1] \\ x[p+2] \\ \vdots \\ x[2p] \end{bmatrix}. \quad (6)$$

for coefficients $a[n]$.

At the second stage, the roots of the polynomial defined by equation [19] are determined

$$\prod_{k=1}^p (z - z_k) = \sum_{m=0}^p a[m] \cdot z^{p-m}. \quad (7)$$

The solution of equation (7) with respect to the roots z_i makes it possible to calculate the attenuation coefficient α_i and the frequency of the sinusoid f_i using relations [19]

$$\alpha_i = \frac{\ln|z_i|}{T}, s^{-1}; \quad (8)$$

$$f_i = \frac{\arctg\left[\frac{\operatorname{Re}(z_i)}{\operatorname{Im}(z_i)}\right]}{2 \cdot \pi \cdot T}, \text{Hz}. \quad (9)$$

To complete the Prony's procedure, the roots of the polynomial calculated at the second stage are further used to form the matrix elements of equation (10), which is then solved with respect to p complex parameters h_1, \dots, h_p [19].

$$\begin{bmatrix} z_1^0 & z_2^0 & \dots & z_p^0 \\ z_1^1 & z_2^1 & \dots & z_p^1 \\ \vdots & \vdots & \dots & \vdots \\ z_1^{n-1} & z_2^{n-1} & \dots & z_p^{n-1} \end{bmatrix} \cdot \begin{bmatrix} h_1 \\ h_2 \\ \vdots \\ h_p \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_p \end{bmatrix}. \quad (10)$$

Each parameter h_i is further used to determine the amplitude A_i and the initial phase θ_i , which are calculated using the expressions [19]

$$A_i = |h_i|; \quad (11)$$

$$\theta_i = \arctg\left[\frac{\operatorname{Re}(h_i)}{\operatorname{Im}(h_i)}\right], \text{rad}. \quad (12)$$

The Prony's spectrum is defined in terms of the exponential approximation $\hat{x}[n]$, and not in terms of the original time sequence $x[n]$. Equation (10) can be concisely written in the form

$$\hat{x}[n] = \sum_{k=1}^p h_k \cdot z_k^{n-1}, \quad (13)$$

If the signal $x[n]$ is valid, then the exponents will appear as complex conjugate pairs $\exp\{\pm j[2 \cdot \pi \cdot f_k + \theta_k]\}$, which will ensure the formation of one cosine term $\cos(2 \cdot \pi \cdot f_k + \theta_k)$ z-transformation from (13)

$$\hat{X}_1[z] = \sum_{k=1}^p \frac{h_k}{1 - z_k \cdot z_k^{-1}}, \quad (14)$$

which converges for $|z_k| < |z|$. It is also assumed here that $|z_k| < 1$, i.e., in other words, all the attenuation parameters are negative, giving decaying exponents. If this is so, then substituting the form $z = \exp(j2 \cdot \pi \cdot f \cdot T)$ into expression (13) will give the discrete-time Fourier transform (DFT) of the time sequence $\hat{x}[n]$ with finite energy. Therefore, the Prony's spectral energy density (SED) for the one-sided exponential model under consideration will be determined by the expression [19]

$$S_1[f] = \left| T \cdot \hat{X}_1 \cdot \left(\exp[j2 \cdot \pi \cdot f \cdot T] \right) \right|^2, \quad (15)$$

which is defined in the frequency interval $-1/(2 \cdot T) \leq f \leq 1/(2 \cdot T)$. This spectrum is convenient for describing short-time signals.

To implement the algorithm shown in Fig. 1, the issue of determining the order of the model (p) remains unresolved. The authors proposed to use the autoregressive transfer function criterion to select a model [19]

$$ATFC[p] = \left(\frac{1}{N} \cdot \sum_{j=1}^p \bar{\rho}_j^{-1} \right) - \sum_{j=1}^p \bar{\rho}_j^{-1}, \quad (16)$$

where

$$\bar{\rho}_j = \frac{N}{N-j} \cdot \hat{\rho}_j. \quad (17)$$

In expression (15), the value of p is chosen in such a way as to minimize $ATFC[p]$. $\hat{\rho}_j$ in expression (16) is the sum of squared errors defined by the expression

$$\hat{\rho}_j = \sum_{n=1}^N |\varepsilon[n]|^2, \quad (18)$$

where

$$\varepsilon[n] = x[n] - \hat{x}[n] = x[n] - \sum_{k=1}^p h_k \cdot z_k^{n-1}. \quad (19)$$

This algorithm for determining the order of the model is effective in the absence of noise. Since the power part of the traction drive contains noises caused by temperature processes during the flow of current through the motor windings, the application of the specified criterion to determine the order of the model is incorrect.

It is proposed to apply the Wiener-Hopf procedure to the phase current signals of an induction motor [20]. The Wiener-Hopf theorem for determining stator phase currents for discrete signals has the form [21]

$$\begin{cases} x(t-kT, t-nT) = \sum_{i=0}^{N_1} \sum_{j=0}^{N_2} c_{i,j} \cdot K_I(t-(k-i) \cdot T, t-(n-j) \cdot T); \\ k \in N_1, \quad n \in N_2, \end{cases} \quad (20)$$

where $x(t-kT, t-nT)$ - function of mutual correlation of stator phase current signals and noise;
 $K_I(t-(k-i) \cdot T, t-(n-j) \cdot T)$ - autocorrelation function of the stator phase current signal.

The solution of equation (20) with respect to all unknowns $c_{i,j}$, the total number of which will be N_1+N_2+2 , made it possible to find the impulse function that minimizes the root-mean-square filtering errors of the stochastic value of the stator phase current.

Then the algorithm that implements the Prony's method for performing the task of diagnosing the AM rotor eccentricity during the rolling stock operation looks like it is shown in Fig. 2.

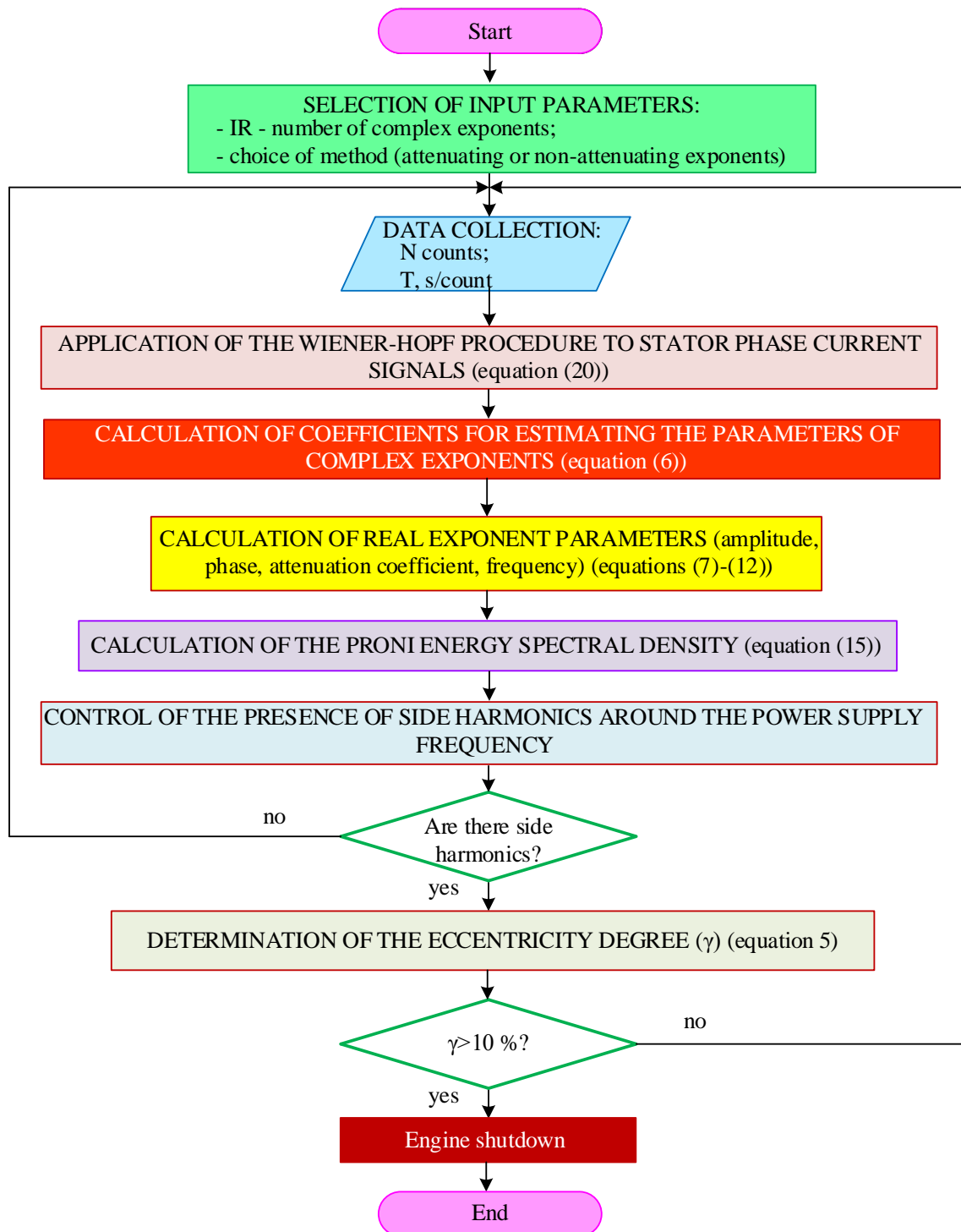


Fig. 2. Block diagram of the algorithm that implements the Prony's method for performing the task of diagnosing the AM rotor eccentricity during the rolling stock operation

In Fig. 2, the "DETERMINATION OF THE ECCENTRICITY DEGREE" unit is applied. Its use is based on such considerations. The presence of eccentricity in AM leads to the modulation of stator phase current signals by the frequencies of side harmonics (5). The presence of modulation of stator phase current signals causes the appearance of a torque on the motor shaft, which leads to a deterioration of the energy performance of the rolling stock traction drive. On the other hand, a large eccentricity degree

can lead to such a phenomenon as the engagement of the rotor of the stator windings, which will lead to damage to the motor. Therefore, with an eccentricity degree greater than 10%, the diagnostic system decides to turn off the motor.

Development of a structural diagram of the system of functional diagnostics of an induction traction motor. The rolling stock with induction traction motors operated on the railways of Ukraine uses a vector control system. Therefore, the proposed system of functional diagnostics was developed for traction drive with this control system. The structural diagram of the vector control system is shown in Fig. 3 [22].

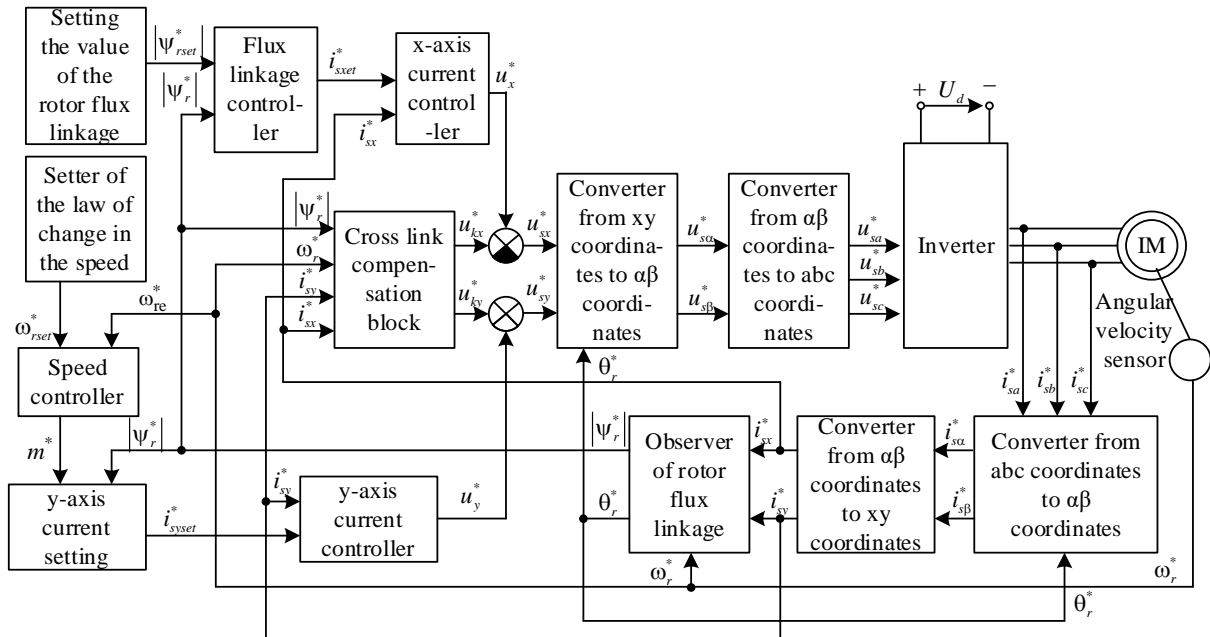


Fig. 3. Structural system of vector control of an induction traction motor

To implement the Prony's method algorithm, the following signals are required to perform the task of diagnosing the IM rotor eccentricity during the rolling stock operation (Fig. 2): stator phase currents I_{sa}, I_{sb}, I_{sc} ; slip s , frequency of the supply voltage f_s and frequency of passage of the rotor grooves f_r . The specified stator phase current signals are obtained from current sensors connected to the corresponding stator phases. In the "Observer of rotor flux linkage" unit, the angle of rotation of the coordinate system θ is determined using the equation [22]

$$\theta = \int \omega_k dt, \quad (21)$$

where ω_k – the angular frequency of rotation of the coordinate system, which is the angular frequency of the supply voltage. It is defined as

$$\omega_k = \omega_m + s, \quad (22)$$

where ω_m – the mechanical angular frequency of rotation of the motor shaft;
 s – rotor slip.

The rotor slip is determined from the equation [22]

$$s = \frac{I_{sy} \cdot k_r \cdot R_r}{\Psi_r} \tag{23}$$

That is, two more signals are additionally output from the "Observer of rotor flux linkage" unit – rotor slip s and angular frequency of rotation of the coordinate system ω_k . Since the angular frequency of rotation of the coordinate system ω_k is determined in relative units in the "Observer of rotor flux linkage" unit, the value of ω_k should be multiplied by the nominal value of the frequency of the IM supply voltage f_{snom} . The frequency of passage of the rotor grooves f_r is determined in accordance with expression (4).

Then the structural diagram of the traction drive with IM vector control and the functional diagnostics system is as shown in Fig. 4.

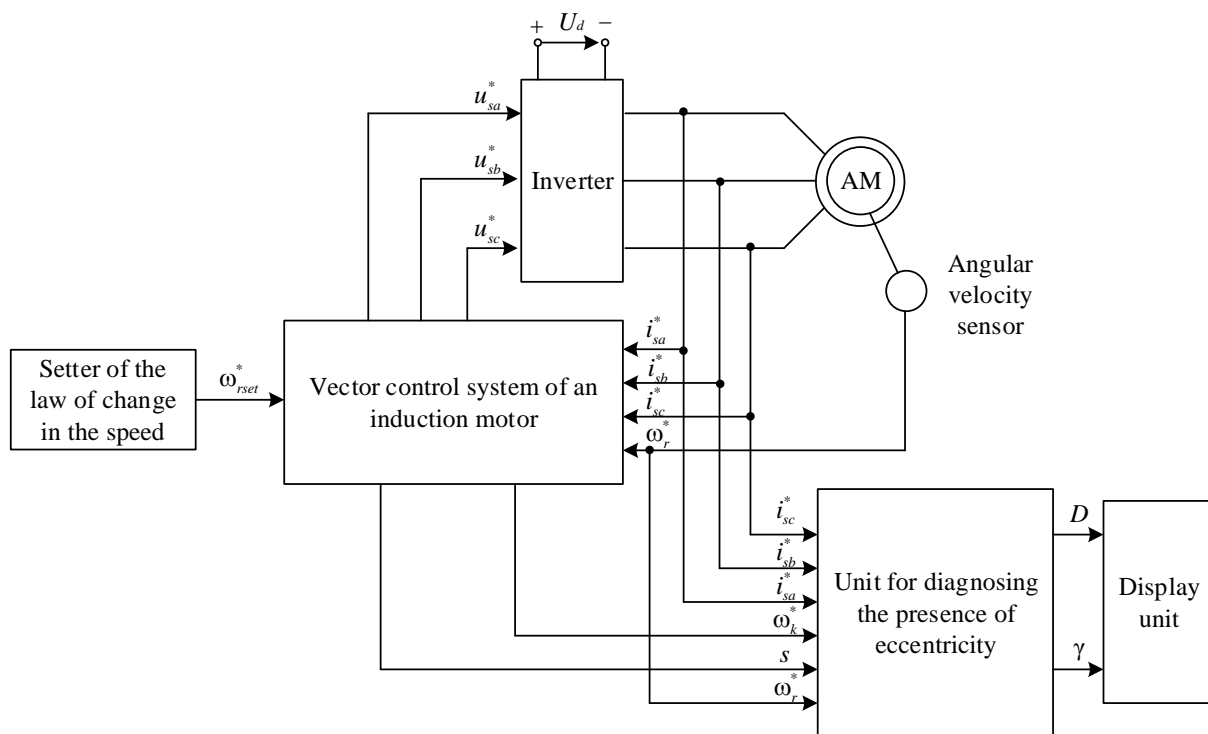


Fig. 4. Structural diagram of traction drive with IM vector control and functional diagnostics system

The structural diagram of the unit for diagnosing the presence of rotor eccentricity is shown in Fig. 5. In the "Unit of conversion from relative units to real values" the values of physical quantities coming from the control system are converted from relative units to real ones. For currents, real physical quantities are determined in accordance with the expression

$$I_s = i_s^* \cdot I_{snom}, \tag{24}$$

where i_s^* – the value of the phase current in relative units;
 I_{snom} – the nominal value of the stator phase current.

For the supply voltage frequency, the real physical quantity is determined in accordance with the expression

$$f_s = \omega_k^* \cdot f_{snom}, \tag{25}$$

where ω_k^* – the value of the angular speed of rotation of the coordinate system in relative units;
 f_{snom} – the nominal value of the supply voltage frequency.

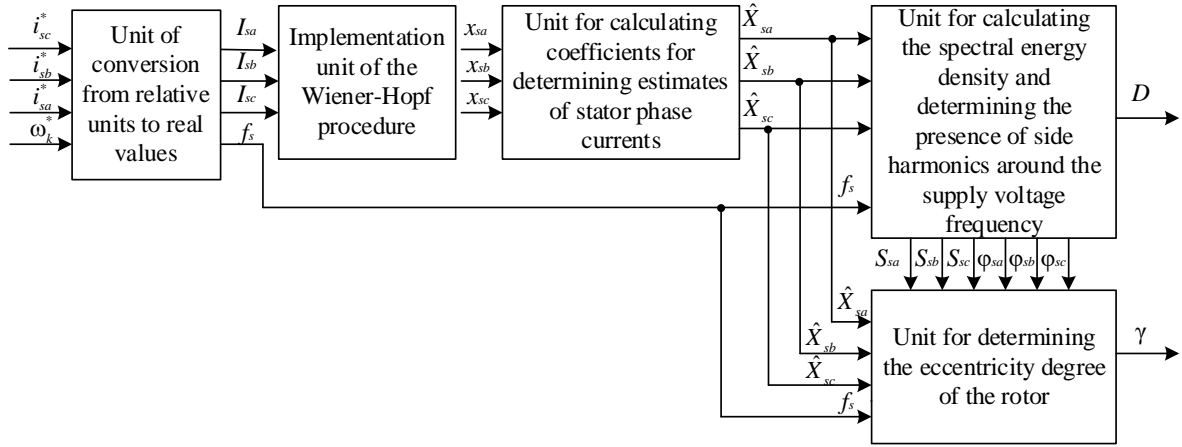


Fig. 5. Structural diagram of the unit for diagnosing the presence of eccentricity

In the Wiener-Hopf procedure implementation unit, the Wiener-Hopf procedure is applied to the stator phase currents. Stator phase current signals, from which noise has been removed (I_{sa}, I_{sb}, I_{sc}), are sent to the "Unit for calculating coefficients for determining estimates of stator phase currents" where their estimates ($\hat{X}_{sa}, \hat{X}_{sb}, \hat{X}_{sc}$) are determined. On the basis of the received estimates of the phase currents of the stator in the "The unit for calculating the spectral energy density and determining the presence of side harmonics around the supply voltage frequency", their spectral components are determined. In the presence of side harmonics around the frequency of the supply voltage, a $D=1$ signal is sent to the output of the specified unit, in the absence of a $D=0$ signal. When the signal value is $D=1$, the amplitude (S_{sa}, S_{sb}, S_{sc}) and phase ($\varphi_{sa}, \varphi_{sb}, \varphi_{sc}$) energy components of the lateral harmonic components are sent to the "Unit for determining the eccentricity degree of the rotor".

The transition from the energy of side harmonics to their amplitudes is carried out in accordance with the expression

$$I_{sm} = \frac{1}{T} \cdot \sqrt{S_s}. \quad (26)$$

The eccentricity degree is determined in accordance with expression (5). In expression (5) instead of $I_{ecc}[i]$ the value $\hat{X}_s[i]$ is substituted, and instead of $I_m - I_{sm}$. In order to avoid an error in determining the eccentricity degree, the reference number is chosen so that it does not correspond to $1/4$ and $3/4$ of the interval under investigation. Since the Wiener-Hopf procedure was applied to the signals of the stator phase currents, that is, the noise was removed, in equation (5) $\beta[i]=0$. The value of the eccentricity degree γ is displayed on the information display block. After that, the driver makes a decision about the need to disconnect the IM with eccentricity.

In the absence of asymmetric regimes of IM windings caused by their damage, the phase currents of the stator are symmetrical. In this case, it is possible to control the presence of eccentricity based on the analysis of the phase current of the stator of one of the phases. However, during the operation of the traction drive, there is a change in the parameters of the locomotive movement all the time. This leads to the appearance of unstable modes in the traction drive, which are characterized by the presence of quasi-asymmetric modes, even in the absence of damage to the IM windings. To avoid errors in diagnosing the presence of eccentricity, it is proposed to analyze the spectral components of the stator

phase currents of all IM phases. Information about the eccentricity degree is derived based on the largest value of γ obtained.

Conclusions. In this work, a system for diagnosing the presence of rotor eccentricity in traction IMs is proposed. The following results are obtained:

- the analysis of the existing methods of processing diagnostic information for the diagnosis of rotor eccentricity in traction IMs was carried out. As a result, it was established that the most effective method of processing diagnostic information when building a functional system for diagnosing the eccentricity of the IM rotor is the Prony's method. Despite its advantages, it has a significant drawback: there are no criteria for choosing the order of the model and the fitting method in conditions where the process of changing the analyzed signal is stochastic;

- the Prony's method algorithm was adapted for conditions when the process of changing the analyzed signals is stochastic. This will make it possible to obtain more correct results when diagnosing the eccentricity of the rotor in the conditions of real operation of the traction drive of the rolling stock;

- a structural diagram of the IM rotor eccentricity diagnosis unit based on the adapted Prony's method was developed;

- a structural diagram of the system for functional diagnostics of the IM rotor eccentricity as part of the traction drive with a vector control system was developed.

In order to avoid errors in determining the eccentricity degree of the rotor under conditions of unstable modes in the traction drive, it is proposed to determine the eccentricity degree for the phase currents of the stator of all IM phases. The decision to turn off the motor should be made based on the value of the largest eccentricity degree of the rotor.

The continuation of this work can be research devoted to the construction of a complex functional system of diagnostics of both a separate traction IM and the entire traction drive of rolling stock.

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Розробка системи діагностики наявності ексцентриситету ротора в тягових асинхронних двигунах

Метою роботи є розробка системи функціональної діагностики наявності ексцентриситету ротора в тягових асинхронних двигунах (АД) рухомого складу залізниць. Для досягнення поставленої мети в роботі були вирішені такі задачі: адаптовано метод Проні для виконання задачі діагностування ексцентриситету ротора асинхронного двигуна під час експлуатації рухомого складу; запропоновано алгоритм функціонування системи функціональної діагностики ексцентриситету ротора на основі адаптованого методу Проні; запропоновано структурну схему блоку діагностики ексцентриситету ротора на основі адаптованого методу Проні; запропоновано структурну схему системи функціональної діагностики ексцентриситету ротора. Найбільш важливими результатами є отримання математичної моделі методу Проні, адаптованого до виконання задачі діагностування ексцентриситету ротора асинхронного двигуна під час експлуатації рухомого складу. Адаптація алгоритму методу Проні виконана шляхом застосування до сигналів, що аналізуються, процедури Вінера-Хопфа. Це дозволить застосовувати запропонований алгоритм в умовах, коли процес зміни аналізованих сигналів носить стохастичний характер. Це дозволить визначати ступінь ексцентриситету ротора АД з більшою точністю і приймати більш правильне рішення щодо експлуатації АД з наявним ексцентриситетом ротора.

Ключові слова: асинхронний двигун, діагностика, ексцентриситет, рухомий склад