1. Sergey GOOLAK[1], 2. Oleg GUBAREVYCH[2], 3. Oleksandr GOROBCHENKO[1], 4. Oleksandr NEVEDROV[1], 5. Kateryna KAMCHATNA-STEPANOVA[3]

[1]State University of Infrastructure and Technologies, Faculty of Railway Rolling Stock Infrastructure, Department of Electromechanics and Rolling Stock Of Railways (1),
[2]Danube Institute of Water Transport of State University of Infrastructure and Technology, Department of Navigation and Operation of Technical Systems on Water Transport (2), 2. National Technical University «Kharkiv Polytechnic Institute», Institute of Education and Science in Mechanical Engineering and Transport, Department of Mechanical Engineering Technology and Metal-Cutting Machines (3)
ORCID: 1. 0000-0002-2294-5676; ORCID:2. 0000-0001-7864-0831; ORCID:3. 0000-0002-9868-3852; ORCID: 4. 0000-0001-9347-0973; ORCID: 5. 0000-0001-7825-1238.

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Investigation of the influence of the quality of the power supply system on the characteristics of an asynchronous motor with a squirrel-cage rotor

Abstract. *The paper presents the results of studies of the influence of the quality of power systems on the characteristics of an asynchronous electric motor with a squirrel-cage rotor. During the research, a mathematical model of an induction motor, made in the MATLab software environment, was used. Based on the simulation results, the coefficients of the torque ripple and the phase current unbalance were determined. The results obtained are compared with previous studies of the manifestation of turn-to-turn closures in the phases of the motor stator winding, which also create an asymmetry of the rotating magnetic field.*

Streszczenie. *W artykule przedstawiono wyniki badań wpływu jakości układów zasilających na charakterystyki silnika indukcyjnego ze zwartym wirnikiem. W badaniach wykorzystano model matematyczny silnika indukcyjnego wykonany w środowisku oprogramowania MATLab. Otrzymane wyniki porównuje się z wcześniejszymi badaniami występowania obwodów międzyzwojowych w fazach uzwojenia stojana silnika, które również tworzą asymetrię wirującego pola magnetycznego..(Badanie wpływu jakości układu zasilania na charakterystyki silnika asynchronicznego z wirnikiem klatkowym*)

Keywords: asynchronous motor, asymmetry, non-sinusoidality, ripple, unbalance.
Słowa kluczowe: silnik asynchroniczny, asymetria, niesinusoidalność, pulsacje, nierównowaga..

Introduction

Squirrel-cage induction motors are widely used in the transport infrastructure. They are used as traction motors and auxiliary drive motors on rolling stock of railways and subways, as pump motors on sea and river vessels, etc. In connection with the widespread operation of asynchronous motors as part of drives of moving objects, the question arises of creating effective diagnostic systems built into the drive to increase the reliability of their operation [1-3].

All damage that occurs in an induction motor leads to sudden failures or to gradual ones. The first type includes damage, in the event of which the electric motor becomes disabled. The second is damage with which the electric motor can still work for some time, but with changes in the values of one or several parameters. Among such damages is the turn-to-turn circuit in the stator windings of the electric motor [4-6]. Despite the fact that with such a defect, the electric motor is in a working condition, its energy performance deteriorates, the power consumed from the network increases, the average value of the stator current increases with a certain imbalance of the stator phase currents and moment pulsations appear on the motor shaft [7, 8].

When diagnosing an interturn short circuit in the stator winding, three methods can be applied. The first method is based on the fact that turn-to-turn closure leads to uneven heating of the stator windings on the one hand and an increase in the total temperature of the electric motor, on the other [9-11]. The second method is based on the fact that the occurrence of turn-to-turn closure leads to the appearance of vibration caused by pulsations of the torque on the motor shaft [12-14]. The third diagnostic method is to analyze the values of the phase currents of the stator of the electric motor [15-17].

Analysis of diagnostic methods showed that the most accurate methods based on the analysis of the values of phase currents and vibration methods [18-20].

Studies carried out in [7] showed that vibrations in an induction motor upon detection of an inter-turn circuit are most pronounced when the electric motor is in idle mode. When the electric motor is running, vibrations decrease with increasing load.

The works [21-23] present the results of scientific and applied research to determine and analyze the influence of the structural perfection of various components of the rolling stock and their connections on traction properties, which also affects the appearance of additional vibrations. However, they do not take into account the poor-quality power system on the starting characteristics of the traction units and the aspects of the influence of structural imperfections are not considered in this work.

The diagnostic systems considered above were based on the assumption that the power supply system of the electric motor is symmetrical, and the voltage waveform is sinusoidal. This hypothesis can take place when building a bench test diagnostic system. When constructing real diagnostic systems built into the composition of the reason for its application, it is incorrect. In particular, in [24-26] it is shown that the voltage system in three-phase general-purpose power supply networks is asymmetric, and the voltage form is non-sinusoidal. Moreover, in work [26] it is shown that in the contact network of the traction power supply system, the process of voltage change is a non-deterministic non-Gaussian process. In other words, in a traction supply system, the process of voltage change is a random process.

Taking into account the factor that the supply voltage system of the induction motor is asymmetric, and the voltage form is non-sinusoidal, the question arises of the influence of a poor-quality power system on the performance of an induction motor and, as a consequence, the choice of a diagnostic method taking this factor into account.

In studies [27, 28], it is shown that the asymmetry of the power supply system and the non-sinusoidal shape of the voltages cause torque ripples on the shaft of an asynchronous motor. But even when asymmetry occurs in the windings of an induction motor, torque ripples also appear [7, 8]. That is, when constructing diagnostic systems using vibration methods, ambiguity arises, caused by the influence on the vibration intensity of both a poor-quality power supply system and the presence of asymmetry in the windings of an asynchronous electric motor due to turn-to-turn closures.

The same problems arise when constructing a diagnostic system based on current methods. Poor-quality power supply of an asynchronous electric motor leads to an increase in the average value of the phase current and to the unbalance of the phase currents [27,28]. The same processes are observed in the presence of asymmetry in the windings of an induction motor [7, 8].

To build diagnostic systems using intelligent systems based on fuzzy logic methods [29], particle swarm methods [30], taboo search methods [31] and other methods of decision theory, it is necessary to determine the degree of influence on the torque pulsations and phase imbalance. currents of both a poor-quality power supply system and asymmetric modes of the windings of an asynchronous electric motor.

In this work, on the basis of the existing model, studies of the influence of a poor-quality power system on the performance of an asynchronous electric motor are carried out. During the research, the hypothesis is used that the asynchronous electric motor receives power from an autonomous thyristor voltage inverter.

The article has the following structure: in the second section, an object of research is selected and the use of a mathematical model of an asynchronous motor is substantiated, which can work with asymmetry and non-sinusoidal voltages of the power supply system. There are four experiments in the third chapter. The first assumes that a sinusoidal system of three-phase voltages is symmetrical at the output of the inverter. In the second, it is taken into account that the output of the inverter is an asymmetric sinusoidal system of three-phase voltages. In the third, it is assumed that the output of the inverter is a symmetrical non-sinusoidal system of three-phase voltages. In the fourth, it is assumed that the output of the inverter is an asymmetric non-sinusoidal system of three-phase voltages. For each of the experiments, the ripple coefficients of the torque on the motor shaft and the unbalance coefficients of the phase currents were calculated. In the fourth section, comparisons of the results obtained with the results obtained in works devoted to the study of the influence of asymmetric modes of windings of an induction motor on its performance are made. By the end of the work, there are conclusions.

Determination of the object of research and justification of the choice of a mathematical model of an asynchronous electric motor

Determination of the object of research

In the course of the research, the results of modeling the effect of a poor-quality power supply system of an asynchronous electric motor are compared with the effect of asymmetric modes of operation on the starting characteristics of an asynchronous electric motor. When determining the object of research, it is advisable to choose the same type and power of an asynchronous motor, for which a number of studies have already been carried out, in particular, the effect of asymmetric modes of its windings on starting characteristics. In works [7, 8], the indicated studies were carried out for an asynchronous electric motor with a squirrel-cage rotor of the AIR132M4 type with a power of 11kW. Therefore, it is logical to choose the specified motor as an object of research.

Technical characteristics of an asynchronous electric motor with a squirrel-cage rotor type AIR132M4 are given in Table 1 [7].

Table 1. Technical characteristics of an asynchronous electric motor with a squirrel-cage rotor of AIR132M4 type

Parameter	Value
Shaft power rating, P_{nom}, kW	11,0
Rated phase voltage, U_{nom}, V	200
Rated frequency of supply voltage, f_s, Hz	50
Rated rotation speed of a motor shaft in idle mode $n_{n.idle}$, rpm	1498
Nominal motor shaft speed n_n, rpm	1450
No loadno-load torque T_{idle}, N·m	0,38
Rated torque on the motor shaft T_n, N·m	72,671

The rest of the parameters of the asynchronous electric motor are not given, since a ready-made simulation model of the electric motor was used. More complete information on the parameters of this electric motor is given in [32].

Justification of the choice of a mathematical model of an asynchronous electric motor

In work [32], a mathematical model of an AIR132M4 induction motor in three-phase coordinates was developed. The simulation model was executed in the MATLab software environment in the form of structural elements. The developed mathematical model of an asynchronous electric motor makes it possible to study its operation in the conditions of asymmetric modes of the stator windings. However, when using it for this study, certain difficulties arose due to the fact that with unbalanced voltages of the power supply system, it is necessary to find the zero, forward and reverse sequence of voltages. After setting each of these parameters, it is necessary to implement their combination in the simulation model when determining the moment, which causes certain inconveniences in the implementation of the model.

In [33], an approach was applied to modeling an induction motor powered by a system of unbalanced voltages. In this model, the electrical part of the motor is made in the form of electrical elements of the MATLab software environment, and the magnetic and mechanical parts are in the form of structural elements. In addition, the mutual inductance of the phases is made in the form of controlled voltage sources. The control signals for these voltage sources are the respective mutual phase flux linkages. This makes it possible to carry out research under conditions of power supply of an asynchronous motor from an asymmetric and non-sinusoidal supply voltage system. Therefore, the model presented in the study [33] was adopted as a basic mathematical model.

Modeling the influence of asymmetry and non-sinusoidality of the supply voltage system of an asynchronous electric motor on its starting characteristics

Modeling the operation of an asynchronous electric motor with a symmetrical sinusoidal system of supply voltages

When carrying out the above experiments, the initial system of voltages of a conventional three-phase thyristor autonomous inverter, which is not of high quality, was taken as the basic system of supply voltages (Fig. 1).

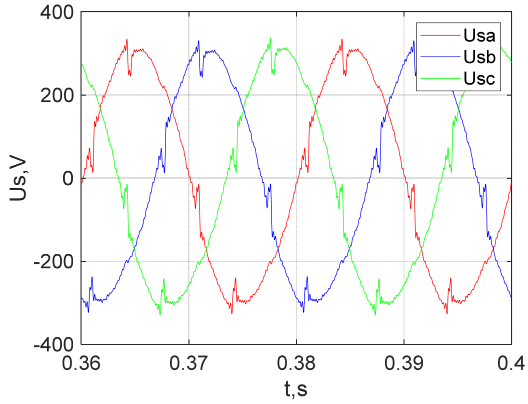

Fig. 1. Timing diagrams of the voltage system at the output of a thyristor three-phase inverter

When carrying out the first experiment, the assumption is used that the asynchronous electric motor is powered by an autonomous voltage inverter, at the output of which a sinusoidal system of three-phase voltages is symmetrical. A symmetrical sinusoidal system of three-phase voltages was obtained by means of modeling a poor-quality power supply system shown in Fig. 1. The amplitude of the voltages and the frequency of this system are equal to the nominal values, the phases of the phase voltages are shifted by 120°. The timing diagrams of such a system of voltages are shown in Fig. 2.

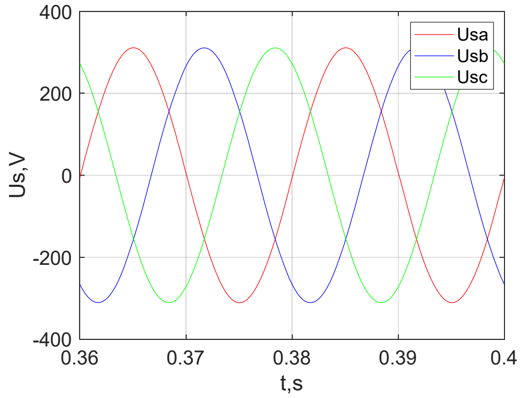

Fig. 2. Timing diagrams of a symmetrical sinusoidal voltage system

During the experiment, as a result of modeling, timing diagrams of stator currents in steady state were obtained (Fig. 3), timing diagrams of the torque on the motor shaft (Fig. 4) and timing diagrams of the motor shaft rotation frequency (Fig. 5).

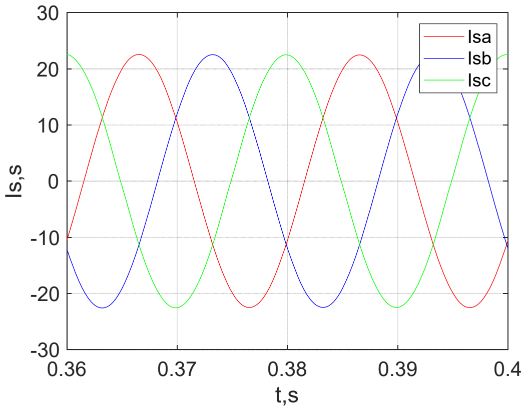

Fig. 3. Timing diagrams of stator currents in steady state, obtained during the first experiment

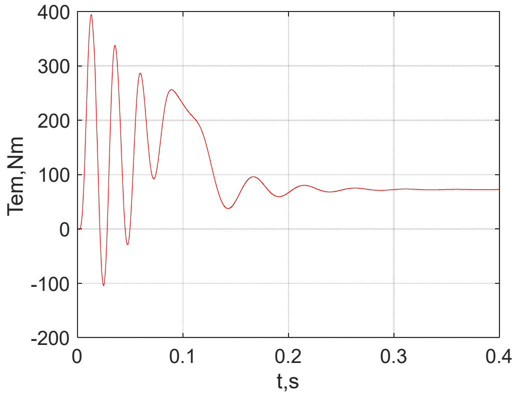

Fig. 4. Timing diagram of the torque on the motor shaft obtained during the first experiment

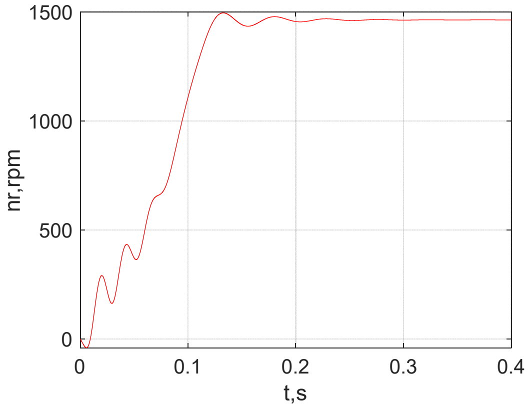

Fig.5. Timing diagram of the motor shaft speed obtained during the first experiment

For steady state, the current values of the stator phase currents in steady state, torque and speed of the motor shaft are obtained. The results of modeling the power supply of an induction motor from an autonomous voltage inverter, the output of which is a symmetrical sinusoidal system of three-phase voltages are shown in table 2 (experiment 1).

Table 2. Результати моделювання

Table 2. Simulation results

Parameter	Experiment No.			
	1	2	3	4
Stator phase current value Isa, A	21,9	22,01	25,48	24,12
Stator phase current value Isb, A	21,9	21,47	25,48	23,17
Stator phase current value Isc, A	21,9	22,87	25,48	25.38
Maximum torque value Tmax, N•m	72,92	76,46	88,69	94,02
The minimum value of the moment Tmin, N•m	72,92	65,06	57,63	52,46
Average value of the moment Tmean, N•m	72,92	70,76	73,16	73,24
Ripple frequency fp, Hz	0	100	100	100
Motor shaft speed nr, rpm	1454	1452	1453	1454
Torque ripple factor kp_T,%	0	8	21,2	28,4
Unbalanced current coefficient knbI,%	0	6,3	0	9,1

Torque ripple coefficient on the motor shaft in Table 2 is calculated according to the ratio [7]

$$(1)\quad k_{pT} = \frac{T_{\max} - T_{\min}}{2 \cdot T_{mean}} \cdot 100\%,$$

where: T_{max} – the maximum torque value, T_{min} –the minimum torque value, T_{mean} – the average torque value.

The unbalance coefficient of the stator phase currents in table 2 is calculated according to the relation [7]

$$(2)\quad k_{imbI} = \frac{I_{smax} - I_{smin}}{I_{ssym.mode}} \cdot 100\%,$$

where I_{smax} – the maximum stator current, I_{smin} – the minimum stator current, $I_{sym.mode}$ – the average stator current in symmetrical mode.

Modeling the operation of an asynchronous electric motor with an asymmetric sinusoidal supply voltage system

When carrying out the second experiment, it was assumed that the asynchronous electric motor is powered by an autonomous voltage inverter, the output of which is an asymmetric sinusoidal system of three-phase voltages. The voltage amplitudes are equal to the first harmonic component of the basic voltage system (Fig. 1): U_{sa} = 311 V, U_{sb} = 307,4 V, U_{sc} = 313,1 V. The voltage frequency is equal to the nominal value, the phases of the phase voltages are shifted by 120 °. The timing diagrams of such a system of voltages are shown in Fig. 6.

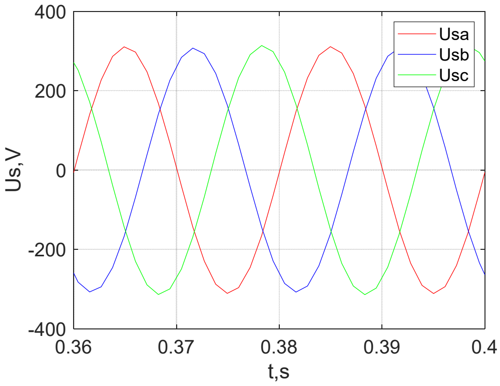

Fig. 6. Timing diagrams of phase voltages for the second experiment

During the research, as a result of modeling, timing diagrams of stator currents in a steady state were obtained (Fig. 7), a timing diagram of the torque on the motor shaft (Fig. 8) and a timing diagram of the motor shaft speed (Fig. 9).

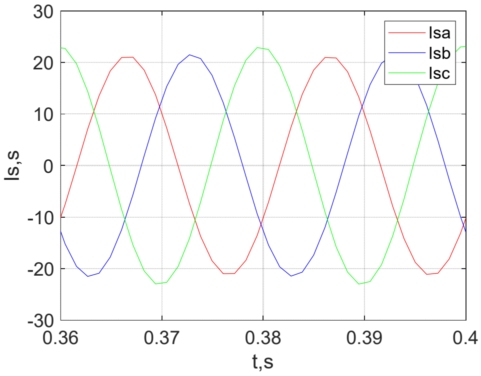

Fig. 7. Timing diagrams of stator currents in steady state, obtained during the second experiment

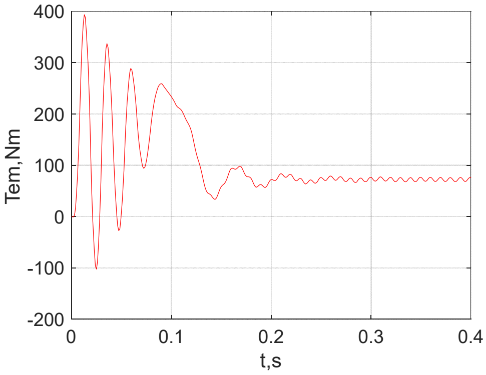

Fig. 8. Timing diagram of the torque on the motor shaft obtained during the second experiment

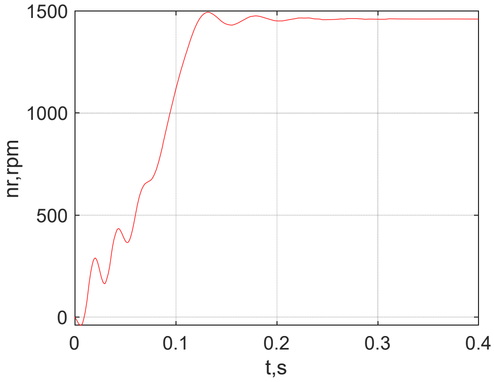

Fig. 9. Timing diagram of the motor speed obtained during the second experiment

For the steady state, the effective values of the stator phase currents, motor torque and motor shaft rotation speed are obtained.

The results of modeling the power supply of an asynchronous electric motor from an autonomous voltage inverter, at the output of which an asymmetric sinusoidal system of three-phase voltages is listed in Table 2 (experiment 2).

The coefficient of pulsation of the moment on the motor shaft (1) and the coefficient of unbalance of stator phase currents (2) were also calculated (see Table 2).

Modeling the operation of an asynchronous electric motor with a symmetrical non-sinusoidal supply voltage system

For the third experiment, the assumption is used that the asynchronous electric motor is powered by an autonomous voltage inverter, the output of which is a symmetrical non-sinusoidal system of three-phase voltages. To organize the specified power supply option, the following changes were made to the basic system: the first harmonic components of the stator phase voltages of phases B and C, equal to U_{sb} = 307.4 V, U_{sc} = 313.1 V, multiplied by the coefficients k_{sB} and k_{sC}, respectively. The first harmonic component of the voltage of phase A remains unchanged, equal to the nominal value U_{sa} = 311 V.

The coefficients k_{sB} and k_{sC} are calculated in accordance with the expressions

$$k_{sB} = \frac{U_{sA}}{U_{sB}}, \tag{3}$$

$$k_{sC} = \frac{U_{sA}}{U_{sC}}. \tag{4}$$

The timing diagrams of such a system of voltages are shown in Fig. 10.

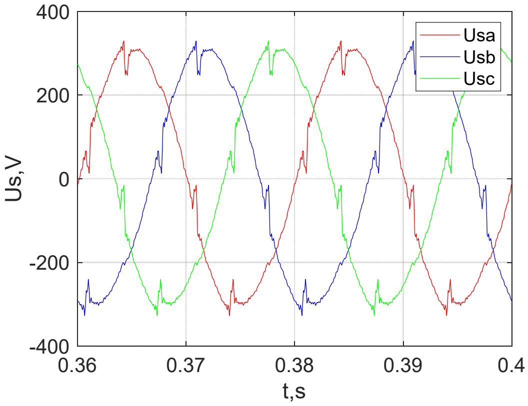

Fig. 10. Timing diagrams of phase voltages for the third experiment

During the experiment, as a result of simulation, timing diagrams of stator currents in steady state were obtained (Fig. 11), a timing diagram of the torque on the motor shaft (Fig. 12) and a timing diagram of the motor shaft rotation frequency (Fig. 13).

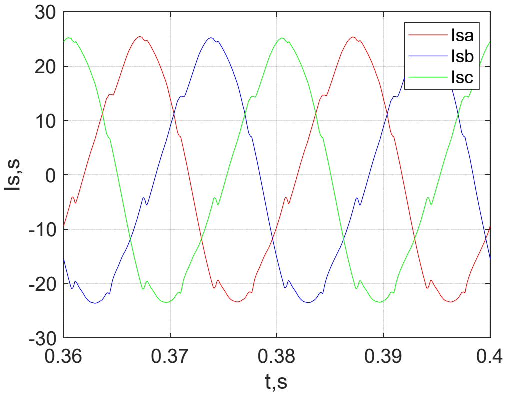

Fig. 11. Timing diagrams of stator currents in steady state, obtained during the third experiment

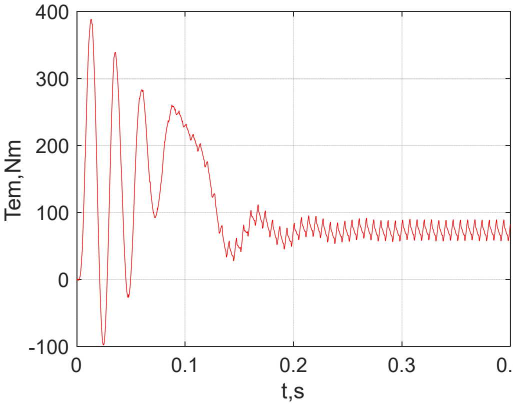

Fig. 12. Timing diagram of the torque on the motor shaft obtained during the third experiment

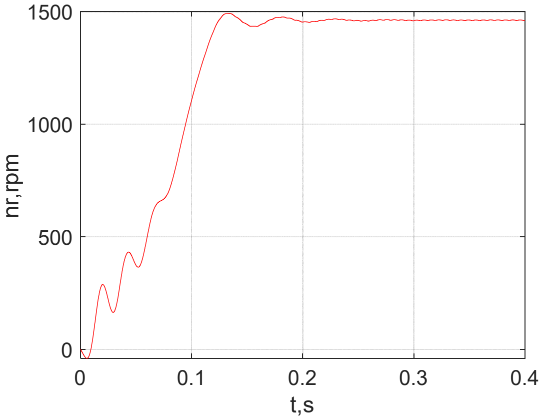

Fig. 13. Timing diagram of the motor speed obtained during the third experiment

For a stable mode, the effective values of the stator phase currents in the steady state, the motor torque and the motor shaft speed are obtained. The results of modeling the power supply of the motor from an autonomous voltage inverter, at the output of which a symmetrical non-sinusoidal system of three-phase voltages are listed in Table 2 (experiment 3).

The calculated ripple coefficients of the torque on the motor shaft (1) and the unbalance of the stator phase currents (2) are given in Table 2.

Modeling the operation of an asynchronous electric motor with an asymmetric non-sinusoidal supply voltage system

For the fourth experiment, a basic, conditionally low-quality voltage system was used as a supply voltage system (Fig. 1).

During the experiment, as a result of modeling, timing diagrams of stator currents in steady state were obtained (Fig. 14), a timing diagram of the torque on the motor shaft (Fig. 15) and a timing diagram of the motor shaft rotation frequency (Fig. 16).

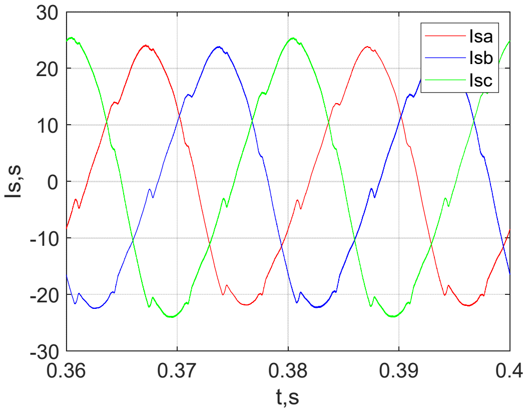

Fig. 14. Timing diagrams of stator currents in steady state, obtained during the fourth experiment

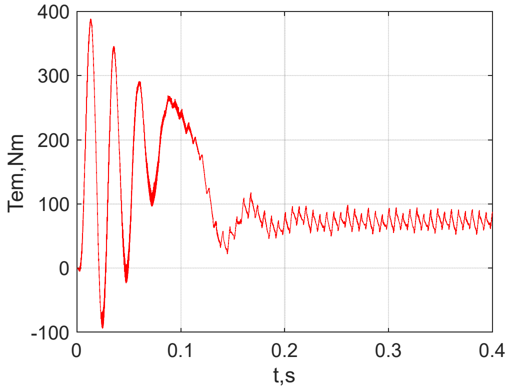

Fig. 15. Timing diagram of the torque on the motor shaft obtained during the fourth experiment

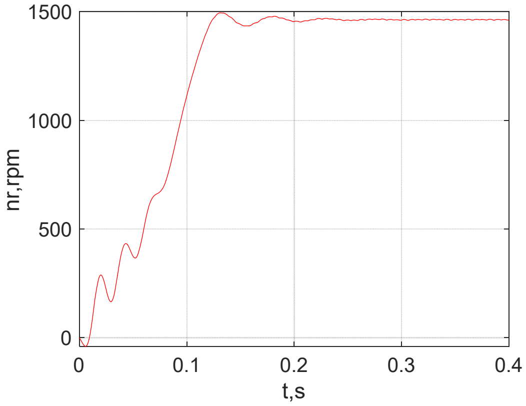

Fig. 16. Timing diagram of the motor speed obtained during the fourth experiment

For a stable mode, the effective values of the stator phase currents in the steady state, the motor torque and the motor shaft speed are obtained. The results of modeling the power supply of the motor from an autonomous voltage inverter, at the output of which an asymmetric non-sinusoidal system of three-phase voltages are listed in Table 2 (experiment 4).

The calculated ripple coefficients of the torque on the motor shaft (1) and the unbalance of the stator phase currents (2) are given in Table 2.

Comparison of the results of studying the influence of power quality with the influence of other asymmetric modes of motor windings on its characteristics

In [7], studies of the influence of the degree of turn-to-turn closure in the phase of the stator winding of the AIR132M4 induction motor on its characteristics are presented. In [8], the development of research for the same motor in the presence of turn-to-turn closure simultaneously in two phases of the winding stator is presented.

In order to determine the possibility of using vibration and current methods for diagnostics of asynchronous electric motors in conditions of a poor-quality power system, a comparison was made of the degree of influence of the power system and turn-to-turn circuit in the windings of an electric motor on its characteristics. The results of calculating the ripple coefficients and unbalance of phase currents obtained in this study and the results obtained in [7] and [8] are summarized in Table 3.

Table 3. Results of comparing the influence of the power supply system and turn-to-turn circuit on the characteristics of an asynchronous electric motor

Asynchronous motor operation mode	Parameter	
	The ripple coefficient of the moment k_{pT}, %	Coefficient of unbalanced currents k_{nbl}, %
Poor power supply system		
Asymmetrical sinusoidal voltage system	8,0	6,3
Symmetrical non-sinusoidal voltage system	21,2	0
Asymmetrical non-sinusoidal voltage system	28,4	9,1
Turn-to-turn circuit on one winding		
Closed 10% of winding turns	2,03	12,1
Closed 20% of winding turns	4,152	24,11
Turn-to-turn closure in two windings at the same time. One of the windings constantly has 20% of closed turns		
The second winding has 10% closed turns	3,424	16,53
The second winding has 20% closed turns	3,777	18,58

Analysis of the results of Table 3 shows the following:

- the influence of a poor-quality power system, as well as the presence of turn-to-turn closures in the windings of an asynchronous electric motor, cause a torque ripple;
- turn-to-turn circuit in the windings of an asynchronous electric motor causes an imbalance in phase currents. With a poor-quality power supply system, phase currents unbalance occurs only when there is an unbalance in the power supply system. With a symmetrical non-sinusoidal power supply system, there is no imbalance in phase currents;
- a poor-quality power system causes greater ripple on the motor shaft than an inter-turn circuit. Yes, the smallest torque ripples are ripples with an asymmetric sinusoidal power supply system – 8%. The largest ripple during turn-to-turn closure is ripple at 20% closure of turns of one phase of the stator winding – 4.152%.
- turn-to-turn closure contributes to the occurrence of a greater imbalance of phase currents than a poor-quality power supply system. So, the smallest unbalance of phase currents is the unbalance at 10% of winding turns closed as a result of damage, which is 12.1%, with a poor-quality power system, the largest is the unbalance caused by an asymmetric non-sinusoidal power system - 9.1%.

From the analysis of the research results, it follows that in order to build a reliable system for diagnosing turn-to-turn faults in the stator winding of the stator of asynchronous electric motors, in the presence of a poor-quality power system, it is advisable to use current methods.

CONCLUSION

To carry out the research cycle, a mathematical model of an asynchronous motor with a squirrel-cage rotor was selected, which allows, without additional model transformations, to investigate the operation of an asynchronous electric motor under conditions of a poor-quality power system. The paper presents the results of four experiments, during which the influence of a poor-quality supply system on the characteristics of an electric motor was investigated. For each of the experiments, the torque ripple coefficient on the motor shaft and the phase current unbalance coefficient were calculated. A comparison of the results obtained, the manifestation of poor-quality power supply with the influence of turn-to-turn closure on the characteristics of the electric motor, obtained in other works is carried out. According to the analysis of the results of the studies carried out, it was found that on the ripple of the torque on the motor shaft, a poor-quality power system has a greater effect than turn-to-turn closures, and turn-to-turn closures have a more significant effect on the phase current imbalance. From the studies carried out, it follows that under the conditions of a poor-quality power supply system, which takes place in transport systems, current methods are more effective than vibration ones. To improve the monitoring of the state of the operating electromechanical equipment, the use of current methods when building a system for diagnosing turn-to-turn faults in the windings of an induction motor is more.

Authors: *PhD Sergey Goolak, State University of Infrastructure and Technologies, Department of Electromechanics and Rolling Stock of Railways, E-mail: sgoolak@gmail.com; PhD, Associate Professor Oleg Gubarevych, Danube Institute of Water Transport of State University of Infrastructure and Technology, Department of Navigation and Operation of Technical Systems on Water Transport, E-mail: oleg.gbr@ukr.net; Prof. Oleksandr Gorobchenko State University of Infrastructure and Technologies, Department of Electromechanics and Rolling Stock of Railways, E-mail: gorobchenko.a.n@gmail.com; Oleksandr Nevedrov State University of Infrastructure and Technologies, Department of Electromechanics and Rolling Stock of Railways, E-mail: anevedrov2017@gmail.com; Kateryna Kamchatna-Stepanova, National Technical University «Kharkiv Polytechnic Institute», Department of Mechanical Engineering Technology and Metal-Cutting Machines, E-mail: katerina.ks@i.ua.*

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