Article citation info:
Gubarevych O, Gerlici J, Gorobchenko O, Kravchenko K, Zaika D. Analysis of the features of application of vibration diagnostic methods of induction motors of transportation infrastructure using mathematical modeling. Diagnostyka. 2023;24(1):2023111. https://doi.org/10.29354/diag/161308.

DIAGNOSTYKA, 2023, Vol. 24, No. 2

e-ISSN 2449-5220
DOI: 10.29354/diag/161308

ANALYSIS OF THE FEATURES OF APPLICATION OF VIBRATION DIAGNOSTIC METHODS OF INDUCTION MOTORS OF TRANSPORTATION INFRASTRUCTURE USING MATHEMATICAL MODELING

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Abstract
In the work, studies were carried out on the use of vibration diagnostic methods for monitoring the state of induction motors with a squirrel-cage rotor, operated in electric drives of transport equipment. The most common and difficult-to-diagnose damage to an induction motor is turn-to-turn short circuits in the stator winding, which require timely determination and establishment of the degree of damage to prevent an emergency shutdown of the equipment. The main purpose of the study is to establish the most effective areas of application of vibration diagnostic methods in determining the technical condition of the stator of induction motors under load. The experiments were carried out using simulation modeling for cases of turn-to-turn short circuits in one and two phases simultaneously, as well as with the influence of a low-quality supply voltage system on vibration parameters. The results of the work are relevant for further improvement of systems for diagnostic control of drives of transport equipment to increase the efficiency and reliability of their work.

Keywords: vibration diagnostics, simulation modelling, induction motor, stator field asymmetry, turn-to-turn short circuits

1. INTRODUCTION

Improving the efficiency of the electromechanical system of transport electrical equipment is associated with the reliable operation of all its components. This is achieved by the constant development and use of modern diagnostic methods in the embedded systems of transport electric drives for operational control, monitoring of the current state, and predicting the trouble-free operation of its elements. The main element of the electric drive, on the reliable operation of which the reliable operation of the entire vehicle depends, is the electric motor. Currently, three-phase induction electric motors with a squirrel-cage rotor, which have a significant list of significant advantages over other types of motors, have received the greatest use in electric drives of modern transport infrastructure. The main advantages include low cost, ease of maintenance and fairly high reliability. However, given the growing compliance with the functions performed by electric drives, the increase in requirements for the level of reliability and the specifics of their operating conditions in modern transport systems, where there is often a complex influence of a number of factors – a sharply changing nature of workloads, the action of vibromechanical loads, including from working mechanisms, high and low temperatures, high humidity, monitoring the current technical condition of electric motors is the most important task.

In addition to improving reliability, it also helps to reduce operating and maintenance costs, as it allows early detection of deterioration in the condition of the induction motor, facilitating preventive response, minimizing unplanned emergency and simple failures [1]. Providing state-based monitoring has become an important task for engineers and researchers mainly in industrial applications such as railways, water transport, industrial process drives, agriculture, etc.

The current state and trends in the field of monitoring for the detection and diagnosis of failures of induction motors are considered in [2, 3], where several monitoring methods are defined and presented for diagnosing faults in induction motors using non-invasive data collection methods.

On the basis of the data obtained, automatic timely maintenance planning and forecasting of failure aspects are carried out. For the development and application of forecasting processes, setting up programs for monitoring the condition of machines, data interpretation and diagnostic methods necessary for accurate prediction, setting up programs for monitoring the condition of machines, the relevant international standards are established [4-6].

This also confirms the special attention to the technical monitoring of operating equipment with the determination of the current state.

In recent years, vibration diagnostics, which is one of the main methods of non-destructive testing, is considered the most common and effective method for determining the technical condition of electric motor elements [7, 8]. Using this method, it is possible to control equipment, diagnose malfunctions, predict the further development of equipment malfunctions and the period of uptime. The advantage of vibration diagnostics is the possibility of monitoring the parameters of the current state of electromechanical equipment during its operation. In [9], the development of a computational model equipped with a classifying algorithm is presented to obtain vibration readings from electric motors and determine whether the machine has a faulty behavior, and if so, the establishment of the type of fault. In order for the algorithm to determine the type of failure, a data set with readings from multiple motors under different failure conditions must be developed to train the model. The active development of vibration diagnostic methods is due to the high information content of the spectra of vibrational defects and the rapid development of computer technologies, which makes it possible to establish the type of defect and analysis without dismantling the equipment. Monitoring and diagnostic systems based on these methods ensure the extraction of informative features from the measured signal and the registration of their exceeding the limit values that must be available for comparison for the entire range of motors used. In [10], an analysis of the operation of electric motors is presented by assessing the vibration characteristics caused by bearing failures, looseness of case bearings and rotor imbalance, and in [11] a method for diagnosing traction electric drives based on vibration levels is developed. For what the value of permissible vibration accelerations of electric machines of electric buses is determined, allowing to evaluate their technical level.

At the same time, taking into account the variety of defects and differences in vibrational spectra at different stages of their development, it complicates the accuracy of their differentiation. Vibration diagnostics has also become widespread in monitoring the state of the corresponding electric drives in modern transport systems. However, there are common defects in induction electric motors, for which it is impossible to accurately determine the type and degree of their development by vibration methods, and at the same time predict their uptime.

2. THE AIM AND OBJECTIVES OF RESEARCH

The aim of research is to establish the features of the application of using vibration methods in diagnosing the current state of the stator winding of a three-phase induction electric motor with a squirrel-cage rotor using mathematical modeling methods.

To achieve this aim, the following tasks were performed:

- a simulation model of an induction electric motor with established adequacy and the ability to create asymmetry of the stator magnetic field due to damage to the winding phases has been selected;
- mathematical modeling was carried out to obtain the values of vibration parameters during turn-to-turn short circuits on one stator phase;
- mathematical modeling was carried out to obtain the values of vibration parameters in case of turn-to-turn short circuits on two phases of the stator simultaneously;
- mathematical modeling was carried out to obtain the values of vibration parameters for an asymmetric (poor quality) system of motor supply voltages;
- an analysis of the obtained values of the vibration parameters was carried out to determine the type of damage to the motor stator.

3. CAUSES OF VIBRATION

Vibrations of electrical machines can occur at idle, then the source of the defect is of a magnetic nature and under load, then the source of the problem is of a mechanical nature. However, there are defects of an electromagnetic nature, and their installation is necessary during the operation of the electric motor, that is, under load [8, 9, 12-14].

Vibration-causing defects include:

in case of damage to the stator

- turn-to-turn short circuit in the stator winding;
- weakening of the pressing of the stator package;
- general weakening of the fastening elements of the stator core;
- delamination of extreme sheets and steel packages;
- ellipse of the internal bore of the stator along the axis of rotation of the rotor;
- incorrect mutual axial mounting of the active packages of the rotor and stator;
- stator eccentricity:
- manufacturing defect of the laminated stator steel package,
- a defect in the installation of the stator during the installation of the electrical machine (may also occur as a result of the weakening of the foundation);

in case of damage to the rotor

- breakage or violation of contact in the rods or rings of the "whitening cage";
- destruction of key connections;
- twisting (bending) of the shaft;
- eccentricity of the outer surface of the rotor relative to the axis of its rotation;
- weakening of the pressing of the entire package of steel of the rotor or only in the area of the teeth;
- unbalance of the rotor; - unsatisfactory articulation of the output end of the shaft with the actuator (quality and defects of the couplings);
- unsatisfactory balance of the machine fan.

in case of violation of the condition of bearing assemblies
- destruction of bearings;
- wear of bearing shields seating surfaces.

For most of the above defects, vibration methods sufficiently meet the requirements of operation and vibration monitoring provides continuous monitoring of the general condition of the machine and alarm in case of exceeding the maximum permissible vibration level. For a number of defects of mechanical damage, such as damage to bearing assemblies, the appearance of an unbalance of the rotor, it is possible to predict the time of trouble-free operation, taking into account the accumulated base of vibration spectra of vibration signals of typical assemblies. One of the most frequent defects of an induction electric motor, which is considered the most difficult to determine, is an turn-to-turn short circuit in the winding stator phase [15-17] (Fig. 1).

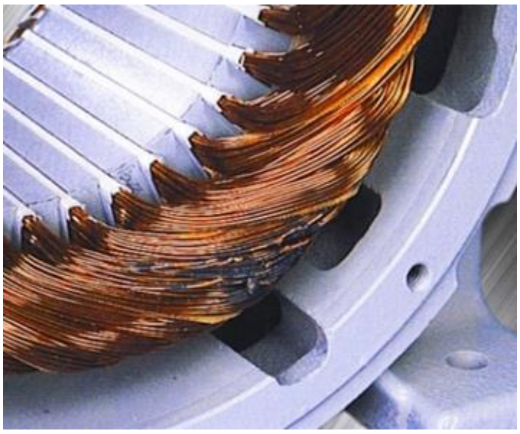


Fig. 1. Turn-to-turn short circuits in the stator winding

The presence of a turn-to-turn circuit in the stator phase leads to the creation of an asymmetric rotating magnetic field, which contributes to the appearance of vibration both in idle mode and under load [12, 18].

From the analysis of the effect of turn-to-turn short circuit in the phase of the stator winding on the characteristics and parameters of an induction motor with a squirrel-cage rotor, carried out in [12], it follows:
- turn-to-turn short circuit in the phase of the stator winding leads to an increase in the pulsations of the electromagnetic torque of the motor and is accompanied by the appearance of vibration;
- turn-to-turn short circuit in the phase of the stator winding leads to an increase in the current in the damaged phase, and, accordingly, to an increase in active power losses, accompanied by an increase in the temperature of the motor parts;
- turn-to-turn short circuit in the stator phase of the winding leads to an increase in the unbalance of the stator phase currents and, as a result, to the asymmetry of the rotating stator field.

From this it follows that thermal, electrical and vibration diagnostic methods can be used to identify, identify and differentiate the indicated malfunction. Examples of using various methods for diagnosing the state of the stator of electric motors are given in [19 -20]

Given that this type of defect has a severe manifestation followed by a sudden failure of the entire electric motor in emergency mode, its identification and determination of the type and degree of damage is one of the main diagnostic tasks for predicting the period of failure-free operation of an induction electric motor. When using various diagnostic methods, it is necessary to use special sensors to detect damage [21-23]. When conducting research on the use of vibration methods for diagnosing turn-to-turn short circuit, the influence of supply voltage asymmetry and the case of damage in two phases of the stator winding at once are not taken into account. To use the vibration characteristics caused by stator damage in the creation of diagnostic systems, additional studies are required.

When conducting modern research to study electromechanical and dynamic processes, establishing a number of patterns and areas of application of various diagnostic methods for their detection, methods of mathematical modeling are widely used [12, 18, 24].

4. MATHEMATICAL MODEL OF AN INDUCTION MOTOR FOR THE STUDY OF VIBRATIONAL PROCESSES IN THE CASE OF TURN-TO-TURN CIRCUIT

The object of research is an induction motor with a squirrel-cage rotor, model AIR132M4 11.0 kW, the passport parameters of which are given in Table 1.

Table 1. Passport parameters of an induction motor with a squirrel-cage rotor AIR 132M4

Parameter	Designation	Unit	Value
Rated motor power	P_n	kW	11,0
Rated phase voltage	U_n	V	220
Supply voltage frequency	f_n	Hz	50
Rotor speed in idle mode	$n_{n.idle}$	rpm	1498
Idle moment	T_{idle}	N·m	0,38
Stator active resistance	r_1	Ohm	0,5
Active resistance of the rotor winding, reduced to the stator winding	r'_2	Ohm	0,36
Stator reactance	x_1	Ohm	0,56
Number of stator phase turns	w	-	96
Average winding length	l_{idle1}	м	0,706
Rotor speed in nominal mode	n_n	rpm	1450
Rated torque on the motor shaft	T_n	N·m	72,671
Motor moment of inertia	J	кg·m^2	0,04

When choosing a mathematical model for researching turn-to-turn short circuits in the phases of the stator winding of an induction motor, it is necessary to take into account the possibility of creating an asymmetric rotating field in it, which occurs during turn-to-turn short circuits of varying degrees.

For research, a simulation model of an induction motor was chosen, made in the MATLab software environment, the principles of which are given in [25], and the implementation is in [12, 18]. The choice of the model is due to the established level of adequacy of its operation in different operating modes [26].

The adopted simulation model of an induction motor with a squirrel-cage rotor is written in retarded coordinates. The systems of equations describing the operation of the motor look like

$$\begin{cases} u_{s\alpha} = r_{s\alpha} \cdot i_{s\alpha} + d\psi_{s\alpha} / dt; \\ u_{s\beta} = r_{s\beta} \cdot i_{s\beta} + d\psi_{s\beta} / dt; \\ u_{s\gamma} = r_{s\gamma} \cdot i_{s\gamma} + d\psi_{s\gamma} / dt; \\ -u_{r\alpha} = r_{r\alpha} \cdot i_{r\alpha} + \dfrac{d\psi_{r\alpha}}{dt} + \dfrac{\left(\psi_{r\beta} - \psi_{r\gamma}\right) \cdot p \cdot \omega_r}{\sqrt{3}}; \\ -u_{r\beta} = r_{r\beta} \cdot i_{r\beta} + \dfrac{d\psi_{r\beta}}{dt} + \dfrac{\left(\psi_{r\gamma} - \psi_{r\alpha}\right) \cdot p \cdot \omega_r}{\sqrt{3}}; \\ -u_{r\gamma} = r_{r\gamma} \cdot i_{r\gamma} + \dfrac{d\psi_{r\gamma}}{dt} + \dfrac{\left(\psi_{r\alpha} - \psi_{r\beta}\right) \cdot p \cdot \omega_r}{\sqrt{3}}, \end{cases} \quad (1)$$

where – u voltage, V; i – current, A; t– time, s; r – resistance, Ohm; ψ – flux linkage, Wb; p – the number of pairs of poles; α, β, γ – indices indicating belonging to the corresponding phase; subscript s – belonging to the stator phase; subscript r –belonging to the phase of the rotor; ωr – rotor speed, rad/s.

The electromagnetic torque equation of an induction motor

$$T_{EM} = \sqrt{3} \cdot M \cdot p \cdot \Big[\left(i_{s\alpha} \cdot i_{r\gamma} + i_{s\beta} \cdot i_{r\alpha} + i_{s\gamma} \cdot i_{r\beta} \right) - \\ - \left(i_{s\alpha} \cdot i_{r\beta} + i_{s\beta} \cdot i_{r\gamma} + i_{s\gamma} \cdot i_{r\alpha} \right) \Big] / 2. \quad (2)$$

The equation of rotation of the motor shaft with a single-mass mechanical system

$$d\omega_r / dt = J \cdot \left(T_{EM} - T_S \right), \quad (3)$$

where T_{EM} – the moment of inertia of the rotating masses on the rotor shaft, N·m; T_S – static torque on the rotor shaft, N·m.

To simulate the operation mode of an induction motor with asymmetric windings, which occurs in the event of damage to one or more stator windings, the model specifies a change in the active resistance of the corresponding winding (windings) and leakage inductance. To determine the change in the mutual inductance of the windings, it is calculated what effect the change in the complex resistance of one winding (several windings) has on the inductance of the magnetic circuit. That is, it is established how much the actual values of the specified parameters differ from the nominal values. After that, changes in the mutual inductance of the windings are taken into account in the proposed model during simulation [25].

Thus, the implementation of the turn-to-turn short circuit on the model is performed by reducing the complex resistance of the stator phase winding, simulating the short circuit of the turns as a percentage of the total number in the undamaged winding phase, taking into account the change in the mutual inductance of the windings.

5. INVESTIGATION OF THE INFLUENCE OF TURN-TO-TURN SHORT CIRCUIT IN ONE PHASE OF THE STATOR WINDING OF AN INDUCTION MOTOR ON THE TORQUE PULSATION ON THE SHAFT

The research methodology includes modeling the values of a number of parameters of an induction motor with an intact stator and in the presence of turn-to-turn short circuits, causing a decrease in the active and complex resistances of one phase of the stator winding. The parameter values are calculated for a symmetrical (intact) stator and with a decrease in the active and complex phase resistances by 10% and 20%, which is caused by the closure of a different number of turns (degree of damage), which corresponds to 90% and 80% of the undamaged part of the winding, respectively. To analyze the nature of the manifestation of turn-to-turn short circuits during the operation of the electric motor, experiments were carried out for idle and nominal mode. The simulation results are presented in Table 2.

In table 2, the pulsation factors of the electromagnetic torque, to assess the manifestations of vibration of the motor rotor, are calculated by the formula [27]:

$$k_{pT} = \frac{T_{\max} - T_{\min}}{2 \cdot T_{mean}} \cdot 100\%, \quad (4)$$

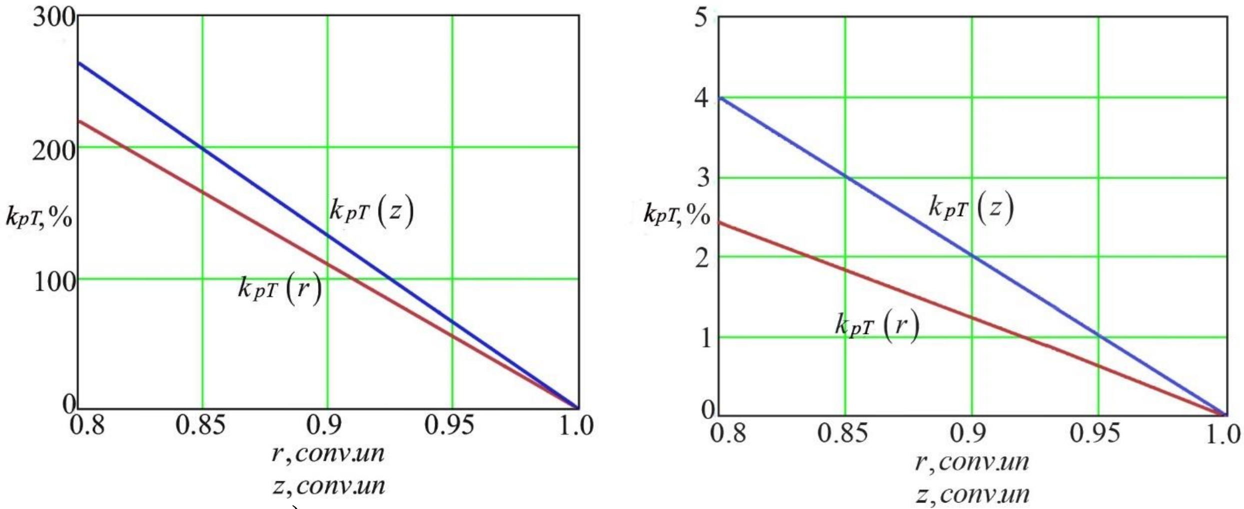
where $T_{\max}$ – the maximum value of the moment $N \cdot m$; $T_{\min}$ – the minimum value of the moment, $N \cdot m$; T_{mean} – the mean value of the moment; $N \cdot m$.

Based on the results of Table 2, graphs of the dependence of the pulsation factor of the electromagnetic torque on the change in the active $k_{pT}(r)$ and complex $k_{pT}(z)$ resistances of the stator phase for the idle mode (Fig. 2, a) and the nominal mode (Fig. 2b) are plotted.

In the presence of damage to one phase of the winding stator, the dependence is linear (Fig. 2). From fig. 2 it follows that more significant changes occur with the pulsation of the electromagnetic torque when the active and complex resistance of one phase changes in the idle mode. So, the change in the pulsation factor in the idle mode is from 0 to 263,67%, while for the nominal mode the range of changes in the coefficient is 0 – 4,0%. That is, the use of the vibration method to effectively determine the turn-to-turn short circuit of the winding stator is advisable in the idle mode, where vibration manifestations are of great importance. It also follows from Figure 2 that the torque pulsation factor depends more on the change in the complex phase resistance than on the change in the active one. In this regard, when conducting further experiments, it is advisable to consider for analysis only the change in the complex resistance of the stator winding phase.

Table 2. The results of modeling the turn-to-turn circuit in one phase of the stator winding of an induction motor

Parameter	Idle mode					Nominal mode				
	Undamaged stator	Active resistance		Complex resistance		Undamaged stator	Active resistance		Complex resistance	
		90%	80%	90%	80%		90%	80%	90%	80%
Rotation frequency, n, rpm	1498	1498	1498	1498	1498	1450	1450	1450	1450	1450
Average electromagnetic moment $T_{mid}, N \cdot m$	0,3804	0,3811	0,3821	0,5064	0,5079	72,443	72,823	74,423	72,695	73,989
Max. electromagnetic moment $T_{\max}, N \cdot m$	0,3804	0,799	1,236	1,1742	1,8471	72,443	73,709	76,261	74,066	76,95
Min. electromagnetic moment, $T_{\min}, N \cdot m$	0,3804	-0,037	-0,4719	-0,1614	-0,8313	72,443	71,937	72,585	71,324	71,028
Torque pulsation frequency, f_{puls}, Hz	0	100	100	100	100	0	100	100	100	100
Effective current of the stator phase A, I_{1A}, A	9,403	9,583	9,762	10,219	11,148	21,8	21,816	22,636	22,996	24,76
Effective current of the stator phase B, I_{1B}, A	9,403	9,379	9,371	9,443	9,465	21,8	21,326	21,681	21,228	20,967
Effective current of the stator phase C, I_{1C}, A	9,403	9,253	9,099	9,52	9,627	21,8	21,051	21,074	21,389	21,297
Lagging angle of current from voltage in phase A, $\varphi_{1A}, grad$	88,38	90,9	91,98	89,92	88,56	31,32	33,3	35,46	32,22	33,3
Lagging angle of current from voltage in phase B, $\varphi_{1B}, grad$	88,38	86,76	85,5	86,76	85,5	31,32	29,16	28,98	30,42	30,42
Lagging angle of current from voltage in phase C, $\varphi_{1C}, grad$	88,38	87,3	87,3	88,38	89,82	31,32	30,78	28,62	31,86	31,86
Operating current of the rotor phase A, I_{2A}, A	0,091	0,041	0,123	0,177	0,317	18,713	18,667	19,059	19,286	19,914
Operating current of the rotor phase B, I_{2B}, A	0,091	0,145	0,233	0,115	0,278	18,713	18,466	18,664	18,661	18,268
Operating current of the rotor phase C, I_{2C}, A	0,091	0,186	0,286	0,292	0,45	18,713	18,859	19,493	19,081	19,491
Rotor current lagging angle from voltage in stator phase A, φ_{2A}, deg	180,18	257,67	329,58	234,36	270,9	187,38	187,38	190,8	188,46	188,46
Rotor current lagging angle from voltage in stator phase B, φ_{2B}, deg	180,18	137,16	16,38	106,92	57,48	187,38	185,58	185,58	184,86	186,66
Rotor current lagging angle from voltage in stator phase C, φ_{2C}, deg	180,18	195,48	199,08	169,56	167,4	187,38	187,2	186,12	184,86	183,78
Pulsation factor of the electromagnetic moment, $k_{pT}, \%$	0	109,62	219,25	131,84	263,67	0	1,217	2,434	2,001	4,002



a) b)

Fig. 2. Graphs of the dependence of the pulsation factor of the electromagnetic torque with a change in the active r and complex z resistance of the phase A of the stator y: a) idle mode; b) nominal mode

6. INVESTIGATION OF THE INFLUENCE OF SIMULTANEOUS TURN-TO-TURN SHORT CIRCUIT ON TWO PHASES OF THE STATOR OF AN INDUCTION MOTOR ON THE TORQUE PULSATION ON THE SHAFT

In order to establish the degree of influence of turn-to-turn short circuits simultaneously on two phases of the stator winding on the pulsation of the electromagnetic torque, the values of the stator parameters were simulated for the following cases:

1) closing 20% of the turns of the winding only on phase A, in which the number of undamaged turns of the winding is 80% of its nominal value;

2) short circuit of 20% of winding turns on phase A and simultaneous short circuit of 10% of turns on phase B, i.e. respectively, at 80% of the undamaged part of the winding A and 90% of the undamaged part of the winding B;

3) closing 20% of the winding turns on phase A and simultaneously closing 20% of the turns on phase B, respectively, with 80% of the undamaged part of the winding A and 80% of the undamaged part of the winding B.

The studies were carried out for idle and nominal mode. Imitation of the degree of damage to the winding is implemented by reducing the corresponding percentage of the complex resistance of the corresponding phases from their nominal value.

The simulation results for various motor operating modes are given in Table 3.

From the simulation results obtained, shown in Table 3, it follows that the pulsation factor of the electromagnetic torque k_{pT} in the idle mode has significantly higher values than for the nominal mode of operation of the electric motor. Based on the simulation results, a graph of the dependence of the coefficient of electromagnetic pulsations on the degree of damage to the winding of phase B was plotted at a constant value of the degree of damage to the winding of phase A of 20% (80% of the undamaged part). Taking into account insignificant fluctuations in the values of the electromagnetic torque pulsation factor at nominal mode, the dependence is plotted only for the motor idle mode and is shown in Figure 3. When plotting the dependence, the complex resistance of the phase B winding changed from the nominal value of 100% (0) to 80% (0,8) in steps of 5% (0,5).

Based on the results of damage modeling simultaneously on two phases of the motor stator winding, a parabolic form of the dependence of the electromagnetic torque pulsation factor on the change in the complex phase resistance was obtained (Fig. 3).

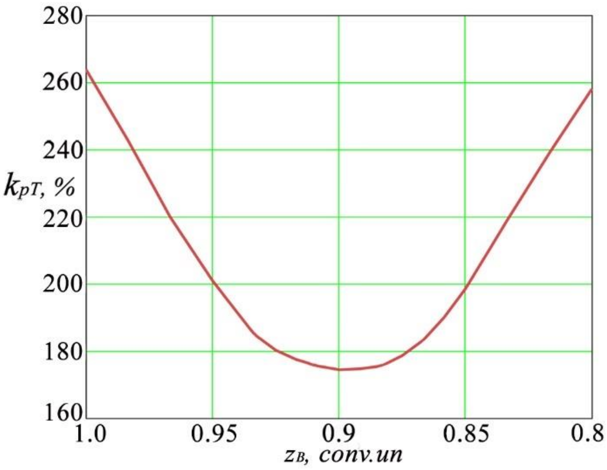


Fig. 3. Graph of the dependence of the pulsation factor of the electromagnetic torque when the complex resistance of phase B changes with a damaged phase A by 20%

Table 3. Simulation results of damages in two phases of the stator winding of an induction motor simultaneously

Parameter	Idle mode			Nominal mode		
	The number of whole turns of the winding of phase A - 80%			The number of whole turns of the winding of phase A - 80%		
	The number of whole turns of the winding of phase B			The number of whole turns of the winding of phase B		
	100%	90%	80%	100%	90%	80%
Rotor speed n, rev/min	1498	1498	1498	1450	1450	1450
Average electromagnetic torque T_{midle}, N·m	0,5079	0,619	0,5276	72,878	73,02	73,24
Maximum electromagnetic torque T_{max}, N·m	1,8471	1,6979	1,8895	74,938	74,56	75,01
Minimum electromagnetic torque T_{min}, N·m	-0,8313	-0,4599	-0,8344	68,886	69,56	69,48
Torque pulsation frequency f_{puls}, Hz	100	100	100	100	100	100
Effective current of the stator phase A I_{1A}, A	11,553	11,99	12,456	25,566	25,52	25,39
Effective current of the stator phase B I_{1B}, B	9,805	10,923	12,244	20,29	23,34	25,12
Effective current of the stator phase C I_{1C}, B	9,974	10,242	10,513	20,318	21,9	21,339
Pulsation factor of the electromagnetic moment k_{pT}, %	263,67	174,32	258,21	4,152	3,424	3,777

Thus, when the pulsations caused by damage to one phase (A) reach a certain vibration frequency (k_{pT} = 263,67%), after the onset of damage to the second phase (B), the pulsation coefficient decreases, which is explained by an increase in the inductive component of the winding
resistance. Such an increase provides intermediate "alignment" of the complex resistances of the motor windings. With a further decrease in the complex resistance of the phase of the second winding (B) by more than 10% of the nominal, the possibility of inductive compensation of its complex resistance is exhausted and the pulsation of the electromagnetic torque increases almost to the initial value (k_{pT} = 258,21%). The parabolic form of the dependence of the coefficient of electromagnetic torque pulsations was also obtained for the nominal mode of operation of the motor, but it has a much less pronounced form (Table 3).

From the results of the studies carried out and the obtained nature of the dependence of electromagnetic pulsations in case of damage to two phases of the stator winding at the same time, it follows that it is impossible to accurately differentiate the degree and type of turn-to-turn short circuit of the stator winding of an induction motor according to the pulsations of the electromagnetic torque, i.e. vibration indicators.

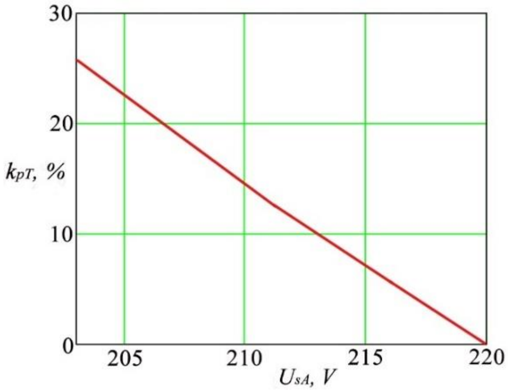
7. INVESTIGATION OF THE INFLUENCE OF THE ASYMMETRY OF THE POWER SUPPLY SYSTEM OF AN INDUCTION MOTOR ON THE PULSATION OF THE ELECTROMAGNETIC TORQUE ON THE SHAFT

To study the influence of the asymmetry of the power supply system of an induction motor, which occurs with a poor-quality power supply system during the operation of transport equipment, mathematical modeling of the operation of an induction motor with a change in the interfacial voltage in the power supply system was carried out. The phase-to-phase voltage varied with a step of 2% of the nominal value between two phases in the supply voltage system of a three-phase induction electric motor. For the nominal mode and idle mode of operation of an induction motor, which has no winding damage, the values of the pulsation coefficients of electromagnetic torques on the shaft are calculated for the following values of the phase supply voltage of phase A: U_{sa1}=220 V, U_{sa2}=215,5 V, U_{sa3}=211 V, U_{sa4}=207 V, U_{sa5}=203 V. In this case, the phase voltages of phases B and C have nominal values (U_{sb}=U_{sc}=220 V). The simulation results are shown in the Table 4.

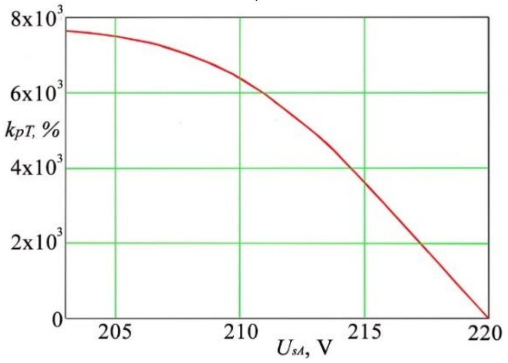
Based on the simulation results, plots of dependences of the pulsation coefficient of the electromagnetic torque with asymmetry of the supply voltage system of the induction motor for the nominal operating mode (Fig. 4, a) and idle mode (Fig. 4, b) are plotted.

Table 4. The results of modeling the parameters of the operation of an induction motor with an asymmetric power system

Parameter	Nominal mode					Idle mode				
	U_{sa1}=220, V	U_{sa2}=215,5 V	U_{sa3}=211, V	U_{sa4}=207, V	U_{sa5}=203, V	U_{sa1}=220, V	U_{sa2}=215,5, V	U_{sa3}=211, V	U_{sa4}=207, V	U_{sa5}=203, V
	U_{sb}=220, V	U_{sb}=220, V	U_{sb}=220, V	U_{sb}=220, V	U_{sb}=220, V	U_{sb}=220, V	U_{sb}=220, V	U_{sb}=220, V	U_{sb}=220, V	U_{sb}=220, V
	U_{sc}=220, V	U_{sc}=220, V	U_{sc}=220, V	U_{sc}=220, V	U_{sc}=220, V	U_{sc}=220, V	U_{sc}=220, V	U_{sc}=220, V	U_{sc}=220, V	U_{sc}=220, V
Average electromagnetic torque T_{midle}, N·m	72,443	71,97	72,01	72,21	71,61	0,3804	0,1485	0,165	0,2	0,25
Maximum electromagnetic torque T_{max}, N·m	72,443	76,61	81,14	85,82	89,33	0,3804	4,991	9,842	14,64	19,36
Minimum electromagnetic torque T_{min}, N·m	72,443	67,33	62,88	58,59	53,89	0,3804	-4,694	-9,512	-14,24	-18,86
Torque pulsation frequency . f_{puls}. Hz	100	100	100	100	100	0	100	100	100	100
Effective current of the stator phase A I_{1A}, A	21,879	21,26	20,25	19,67	18,99	9,403	9,181	7,724	6,324	5,011
Effective current of the stator phase B I_{1B}, *B*	21,879	23,11	24,42	25,99	27,27	9,403	10,96	11,4	12,02	12,83
Effective current of the stator phase C I_{1C}, *B*	21,879	21,68	21,71	21,77	22,03	9,403	11,9	13,16	14,46	15,79
Pulsation factor of the electromagnetic moment k_{pT}, %	0	6,45	12,89	19,34	25,78	0	3260,94	5864,85	7220	7644



a)



b)

Fig. 4. Graphs of the dependence of the pulsation coefficient of the electromagnetic torque with the asymmetry of the supply voltage system for:
a) nominal mode; b) idle mode

As follows from the dependences obtained, when the phase voltage changes in one phase in the motor power supply system, the manifestations of vibration in the idle mode are much higher than in the nominal mode. When the motor is running under load, the value of the pulsation coefficient of the electromagnetic torque when the voltage in one phase changes from 220V to 203V changes in the range of 0 – 25,78%. In the idle mode, the pulsation coefficient of the electromagnetic torque when the phase voltage changes in the limit of 220V – 203V reaches the range of 0 – 7644%, which indicates a high impact on the vibration level of the motor of a poor-quality power supply system.

8. CONCLUSION

In the practical diagnostics of electrical machines, vibration methods and built-in systems for vibration monitoring of the current state are used to solve diagnostic problems of predicting the period of failure-free operation of electromechanical equipment. The most common defects or damage to the stator winding of an induction electric motor with a squirrel-cage rotor, leading to the appearance of an asymmetric stator field, require timely diagnosis and determination of the degree of damage. The asymmetry of the rotating stator field leads to vibration, as well as the asymmetry of the supply voltage system. As a result of a complex of studies using simulation modeling, the features of using vibration diagnostic methods to determine the state of the winding stator have been established. In the presence of an turn-to-turn short circuit in the phase of the stator winding, depending on the degree of damage (the number of closed turns), the pulsation coefficient of the electromagnetic field changes linearly. At the same time, the manifestations of vibration in the idle mode are much higher than in the nominal mode. When closing 20% of the turns of the stator phase winding, the pulsation coefficient of the electromagnetic torque in the idle mode is 219,246%, and in the nominal mode 4,002%, which makes it difficult to recognize this damage during the operation of the electric motor in transport equipment.

According to the results of the studies of the turn-to-turn circuit simultaneously on two phases of the stator, the dependence of the influence of the combination of the degree of damage on vibrations has a parabolic form. In this case, the pulsation coefficient of the electromagnetic torque decreases from 263,67 to 174,32% and again increases to 258,21%, depending on the degree of damage to the second winding in the idle mode. The parabolic form of the dependence of the pulsation coefficient of the electromagnetic torque was also obtained for the nominal mode of motor operation, but it has a much less pronounced form. The parabolic type of dependence does not allow to correctly establish the type and degree of damage to the stator winding and to predict the period of trouble-free operation of the motor.

With a poor-quality power supply system that has a city during the operation of transport equipment, when the voltage on one phase decreases from the nominal 220V to 203V, the electromagnetic torque coefficient changes in the range of 0 – 25,78% when the motor is running under load. In the idle mode, the pulsation coefficient of the electromagnetic torque when the phase voltage changes in the limit of 220V–203V reaches the range of 0–7644%. A poor-quality power supply system also makes it difficult to differentiate stator damage that causes magnetic field asymmetry.

From the analysis of the results of research on the use of vibration diagnostic methods to assess the degree of turn-to-turn short circuits in the stator winding, their inefficiency was established when used for built-in diagnostic systems of operational control during the operation of induction motors of vehicles. Vibration methods can be successfully used to establish the current state of the stator during bench tests or repair work, provided that the power supply system is of high quality and only in idle mode.

The results of the work are relevant for further improvement of the built-in systems for diagnostic monitoring of induction motors of transport equipment.

Further work will be directed to research on determining the type and degree of turn-to-turn short circuits in the phases of the stator winding of an induction electric motor, constantly under load, by methods of changing phase currents for use in the built-in system for operational diagnostics of transport equipment.

Funding: *This publication was issued thanks to support from the Cultural and Educational Grant Agency of the Ministry of Education of the Slovak Republic in the projects, "Implementation of modern methods of computer and experimental analysis of properties of vehicle components in the education of future vehicle designers" (Project No. KEGA 036ŽU-4/2021). This research was also supported by the Slovak Research and Development Agency of the Ministry of Education, Science, Research and Sport of the Slovak Republic in Educational Grant Agency of the Ministry of Education of the Slovak Republic in the project and VEGA 1/0513/22 "Investigation of the properties of railway brake components in simulated operating conditions on a flywheel brake stand". This publication was also realized with support of Operational Program Integrated Infrastructure 2014 - 2020 of the project: Innovative Solutions for Propulsion, Power and Safety Components of Transport Vehicles, code ITMS 313011V334, co-financed by the European Regional Development Fund.*

Author contributions: *research concept and design, O.G., J.G., O.G.; Collection and/or assembly of data, O.G., K.K.; Data analysis and interpretation, O.G., J.G., O.G., K.Z, D.Z.; Writing the article, K.K., D.Z.; Critical revision of the article, O.G., O.G., O.G.; Final approval of the article, J.G.*

Declaration of competing interest: *The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.*

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Received 2022-11-15
Accepted 2023-02-16
Available online 2023-02-17

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