UDC 629.429.3:621.313
DOI: 10.15587/1729-4061.2021.239509

DETERMINING AN ADDITIONAL DIAGNOSTIC PARAMETER FOR IMPROVING THE ACCURACY OF ASSESSMENT OF THE CONDITION OF STATOR WINDINGS IN AN INDUCTION MOTOR

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This paper has proposed and substantiated the application of an additional diagnostic parameter for assessing the state of stator windings of induction motors during operation. The dependences of the values of phase shifts between phase currents and phase voltages have been obtained. These dependences showed that when an inter-turn short circuit occurs in the stator windings, the phase shifts are the same for all phases of the motor. That has made it possible to obtain the dependence of the change in phase shift on the change in the engine shaft rotation frequency.

This study's result has established the dependence of the rates of change of the phase angle on the engine shaft rotation frequency for both one and two damaged phases with varying degrees of damage. When analyzing these dependences, it was found that with an increase in the number of damaged phases of the electric motor, the linear section of the dependences decreases. In addition, with an increase in the degree of phase damage, the angle of inclination of the linear sections of the characteristics decreases. That has made it possible to determine an additional parameter for diagnosing the place and degree of an inter-turn short circuit of the windings in an induction motor with a squirrel-cage rotor. The values of the additional parameter, termed by this paper's authors as a "phase criterion" can be used to assess the condition and degree of damage to the stator winding of induction motors. The values of the phase criteria for various types of damage were: when phase A is damaged by 90 %, $\xi=0.634$, $(deg)^2/(rpm)^2$; when phase A is damaged by 80 %, $\xi=0.393$, $(deg)^2/(rpm)^2$; when phase A is damaged by 80 % and phase B is damaged by 90 %, $\xi=0.25$, $(deg)^2/(rpm)^2$; when phase A is damaged by 80 % and phase B is damaged by 90 %, $\xi=0.173$, $(deg)^2/(rpm)^2$.

The results of this research could be used to select an effective method for diagnosing an inter-turn short circuit in the stator winding when building a diagnostic system for induction motors as part of drives of transport equipment

Keywords: transport infrastructure, induction motor, inter-turn short circuit, phase currents, diagnostic parameters

Received date 07.07.2021
Accepted date 07.09.2021
Published date 29.10.2021

How to Cite: *Gubarevych, O., Goolak, S., Daki, O., Yakusevych, Y. (2021). Determining an additional diagnostic parameter for improving the accuracy of assessment of the condition of stator windings in an induction motor. Eastern-European Journal of Enterprise Technologies, 5 (5 (113)), 21–29. doi: https://doi.org/10.15587/1729-4061.2021.239509*

1. Introduction

For optimal and reliable operation of the transport infrastructure, it is crucial to maintain the operational condition of electric drives, which make up a significant part of the auxiliary equipment of transport systems [1]. A feature of the operation of these drives is the lack of the possibility of operational diagnostics and monitoring of the current state of electrical equipment. Induction motors with a squirrel-cage rotor have been widely used for the engines of auxiliary electric drives of transport infrastructure and as traction motors (in railroad transport).

Timely monitoring and diagnostics of the state of induction electric motors contribute to improving the reliability and efficiency of the entire transport system. During the operation of the transport, various kinds of malfunctions occur, causing a sudden failure of the engine or a deviation of its parameters from the rated values. When a series of parameters fail to meet the established boundaries, it causes an increase in energy losses in the engine [2, 3] and, as a result, a deterioration in its performance characteristics and parameters [4, 5].

One of the hard-to-diagnose defects that cause the deviation of the engine parameters from the rated values and contributes to the transition from a gradual rejection to a sudden one is the inter-turn short circuit in the stator windings. With this defect, given a small number of squirrel-closed turns of the damaged phase of the winding, the induction motor may stay in working condition. At the same time, the value of the current in the damaged phase increases, the power consumed from the network increases, the efficiency and power factors decrease [4, 5]. With a further increase in the number of squirrel-closed turns in the winding phase, the electric motor enters an inoperable state due to the critically increased value of the phase current in the damaged phase [6].

To build a diagnostic system of an induction motor, it is necessary to have information about the diagnostic parameters that would make it possible to establish the existence of a defect, its identification, the degree of damage to the engine, and the forecast of its trouble-free operation [7, 8]. An increase in the number of objective diagnostic parameters for assessing the current state of the engine contributes to the creation of the most accurate diagnostic system [9].

Thus, it is a relevant task to identify additional diagnostic parameters when diagnosing an inter-turn short circuit in the stator windings of the induction motor.

2. Literature review and problem statement

Work [10] categorizes malfunctions of the induction motor with a squirrel-cage rotor. It is shown that the largest number of failures relate to damage to the stator of the engine, but non-analyzed questions remained regarding the causes of failures in the stator of the induction motor.

Analysis of the causes of malfunctions in the stator winding of an induction motor with a squirrel-cage rotor is given in work [11]. It is indicated that the greatest number of failures of the stator winding is associated with such a defect as an inter-turn short circuit in the stator winding. In addition, the authors noted that when such a defect occurs, certain difficulties arise in its diagnosis. Those difficulties are related to the fact that when this defect occurs, the engine is in working condition, and only its performance characteristics change. With the development of that defect, the engine may enter a non-working state, but the issues of methods for diagnosing an inter-turn short circuit are not considered.

The solution to this problem is considered in work [12], where the author analyzes the effect of an inter-turn short circuit on the performance characteristics of the induction motor and indicates that the methods for diagnosing an inter-turn short circuit include the temperature-, vibration-, and current-based ones. However, in the cited work, the methods are considered only conceptually; their actual implementation is not proposed.

Studies of classical implementations of temperature methods for diagnosing inter-turn faults of stator windings of an induction motor are reported in [13, 14]. Work [13] investigated changes in the propagation of the internal temperature of the engine in the event of an inter-turn short circuit of the stator windings. Paper [14] examined the change in heating the stator windings of the motor in the event of an inter-turn short circuit of the stator windings and asymmetrical voltage. The authors of both cited works concluded that classical temperature methods for diagnosing inter-turn faults do not make it possible to identify with the necessary accuracy the degree of damage to the stator winding. In addition, given the inertia of those methods, it is not possible to reliably diagnose this type of damage, which can lead to a sudden failure of the induction motor.

The application of thermal methods for diagnosing an inter-turn short circuit of stator windings of an induction motor is investigated in the study reported in [15]. Two schemes for detecting inter-turn stator faults are proposed: using the infrared matrix of thermobattery sensors and using the sensor matrix based on the Hall effect. That allows the direct measurement of temperature and distribution of magnetic flux along the terminal area of the winding in a non-contact way. Thus, it is easy to estimate the deviation of thermal and magnetic symmetry caused by an inter-turn short circuit in the winding phase. This approach to diagnostics is effective in bench tests. Its implementation is difficult when building a diagnostic system built into the drive.

The implementation of methods of vibration diagnostics is described in [16–18]. In study [16,] the authors proposed a method of processing vibration sensor signals based on the fast Fourier transform. In [17], for processing signals from vibration sensors, the authors proposed to use a discrete wavelet transform. Despite the high accuracy of detecting the degree of damage to the stator winding of an induction motor, the diagnostic methods proposed in works [16, 17] require a base of a priori spectral power of vibration signals for cases with different degrees of damage to the windings.

Addressing the issue may involve the method of vibration diagnostics, considered in [18]. It is proposed, to determine the degree of damage to the stator winding, to use a combined method: the method of vibration diagnostics and the method of current diagnostics. Given a rather expedient approach to solving the problem of the need for a base of a priori spectral capacities of vibration signals, a series of certain difficulties arise when using that method. A significant reason behind these difficulties is the high cost of vibration sensors necessary to build a vibration diagnostic system. In addition, it should be noted that vibration diagnostic systems can be effective only in bench tests. As part of the drive of the vehicle itself, the system for collecting and processing information about vibration signals is difficult to implement constructively. It is also necessary to have storage conditions for the base of varying degrees of damage and vibration characteristics of an intact engine of specific power and type. In addition, the nature of the dependence of the pulsation coefficient on the motor shaft in the event of an inter-turn short circuit in two phases simultaneously shows that in this type of defect, the use of vibration diagnostic methods is incorrect [5].

In works [19–21], the implementation of a diagnostic system is given, which is based on current methods. Study [19] considers the current diagnostic method, which is based on the study of the harmonic composition of stator currents. Work [20] reports a study into diagnosing an inter-turn short circuit of the stator winding of the induction motor by investigating the complex amplitudes of the phase currents of the stator. The use of current methods makes it possible to obtain more accurate diagnostic results and the possibility of building a diagnostic system built into the drive, but the presence of asymmetry in the power supply system of the induction motor makes it difficult to apply both methods.

A solution to this problem is considered by the authors of [21]. A method using neural networks is proposed, which makes it possible, based on changes in performance characteristics, to determine what causes these changes (inter-turn short circuit or unbalanced power system). When implementing this method for creating a built-in diagnostic system, objective difficulties arise related to the complexity of implementing an information collection and processing system. This method could be used as part of bench diagnostics. In addition, the question of determining the degree of defect in the operation of an electric motor with a variable load remains open. The lack of complete information about the defect does not make it possible to predict the period of trouble-free operation of the electric motor.

Advancing the methods of current diagnostics may employ methods based on the use of the generalized Park vector [22, 23]. Paper [22] reports a study of the possibility of using the generalized hodograph of the Park vector to determine the occurrence of an inter-turn short circuit in the stator windings of the induction motor at an early stage of the defect. However, the studies conducted are purely conceptual in nature. The dependence between the shape of the Park vector and the degree of defect under different engine loads has not been established; the results have not been corrected taking into consideration unbalanced power.

The authors of work [23], for diagnosing an inter-turn short circuit, proposed the use of the extended method of the Park vector. To assess the mathematical relationship between the asymmetrical stator voltage, load change, and reverse sequence current, the authors proposed the use of the Freis-Buchholz-Dpenbrock algorithm and the nonlinear method of least squares.

Diagnostic systems built on the basis of the Park vector can be successfully used only in bench diagnostics. This is due to the need to organize an indication system, which displays the shape of the Park vector hodograph for subsequent assessment of the presence and degree of damage to the elements of the electric motor.

One of the options for improving the accuracy of determining the degree of damage to the stator winding of an induction motor in the event of an inter-turn short circuit is a method involving an additional diagnostic parameter. The would-be results of the present research could be used to select and organize an effective method for constructing diagnostic schemes for induction motors with a squirrel-cage rotor as part of a transport drive.

3. The aim and objectives of the study

The aim of this work is to determine and study the diagnostic parameter that makes it possible to identify the degree of damage to the stator winding during the operation of an induction motor with a variable load.

To accomplish the aim, the following tasks have been set:

– to choose a mathematical model of an induction motor that would make it possible to conduct research provided that an asymmetrical field of stator windings is generated and to implement on it an asymmetrical field of stator windings induced by the short circuit of turns in one and simultaneous in two phases of the winding;

– to investigate the influence of the degree of an inter-turn short circuit on phase shifts between phase voltages and currents when the motor load changes;

– to investigate the nature of the change in the first and second derivatives from phase shifts between phase voltages and currents when the stator changes at the actual speeds of the motor shaft;

– to determine the parameters and criteria necessary for reliable identification of inter-turn short circuits in one and two phases simultaneously when constructing a built-in system for diagnosing and monitoring the electric drive as part of transport systems.

4. The study materials and methods

The chosen object of research is an induction motor with a squirrel-cage rotor from the general industrial series AIR132M4 11.0 kW type (Ukraine); its specifications are given in Table 1.

Table 1

Specifications of the induction motor with squirrel-cage rotor *AIR* 132*M*4

Parameter	Designation	Measuring unit	Value
Shaft rated power	P_n	kW	11.0
Rated phase voltage	U_n	V	220
Supply voltage rated frequency	f_n	Hz	50
Rated rotor rotation frequency when idling	$n_{n.idle}$	rpm	1,498
Idling load moment	T_{idle}	N·m	0.38
Stator winding active resistance	r_1	Ω	0.5
Rotor winding active resistance brought to stator winding	r_2'	Ω	0.36
Stator winding reactive resistance	x_1	Ω	0.56
Rated motor rotation frequency	n_n	rpm	1,450
Rated moment on motor shaft	T_n	N·m	72.671
Motor moment of inertia	J	kg·m^2	0.04

We studied the influence of the degree of an inter-turn short circuit in the stator windings of the induction motor on its operating parameters based on its mathematical model, the equations of which are recorded in three-phase coordinates.

These equations were supplemented with equations that make it possible to take into consideration the change in the values of the mutual phase inductances and the main inductance of the magnetization circuit when the geometry of the stator winding changes due to the short circuits of the turns.

The proposed method implies studying the nature of change in the phase angle of the stator current when the load changes by mathematical modeling methods. As an additional diagnostic parameter, the use of the value of the second derivative from the change in the phase angle of the stator current at the actual speeds of the motor shaft is proposed. This could make it possible to more accurately determine the degree of damage to the stator winding, determine the exact number of damaged phases, and predict the residual life of the engine. The assumptions made in our research relate to the power supply system of the induction motor, which is considered strictly symmetrical, and the shape of stresses – sinusoidal.

The simulation model of the traction induction motor is implemented in the MATLAB (USA) programming environment.

When studying the operation of the electric motor on a simulation model, five experiments were conducted. The first experiment was to obtain operating parameters for an intact engine. The second – provided that in phase *A* of the stator winding there was an inter-turn short circuit of 10 % of the winding turns. The third experiment – for the condition of inter-turn short circuit in phase *A* of the stator winding with a short circuit of 20 % of the turns. The fourth – under the condition of simultaneous inter-turn short circuit in phase *A* and phase *B*, and, in phase *A*, the inter-turn short circuit was 20 %, and in phase *B* – 10 % of the winding turns. The fifth – under the condition of simultaneous inter-turn short circuit in phase *A* and phase *B*, and, in phase *A* and phase *B*, the inter-turn short circuit was 20 % of the total number of turns of the winding in each phase.

5. The results of studying the influence of inter-turn faults on a change in the phase shifts between phase voltages and currents

5. 1. Selecting a mathematical model of the induction motor

When choosing a model for conducting inter-turn short circuit studies simultaneously in several phases of the stator of the induction motor, the possibility of simulating an asymmetrical mode of stator windings should be taken into consideration.

In works [4, 5], it is shown that it is most expedient for further studies of the influence of inter-turn short circuit simultaneously in several phases of stator winding on the characteristics of an induction motor to apply the mathematical model given in paper [24]. The proposed simulation model of an induction motor with a squirrel-cage rotor is made in “braked coordinates” and implemented in the MATLAB (USA) programming environment.

When organizing an asymmetrical mode, changes in the mutual inductance of stator windings were taken into consideration. To determine the change in the mutual inductances of the windings, the effect that the change in the complex resistance of one winding (several windings) has on the inductance of the magnetic circuit according to the algorithm presented in work [25] was determined. In works [4, 5], that algorithm is implemented for the study of inter-turn short circuits in the stator winding at one and simultaneously in two phases.

5. 2. Investigating the influence of an inter-turn short circuit on phase shifts between phase voltages and currents on motor parameters

Preliminary analysis of the effect of simultaneous inter-turn short circuit in two phases on mechanical and operating characteristics [5] revealed that the type of dependences is similar to that of inter-turn short circuit in one phase [4]. In addition, based on the reported studies in work [5], it was established that for the construction of a system of built-in diagnostics, with accurate identification of the type and nature of the resulting defect of the stator winding, the available diagnostic parameters are not enough.

To improve the reliability of diagnosing, it is proposed to use the dependence of the change in the angles of phase shift for each phase when the load and, accordingly, the engine speed change as an additional criterion. For this purpose, a model given in [24] was used to obtain the dependences of the amplitudes and angles of phase shifts φ between phase currents and voltages with an intact stator on the rotation speed of the rotor of the motor n. The results of the modeling are given in Table 2. Similar characteristics were obtained for a series of types of damage to the phases of the stator winding, which was taken into consideration by reducing the complex resistance of the phase, simulating inter-turn short circuit of varying degrees (different number of short-circuited turns). Thus, the characteristics are obtained at the following engine parameters:

– 90 % of the complex resistance of phase A from the rated (serviceable) value (Table 3);

– 80 % of the complex resistance of phase A (Table 4);

– 80 % of the resistance of phase A in combination with 90 % of the resistance of phase B (Table 5);

– 80 % of the resistance of phase A in combination with 80 % of phase B (Table 6).

Based on the values of phase shifts φ_i obtained as a result of modeling, we determined the changes in phase shifts $\Delta\varphi$ between phase currents and voltages for each rotation frequency of the motor rotor:

$$\Delta\varphi_i = \varphi_i - \varphi_{i-1}, \tag{1}$$

where φ_i is the phase shift between phase currents and voltages at motor shaft speed n_i;

φ_{i-1} is the phase shift between phase currents and voltages at the speed of the motor shaft n_{i-1}.

The calculation results are given in Tables 2–6. Analysis of the research results (Tables 2–6) has shown that for all phases of changes in the angles of shift between phase currents and voltages, $\Delta\varphi$ are equal for each motor shaft speed:

$$\Delta\varphi_{Ai} = \Delta\varphi_{Bi} = \Delta\varphi_{Ci} = \Delta\varphi_i. \tag{2}$$

It follows from equality (2) that the assessment of the state of the phase windings of the stator by changing the angles of phase shifts between phase currents and voltages is impossible.

Table 2

Dependence of the amplitudes of phase currents (I_A, I_B, I_C) and phase shift angles (φ_A, φ_B, φ_C) at an intact stator on the actual speed of the motor rotor (n)

n, rpm	Phase A			Phase B			Phase C			$\Delta\varphi$, deg	$\chi_i = \Delta\varphi_i/\Delta n_i$, deg/rpm
	I_A, A	φ_A, deg	$\Delta\varphi_A$, deg	I_B, A	φ_B, deg	$\Delta\varphi_B$, deg	I_C, A	φ_C, deg	$\Delta\varphi_C$, deg		
1,498.0	9.403	88.92	0	9.403	88.92	0	9.403	88.92	0	0	0
1,497.9	9.406	85.86	–3.06	9.406	85.86	–3.06	9.406	85.86	–3.06	–3.06	1.457
1,496.4	9.445	83.16	–2.7	9.445	83.16	–2.7	9.445	83.16	–2.7	–2.7	1.8
1,494.8	9.53	80.28	–2.88	9.53	80.28	–2.88	9.53	80.28	–2.88	–2.88	1.8
1,493.3	9.645	76.5	–3.78	9.645	76.5	–3.78	9.645	76.5	–3.78	–3.78	2.52
1,490.8	9.927	70.92	–5.58	9.927	70.92	–5.58	9.927	70.92	–5.58	–5.58	2.232
1,488.3	10.294	66.06	–4.86	10.294	66.06	–4.86	10.294	66.06	–4.86	–4.86	1.944
1,485.8	10.739	61.38	–4.68	10.739	61.38	–4.68	10.739	61.38	–4.68	–4.68	1.872
1,470.8	14.54	42.66	–18.7	14.54	42.66	–18.7	14.54	42.66	–18.7	–18.7	1.248
1,450.0	21.879	31.32	–11.3	21.879	31.32	–11.3	21.879	31.32	–11.3	–11.34	0.545
1,440.8	24.218	29.52	–1.8	24.218	29.52	–1.8	24.218	29.52	–1.8	–1.8	0.196
1,425.7	29.169	27.72	–1.8	29.169	27.72	–1.8	29.169	27.72	–1.8	–1.8	0.119

Table 3

Dependence of the amplitudes of phase currents (I_A, I_B, I_C) and phase shift angles (φ_A, φ_B, φ_C) at 90 % of the rated resistance of phase *A* on the actual speed of the motor rotor (*n*)

n, rpm	Phase A			Phase B			Phase C			$\Delta\varphi$, deg	$\chi_i=\Delta\varphi_i/\Delta n_i$, deg/rpm
	I_A, A	φ_A, deg	$\Delta\varphi_A$, deg	I_B, A	φ_B, deg	$\Delta\varphi_B$, deg	I_C, A	φ_C, deg	$\Delta\varphi_C$, deg		
1,498.0	10.36	89.82	0	9.486	87.66	0	9.959	89.46	0	0	0
1,497.9	10.398	87.66	–2.16	9.609	85.5	–2.16	9.687	87.3	–2.16	–2.16	1.29
1,496.4	10.435	84.24	–3.42	9.644	82.08	–3.42	9.721	83.88	–3.42	–3.42	2.28
1,494.8	10.52	80.46	–3.78	9.723	78.3	–3.78	9.798	80.1	–3.78	–3.78	2.362
1,493.3	10.636	77.58	–2.88	9.829	75.42	–2.88	9.905	77.22	–2.88	–2.88	1.92
1,490.8	10.918	71.82	–5.76	10.09	69.66	–5.76	10.167	71.46	–5.76	–5.76	2.304
1,488.3	11.288	68.22	–3.6	10.431	66.06	–3.6	10.508	67.86	–3.6	–3.6	1.44
1,485.8	11.738	62.28	–5.94	10.847	60.12	–5.94	10.927	61.92	–5.94	–5.94	2.376
1,470.8	15.65	44.64	–17.6	14.454	42.48	–17.64	14.559	44.28	–17.6	–17.6	1.176
1,450.0	23.382	32.58	–12.0	20.744	30.42	–12.06	20.29	32.22	–12.0	–12.0	0.58
1,440.8	25.799	31.32	–1.26	23.815	29.16	–1.26	23.996	30.96	–1.26	–1.26	0.137
1,425.7	30.957	28.62	–2.7	28.573	26.46	–2.7	28.794	28.26	–2.7	–2.7	0.179

Table 4

Dependence of the amplitudes of phase currents (I_A, I_B, I_C) and the angles of phase shifts (φ_A, φ_B, φ_C) at 80 % of the rated resistance of phase *A* on the actual speed of the motor rotor (*n*)

n, rpm	Phase A			Phase B			Phase C			$\Delta\varphi$, deg	$\chi_i=\Delta\varphi_i/\Delta n_i$, deg/rpm
	I_A, A	φ_A, deg	$\Delta\varphi_A$, deg	I_B, A	φ_B, deg	$\Delta\varphi_B$, deg	I_C, A	φ_C, deg	$\Delta\varphi_C$, deg		
1,498.0	11.553	89.82	0	9.805	85.68	0	9.974	89.46	0	0	0
1,497.9	11.556	88.56	–1.26	9.809	84.42	–1.26	9.976	88.2	–1.26	–1.26	0.6
1,496.4	11.592	84.24	–4.32	9.84	80.1	–4.32	10.005	83.88	–4.32	–4.32	2.88
1,494.8	11.677	81.54	–2.7	9.913	77.4	–2.7	10.077	81.18	–2.7	–2.7	1.687
1,493.3	11.792	78.48	–3.06	10.011	74.34	–3.06	10.175	78.12	–3.06	–3.06	2.04
1,490.8	12.077	73.8	–4.68	10.252	69.66	–4.68	10.415	73.44	–4.68	–4.68	1.872
1,488.3	12.45	68.04	–5.76	10.568	63.9	–5.76	10.735	67.68	–5.76	–5.76	2.304
1,485.8	12.905	64.44	–3.6	10.952	60.3	–3.6	11.123	64.08	–3.6	–3.6	1.44
1,470.8	16.93	46.44	–18.0	14.351	42.3	–18.0	14.572	46.08	–18.0	–18.0	1.2
1,450.0	25.566	34.2	–12.2	20.29	30.06	–12.2	20.318	33.84	–12.2	–12.2	0.588
1,440.8	27.586	32.4	–1.8	23.359	28.26	–1.8	23.733	32.04	–1.8	–1.8	0.196
1,425.7	32.961	30.42	–1.98	27.905	26.28	–1.98	28.359	30.06	–1.98	–1.98	0.131

Table 5

Dependence of the amplitudes of phase currents (I_A, I_B, I_C) and phase shift angles (φ_A, φ_B, φ_C) at 80 % of the rated resistance of phase *A* and 90 % of the rated resistance of phase *B* on the actual speed of the motor rotor (*n*)

n, rpm	Phase A			Phase B			Phase C			$\Delta\varphi$, deg	$\chi_i=\Delta\varphi_i/\Delta n_i$, deg/rpm
	I_A, A	φ_A, deg	$\Delta\varphi_A$, deg	I_B, A	φ_B, deg	$\Delta\varphi_B$, deg	I_C, A	φ_C, deg	$\Delta\varphi_C$, deg		
1498.0	11.99	90.72	0	10.923	85.68	0	10.242	88.38	0	0	0
1497.9	11.992	88.92	–1.8	10.926	83.88	–1.8	10.244	86.58	–1.8	–1.8	0.857
1496.4	12.024	85.86	–3.06	10.957	80.82	–3.06	10.271	83.52	–3.06	–3.06	2.04
1494.8	12.101	83.34	–2.52	11.029	78.3	–2.52	10.336	81.0	–2.52	–2.52	1.575
1493.3	12.207	80.28	–3.06	11.126	75.24	–3.06	10.426	78.12	–3.06	–3.06	2.04
1490.8	12.471	74.88	–5.4	11.367	69.84	–5.4	10.648	72.72	–5.4	–5.4	2.16
1488.3	12.817	70.92	–3.96	11.684	66.98	–3.96	10.942	68.76	–3.96	–3.96	1.584
1485.8	13.242	66.06	–4.86	12.072	62.12	–4.86	10.942	63.9	–4.86	–4.86	1.944
1470.8	17.067	48.24	–17.2	15.552	44.28	–17.8	14.55	46.08	–17.8	–17.8	1.188
1450.0	25.519	36.18	–12.1	23.336	32.22	–12.1	21.903	34.02	–12.1	–12.0	0.258
1440.8	27.467	34.02	–2.16	25.005	30.06	–2.16	23.399	31.86	–2.16	–2.16	0.235
1425.7	32.643	32.22	–1.8	29.711	28.26	–1.8	27.805	30.06	–1.8	–1.8	0.119

Table 6

Dependence of the amplitudes of phase currents (I_A, I_B, I_C) and the angles of phase shifts (φ_A, φ_B, φ_C) at 80 % of the rated resistance of phase *A* and 80 % of the rated resistance of phase *B* on the actual speed of the motor rotor (*n*)

n, rpm	Phase *A*			Phase *B*			Phase *C*			Δφ, deg	$\chi_i=\Delta\varphi_i/\Delta n_i$, deg/rpm
	I_A, A	φ_A, deg	$\Delta\varphi_A$, deg	I_B, A	φ_B, deg	$\Delta\varphi_B$, deg	I_C, A	φ_C, deg	$\Delta\varphi_C$, deg		
1,498.0	12.456	91.62	0	12.244	86.22	0	10.513	87.84	0	0	0
1,497.9	12.456	90.0	–1.62	12.246	84.6	–1.62	10.515	86.22	–1.62	–1.62	0.771
1,496.4	12.484	86.76	–3.24	12.276	81.36	–3.24	10.539	82.98	–3.24	–3.24	2.16
1,494.8	12.554	83.88	–2.88	12.347	78.48	–2.88	10.599	80.1	–2.88	–2.88	1.8
1,493.3	12.651	81.72	–2.16	12.446	76.32	–2.16	10.681	77.94	–2.16	–2.16	1.44
1,490.8	12.891	76.86	–4.86	12.685	71.46	–4.86	10.883	73.08	–4.86	–4.86	1.944
1,488.3	13.209	72.36	–4.5	13.002	66.96	–4.5	11.152	68.58	–4.5	–4.5	1.8
1,485.8	13.608	68.58	–3.78	13.398	64.08	–3.78	11.488	64.8	–3.78	–3.78	1.52
1,470.8	17.2	50.4	–18.2	16.939	45.9	–18.18	14.507	46.62	–18.2	–18.2	1.212
1,450.0	25.393	38.16	–12.2	25.116	33.66	–12.24	21.329	34.38	–12.2	–12.2	0.588
1,440.8	27.051	36.0	–2.16	26.625	31.5	–2.16	22.791	32.22	–2.16	–2.16	0.235
1,425.7	46.439	33.12	–2.88	31.782	28.62	–2.88	27.207	29.34	–2.88	–2.88	0.191

5. 3. Investigating changes in the first and second derivatives induced by phase shifts between phase voltages and currents

We studied the nature of change in the first and second derivatives induced by phase shifts between phase voltages and currents at the actual rotation frequencies of the motor shaft.

For the obtained values (Tables 2–6), an additional parameter χ_i was calculated to assess the change in the increment of the phase shift between phase currents and voltages induced by the increment of the rotor speed of the motor

$$\chi_i=\frac{\Delta\varphi_i}{\Delta n_i}. \qquad (3)$$

Based on the results given in Tables 2–6, we plotted the dependences of the parameters of the phase shift rate between phase currents and voltages χ_i on the rotation frequency of the motor rotor (Fig. 1).

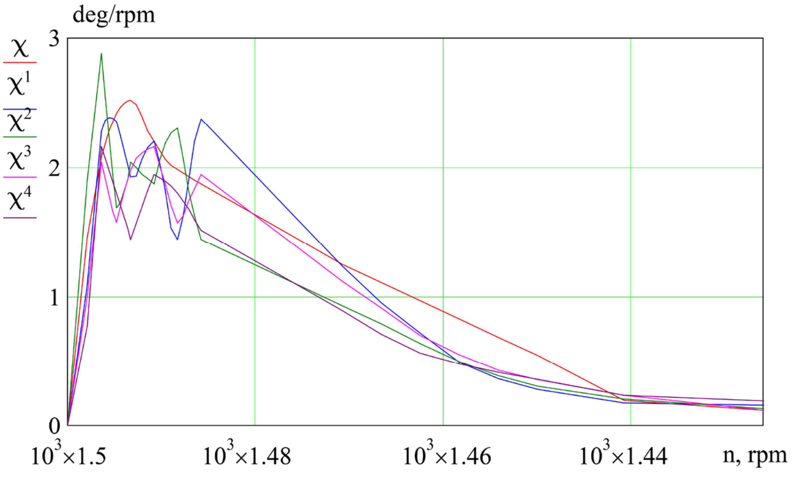

Fig. 1. Dependence of the rate of change in the phase shift between phase currents and voltages (χ_i) on the change in the speed of the motor rotor (*n*, rpm)

In Fig. 1, χ, χ_1, χ_2, χ_3, χ_4 denote the parameters of change in the rate of increment of phase shift between phase currents and voltages to the increment of the rotor speed of the motor:

– with the intact stator (χ);

– at 90 % of the rated resistance of the phase *A* winding (χ_1);

– at 80 % of the rated resistance of the phase *B* winding (χ_2);

– at 80 % of the rated resistance of the phase *A* winding and 90 % of the resistance of the phase *B* winding at the same time (χ_3);

– at 80 % of the rated resistance of the phase *A* winding and 80 % of the rated resistance of the phase *B* winding at the same time (χ_4).

5. 4. Determining an additional diagnostic parameter for the identification of the inter-turn short circuit

The dependences shown in Fig. 1 have, in the region of an idling mode and close to it rotor rotation frequencies in the range of 1,498–1,488 rpm, which corresponds to a low engine load, abrupt character. This part of engine operation cannot be used for diagnostics. With a further load of the engine, linear sections follow, which continue almost to the rated rotor speed (Fig. 1). Thus, for an intact stator, the range of the rectilinear section is from 1,490.8 rpm to 1,450 rpm. For damage to one phase of the stator – from 1,485.8 rpm to 1,458.32 rpm; for damage to two phases of the stator – from 1,485.8 rpm to 1,466.4 rpm, etc. Hence, it follows that with an increase in the number of damaged phases and the degree of damage (the number of short-circuited turns), the range of the rectilinear section of the dependence $\chi=f(n)$ decreases.

Our analysis of the obtained dependences in Fig. 1 also led to the following conclusion. If the same number of phases is damaged with different degrees of damage, the second derivative of the change in the phase shift rate between the phase currents and voltages induced by the change in the speed of the motor shaft changes in different ways.

$$\xi_i=\frac{\Delta\chi_i}{\Delta n_i}. \qquad (4)$$

The parameter ξ from expression (4) can be used as a criterion for diagnosing defects in the induction motor caused by the inter-turn short circuits of the stator winding phases in the construction of a diagnostic system. Hereafter, this parameter is termed a "phase criterion". The defined phase criterion can be used to assess the state of the stator winding in the construction of a built-in system for diagnosing and monitoring the electric drive as part of transport systems.

6. Discussion of results of studying the application of an additional parameter for diagnosing a stator winding

For this research, a mathematical model of an induction motor with the possibility of generating an asymmetrical field of stator windings was chosen. Inter-turn short circuits on the stator phases in the model are implemented by reducing the integrated resistance of one or two phases simultaneously, which generates an asymmetrical field of stator windings.

Our study of the effect of an inter-turn short circuit on phase shifts between phase voltages and currents has shown that phase shifts remain equal for all phases at each value of the motor shaft speed (Table 1). That has made it possible to hypothesize that an additional diagnostic parameter of the state of the stator windings can be obtained as a result of investigating the phase characteristics of the induction motor. However, it follows from the obtained equality $\Delta\varphi_{Ai}=\Delta\varphi_{Bi}=\Delta\varphi_{Ci}=\Delta\varphi_i$ that the assessment of the state of the phase windings of the stator by the values of the change in the angles of phase shifts between phase currents and voltages is impossible.

We studied the nature of the change in the first and second derivatives induced by phase shifts between phase voltages and currents when the stator changes at the actual rotation frequencies of the motor shaft. The analysis of dependences shown in Fig. 1 has revealed that the dependences have ranges with linear sections. Herewith:

– for an intact stator, the range of the rectilinear section is from 1,490.8 rpm to 1,450 rpm;

– for damage to one phase of the stator – from 1,485.8 rpm to 1,458.32 rpm;

– for damage to two phases of the stator – from 1,485.8 rpm to 1,466.4 rpm.

Given this, it was established that with an increase in the number of damaged phases, the range of the linear section of characteristics decreases. At the same time, a decrease in the range occurs with an increase in the load of the engine.

Our analysis of the characteristics shown in Fig. 1 has demonstrated that with an increase in the degree of damage to the stator windings, the angle of inclination of these characteristics decreases; we have termed it a "phase criterion". Thus, for varying degrees of damage, the phase criteria were:

– at the damage to phase *A* of 90 %, ξ=0.634, $(\text{deg})^2/(\text{rpm})^2$;

– at the damage to phase *A* of 80 %, ξ=0.393, $(\text{deg})^2/(\text{rpm})^2$;

– at the damage to phase *A* of 80 % and damage to phase *B* of 90 %, ξ=0.25, $(\text{deg})^2/(\text{rpm})^2$;

– at the damage to phase A of 80 % and damage to phase *B* of 80 %, ξ=0.173, $(\text{deg})^2/(\text{rpm})^2$.

That has made it possible to conclude that the phase criterion could serve as an additional diagnostic parameter in diagnosing the state of the stator windings in order to determine the degree of their damage in the event of an inter-turn short circuit.

Given that the values of the phase criterion were obtained when changing the load and, accordingly, the speed of the electric motor, this parameter is correct in the study of the state of the stator windings when the motor is running as part of the drive.

The limitation of the application of the phase criterion is associated with the previously accepted assumption about conducting research involving a symmetrical sinusoidal motor power system. With a poor-quality power system, the correctness of the application of the phase criterion requires further research.

The results of this work could be used to select and organize an effective method for constructing diagnostic schemes for induction motors with a squirrel-cage rotor as part of the drive of transport mechanisms.

7. Conclusions

1. The mathematical model of an induction motor with a squirrel-cage rotor, adopted for research, makes it possible to simulate inter-turn faults taking into consideration changes in the mutual inductance of stator windings. The inter-turn short circuits have been realized by changing the integrated resistance of one or more windings, taking into consideration their effect on the inductance of the stator magnetic circuit.

2. We have studied the influence of the degree of an inter-turn short circuit on phase shifts between phase voltages and currents when the motor load changes. It has demonstrated that phase shifts remain the same for all phases of the motor when changing the shaft speed over the entire operating range – from 1,425.7 rpm to 1,498.0 rpm.

3. Our analysis of the dependences of the influence of the degree of an inter-turn short circuit on phase shifts between phase voltages and currents when the motor load changes has revealed that the dependences have ranges with linear sections. Herewith:

– for the undamaged stator, a straight-line range is from 1,490.8 rpm to 1,450 rpm;

– for damage to one phase of the stator – from 1,485.8 rpm to 1,458.32 rpm;

– for damage to two phases of the stator – from 1,485.8 rpm to 1,466.4 rpm.

In addition, the analysis of the obtained characteristics showed that for different degrees of damage, phase criteria accept different values. These values can be used to assess the condition and extent of damage to the stator winding of induction motors. The values of the phase criteria for various types of damage were:

– at the damage to phase A of 90 %, ξ=0.634, $(\text{deg})^2/(\text{rpm})^2$;

– at the damage to phase A of 80 %, ξ=0.393, $(\text{deg})^2/(\text{rpm})^2$;

– at the damage to phase A of 80 % and damage to phase *B* of 90 %, ξ=0.25, $(\text{deg})^2/(\text{rpm})^2$;

– at the damage to phase A of 80 % and damage to phase *B* of 80 %, ξ=0.173, $(\text{deg})^2/(\text{rpm})^2$.

4. Our study of the dependences of the influence of the degree of an inter-turn short circuit on phase shifts between phase voltages and currents when the load changes has allowed us to establish the following:

– with an increase in the number of damaged phases, the range of the linear section of characteristics decreases;

– with an increase in the degree of damage to the stator windings, the angle of inclination of these characteristics (a phase criterion) decreases, which corresponds to its lower values.

Thus, the obtained phase criterion could be used to select and organize an effective method in the construction of diagnostic schemes for induction motors with a squirrel-cage rotor as part of a transport drive.

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