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SYNTHESIS OF THE STRUCTURAL DIAGRAM WITH ALGORITHMS OF THE UNITS OF THE ON-BOARD DIAGNOSTIC SYSTEM OF INDUCTION MOTORS OF VEHICLES

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Abstract

In this comprehensive study, the concept and structural diagram of the system for diagnostics of induction electric motors of vehicles with the development of algorithms for the operation of modular units for monitoring the state of the main structural elements are proposed. During the development of the diagnostic system, the peculiarities of the construction of diagnostic systems of rotating electric machines were investigated in the real conditions of their operation, and modern methods of current and vibration diagnostics were implemented. The work algorithms of each module are presented in the functional diagram of the general diagnostic system of and cover important defects of induction motors. The diagnostic system combines methods that use different diagnostic principles and criteria and are adapted for use in an embedded diagnostic system. The developed functional diagram of the diagnostic system can be used for practical implementation in physical form. The use of the proposed diagnostic system will make it possible to obtain continuous information about the state of both electrical and mechanical components of the induction motor when operating under load with a poor-quality power system in real operating conditions.

Keywords: induction motor, damage detection, equipment monitoring, diagnostic system, diagnostic process, transport equipment monitoring, on-board diagnostic system, diagnostic process

1. INTRODUCTION

Increasing the efficiency and reliability of transport is an urgent task for the development of the infrastructure of every country, which is primarily related to increasing its economy and safety. With the modern trend of increasing requirements for the operational level of transport equipment, constant control and timely maintenance of its main elements is of crucial importance [32]. The main elements of transport equipment, which have a fairly high level of damage compared to other elements of the transport system, are electromechanical drives with electric motors. The most common type of electric motors used in the transport sector are induction motors with a short-circuited rotor. Induction motors have high reliability, ease of maintenance and low price, which makes them the main type of electric machines for various drives in the transport industry. In modern railway transport, squirrel cage induction motor are actively spreading and are used both as traction motors and for driving auxiliary machines that ensure the operation of the entire electric rolling stock [19, 47, 52]. This type of electric motors is also mostly used in the drives of pumps and compressors of sea and air transport.

However, the more efficient use of induction motors is hindered by their existing damage, which leads to an emergency stop of transport mechanisms if the defect is not detected in time. According to the statistics of repair enterprises, 20-25% of the total number of installed electric motors are damaged annually [45]. In addition, the occurrence of parametric failures during operation due to damage to individual elements of electric motors affects the deterioration of the drive characteristics and,

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accordingly, the accuracy of the functions performed by it. The development of undetected damage in a timely manner leads to secondary already catastrophic failures in emergency mode with more serious consequences for recovery when the losses for their elimination increase.

Thus, increasing transportation safety, reliability and efficiency of transport equipment depends on increasing the level of monitoring and diagnostics of systems for the current state of engine elements during operation. In addition, the detection of damage in the early stages creates prerequisites for planning the time of maintenance and repairs of equipment with the set volume according to the technical condition, which is a more effective maintenance system than scheduled.

Taking into account the conditions and purpose of electric motors, as well as the specifics of the transport industry, a condition control system is necessary, which allows detecting the degree of damage to the elements of motors in order to predict uptime until the possibility of carrying out restoration work or debugging. That is, solving the problem of assessing the current state of electric motors of transport equipment is associated with the importance of developing and implementing a comprehensive system for continuous monitoring of the main engine components in real operating conditions [6, 34].

Based on this, there is currently a desire to create the most automated on-board diagnostic systems of electric motors with the detection of actual damage to its main functional elements at the initial stages during the equipment's operation under load [4].

To diagnose damage to working technical equipment, non-invasive methods of functional diagnostics are used in most cases, which are economically feasible, as they do not require temporary removal of the equipment from operation [11, 53]. The most informative and common types of signals for use in diagnostic systems are current and vibration, which can be used in one diagnostic system [16, 21].

The process of processing the vibration signal is considered one of the most common methods for detecting mechanical damage and monitoring the condition of rotating mechanisms [22, 30].

Vibration characteristics are also used to determine rotor winding damage [54, 41]. A number of studies have used vibration monitoring techniques to diagnose mechanical faults such as bearing defects and rotor wear [28]. However, there is not enough vibration data to determine the number of types and degrees of damage to elements of some equipment [24]. When diagnosing bearings, the method of spectral signal analysis is most often used. To reduce noise interference when diagnosing bearings based on vibration spectra, a Kalman filter is used [10]. Diagnosis of early motor bearing damage can be performed using an intelligent algorithm based on meta-learning with generation of missing samples and enhancement of weak features at the Wasserstein distance [38]. Studies [7, 9, 48] use stator current analysis methods to identify a number of mechanical damages, imbalances and misalignments in rotating machines.

Among other methods, current methods are the most effective for determining electrical damage of induction motors [44]. Using the stator current allows one to obtain diagnostic signs of damage to the stator [43, 51] and rotor winding [2, 13]. One of the widely studied methods using current signals is the Park`s vector method [29, 49].

The works [18, 42] present the results of using the Park vector method to identify defects in the stator winding and short-circuited rotor winding of induction motors. Among the methods of diagnosing electrical faults of electric motors, there are also methods based on the Herzel algorithm and random forest [39], acoustic emission [5], convolutional neural network [3] and etc., but they did not receive practical development for use in on-board diagnostic systems.

For the purpose of current control of the state of insulating materials of conductive parts of electrical equipment, the most effective methods of monitoring partial discharges remain [12, 14], which are an important tool for predicting fault-free operation.

From the analysis of modern research it follows that today there are a number of methods for operational monitoring of the condition of induction motors of varying degrees of accuracy. To assess the technical condition, these methods use various diagnostic parameters.

Such methods do not meet the requirements for industrial operation of transport equipment. The task of creating an effective diagnostic system for monitoring the status of induction motors of transport equipment, which meets modern operational requirements, continues to be relevant.

2. THE RESEARCH PURPOSE

Research was conducted for to build a concept of a system of complex diagnostics of induction motors of vehicles and to develop a structural and functional scheme for practical use in an on-board condition control system.

For this purpose the following tasks were set:

- conduct an analysis of the damageability of squirrel cage induction motors and establish elements and types of their damage that are necessary for control;
- determine the concept of construction of the structural scheme and control of the specified nodes and elements;
- develop a diagram of a complex for monitoring elements of induction motors during their operation;
- determine the principles of work and develop algorithms for control modules of specified

damages as part of the diagnostic system with determination of the degree of damages.
- to develop a functional diagram of an on-board diagnostic system for induction motors to monitor the condition and degree of damage to engine elements for practical use.

The implementation of the proposed diagnostic system will allow establishing the type and degree of damage to the elements of induction motors during their operation in the early stages to prevent emergency failures with the complication of their elimination in the event of the development of defects before the appearance of secondary, already catastrophic, failures. Control the development of detected defects is very important for predicting trouble-free operation and planning the time for their elimination. This will improve the efficiency, reliability and safety of transport equipment. Current monitoring of the state of electromechanical equipment by on-board diagnostic systems affects the efficiency, reliability and economy of the transport industry.

3. DAMAGE ANALYSIS AND DETERMINATION OF METHODS FOR DIAGNOSING ELEMENTS OF INDUCTION MOTORS

In order to develop a structural diagram of the induction electric motor diagnostics system, it is necessary to conduct an analysis of node damage and types of defects with the determination of a rational list of necessary elements for control and methods of their installation. According to the results of operational statistics, it is possible to determine the types of damage to induction electric motors based on the main structural elements, which are shown in Fig. 1 [16, 17, 27, 55].

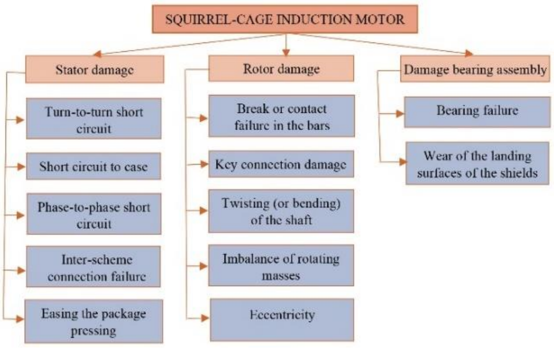


Fig. 1. The main types of induction motor damage

Some of those shown in Fig. 1 damage is characterized by a sudden (catastrophic) failure that cannot be predicted and occurs as a result of emergency processes that exceed the expected electromechanical strength of the equipment. It makes no sense to monitor such failures in the diagnostic system. In addition, a number of defects have a small proportion of non-operability-critical failures that can be eliminated during scheduled motor repairs or maintenance. In order to increase information about the current state, it is advisable to combine such defects in a separate group and obtain general information about deviations and violations of the state to be taken into account during maintenance. When constructing a structural diagram, it is important to take into account the most statistically significant phenomena, types of defects, the development of which must be monitored and observed in order to prevent an emergency stop. This will also help establish trouble-free operation time with maintenance planning. Based on various operational statistics data [7, 27, 11], a quantitative analysis of damage to an induction motor with a squirrel-cage rotor was carried out.

The results of the analysis are combined into groups and presented in Fig. 2

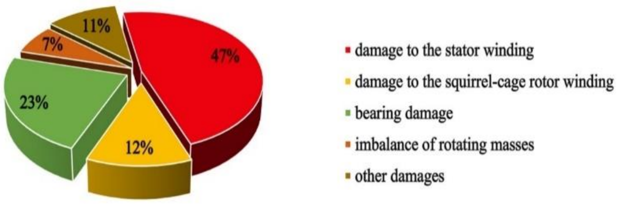
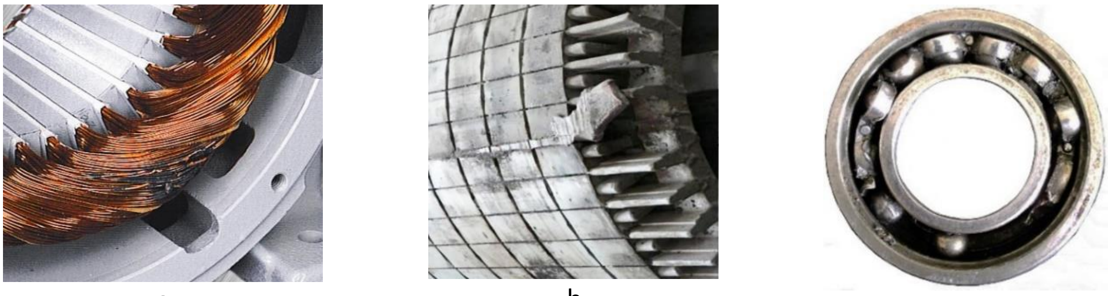


Fig. 2. Distribution of the main types of induction motor damage

As follows from Figure 2, the largest share of failures of an induction electric motor is attributed to the stator (47%). Among the most frequent stator damages that need to be controlled, and which can reach 75-90% of all failures for different types of induction electric motor applications in the railway industry, are inter turn short circuits in the winding [18]. Inter turn short circuit in most cases is parametric in nature, but this damage is prone to develop and, over time, lead to an emergency motor stop with a phase-to-phase or short-to-frame. The short circuit of the phase turns of the stator winding forms an asymmetrical magnetic field of the stator. This causes additional vibration when the engine is running. In addition, the current increases in the closed section, which contributes to the increase of local heating of the winding, the energy indicators decrease and the working and operational characteristics deteriorate. In Fig. 3, a shows damage to the stator winding during an interturn short circuit. Determining the degree of damage to the stator winding is a necessary element of the diagnostic system. The degree of winding damage involves determining the exact number of closed turns.



a b c

Fig. 3. Manifestations of the main defects of an induction motor: a – inter-turn in the stator winding; b – damage to the rotor; c – bearing failure

Inter-turn short circuits are the result of insulation deterioration due to a number of different causes, including periodic operational overcurrents, operating conditions, or the effects of aging and wear. In order to prevent the breakdown of insulating materials during the operation of the electric motor, it is also necessary to carry out a preventive control of the current state of the insulation. The effect of inter-turn short circuits in the winding phase on the parameters and characteristics of the motor during operation is discussed in detail in the work [18].

In addition to detecting short circuits in the stator winding, current monitoring of the condition of the rotor winding is also important. Rotor failures account for up to 12% of the total number of failures of induction motors (Fig. 2). Damage to the short-circuited rotor winding is also an electrical type of damage. Violation of the integrity of the rotor winding rods increases acceleration time and additional losses. This leads to a decrease in efficiency and power factor [1, 25]. In this case, vibration appears and a significant increase in current strength in the undamaged rods. At the time of occurrence and during operation, such a defect does not have an obvious external effect on the machine's performance, but its operation becomes critically dangerous. In this case, the load on those rods that remain intact increases. This contributes to their additional overheating, especially during engine startup and the subsequent “burnout” of the remaining rods. This whole process of destruction of the rotor winding is accompanied by a loss of power of the electric motor, until it gradually overheats and fails. In addition, the breakage of one rod of the short-circuited rotor of a powerful high-voltage induction motor can manifest itself at the stage of exit towards the air gap under the action of centrifugal forces during operation. At the same time, the rotor rod gets caught on the stator winding and magnet wire, which can lead to significant complications in motor restoration and additional financial losses. An example of damage and displacement of the rod of the short-circuited rotor winding from the groove is shown in Fig. 3, b.

Identifying the initial signs of contact failure in the structure of the "white cell" of the rotor is a very urgent task and allows to increase the reliability of induction motors with a short-circuited rotor.

Therefore, current control of the state of the winding of a squirrel-cage rotor of an induction motor during operation is a necessary component for an effective on-board diagnostic system for electric motors of transport.

Taking into account the large mass of the rotor and its inertia, the production or destruction of bearings during motor operation leads to the most serious accidents, especially powerful motors. Bearing failures make up a large share of total failures and, depending on the field of use and motor operation mode, can reach 23-45% (Fig. 2) [38, 40]. An example of the destruction of the bearing structure is shown in Fig. 3, p. The sudden occurrence of eccentricity of the rotor as a result of wear and, accordingly, an increase in the radial clearance of the bearing, taking into account the small design values of the air gap, leads to the hooking of the rotor to the core and stator winding. As a result of the engagement of the rotor core with the elements of the stator structure, damage occurs, which requires a long-term restorative repair of the motor. The costs in this case are close to the cost of a new car. Therefore, the current control of the condition of the motor bearings is also the most important in the on-board system of diagnostics of induction motors to increase the reliability of the operation of the transport rotating equipment.

Unbalance of rotating rotor masses makes up to 7% of the total number of motor malfunctions (Fig. 2) and is one of the most common defects of rotating equipment. The imbalance of rotating masses usually leads to a sharp increase in the vibration of transport units, the emergence of eccentricity, which contributes to the deterioration of the condition of almost all motor design elements and the development of other defects. For this reason, great attention should be paid to issues of control and means of prompt elimination of imbalances during the operation of particularly powerful induction electric motors.

The nature of the occurrence of imbalance in motors can be different. Imbalance and eccentricity are a consequence of the development of processes of uneven wear and destruction of the rotor structure, its aging, the appearance of various residual deformations after abnormal modes, especially dynamic shocks, and also as a result of periodic effects of real technological processes and features of the operation of this motor, which lead to uneven heating and distortion of rotors. In addition, unbalance and eccentricity can occur as a result of defects in the manufacture of the rotor, or after carrying out repairs and maintenance. The presence of imbalance during motor operation reaches up to 7% of the total number of damages (Fig. 2).

From the considered analysis of engine faults that are subject to monitoring, it follows that there are groups that are fundamentally different in nature and, accordingly, in the method of determining damage: one part corresponds to malfunctions of electrical origin (stator winding, rotor winding, insulating materials) and the other - to, conditionally, of a mechanical nature (bearings, imbalance of rotating masses). In order to achieve effective results of diagnosis and optimization of the components of the on-board diagnostic system, it is proposed to use in a single structural diagram of units with methods corresponding to damage, that is, according to electrical parameters and according to mechanical parameters.

At the same time, there is a significant number of other defects arising during the operation of the motor with small cases of each, most of which have manifestations in the form of vibration without catastrophic consequences. The share of such damage is up to 11% of total failures (Fig. 2), but it also requires development control and elimination during the nearest maintenance. For this purpose, in the diagnostic system, when vibration signals are detected that do not correspond to specific damage and exceed the specified limit level of motor vibration, it is proposed to create a collective unit - "other damage".

To control selected defects and malfunctions of induction motors, methods based on the principle of state determination, shown in Fig. 4.

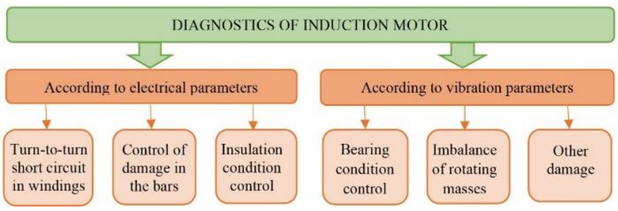


Fig. 4. General scheme of methods of controlling defects of an induction motor

When choosing the methods of effective operation of the system of diagnostics of electric motors of vehicles in real time, it is necessary to ensure compliance with the following conceptual principles:

- diagnostics is carried out without disconnecting the electric motor from the power supply;
- diagnosis is carried out without disconnection from the executive device;
- diagnostic methods do not use separate autonomous devices and mechanisms;
- ensuring the accuracy of diagnostic results in the case of a poor-quality power supply system and under load;
- ensuring the necessary informativeness of diagnostic results for the objective degree of predicting accident-free operation;
- separate external sources of direct or alternating current are not used during operation of the diagnostic system;
- the possibility of automating the diagnosis process.

4. CREATING A DIAGNOSTIC SYSTEM DIAGRAM

When creating a diagnostic system, which is designed to monitor the current state of the electric motor in real time, damage control modules are selected that do not lead to sudden equipment failure. However, the appearance of such defects contributes to the development of further destruction of the structure of individual nodes and leads to a decrease in the reliability of the equipment, an increase in energy consumption, vibration, a general decrease in the quality of the performed functions and the prospect of secondary failures of an emergency nature. Therefore, the main goal of the technical diagnostics system is the organization of effective processes for determining the technical condition of elements of electric motors of vehicles with the installation of damaged elements [20]. In addition, according to modern approaches to the operation of transport equipment, the diagnostic system must not only determine the deviation of individual parameters beyond the established limits, but also establish the type and degree of damage. This increases the accuracy of predicting the trouble-free operation of engine elements for planning the time of its maintenance or repair. Depending on the type and method of detecting damage by means of the on-board diagnostic system, special technical means are used that allow the implementation of algorithms for identifying faults.

In Fig. 5 shows a diagram of the diagnostic system for an induction electric motor. When creating the diagram, the main damage and defects were taken into account (Fig. 2).

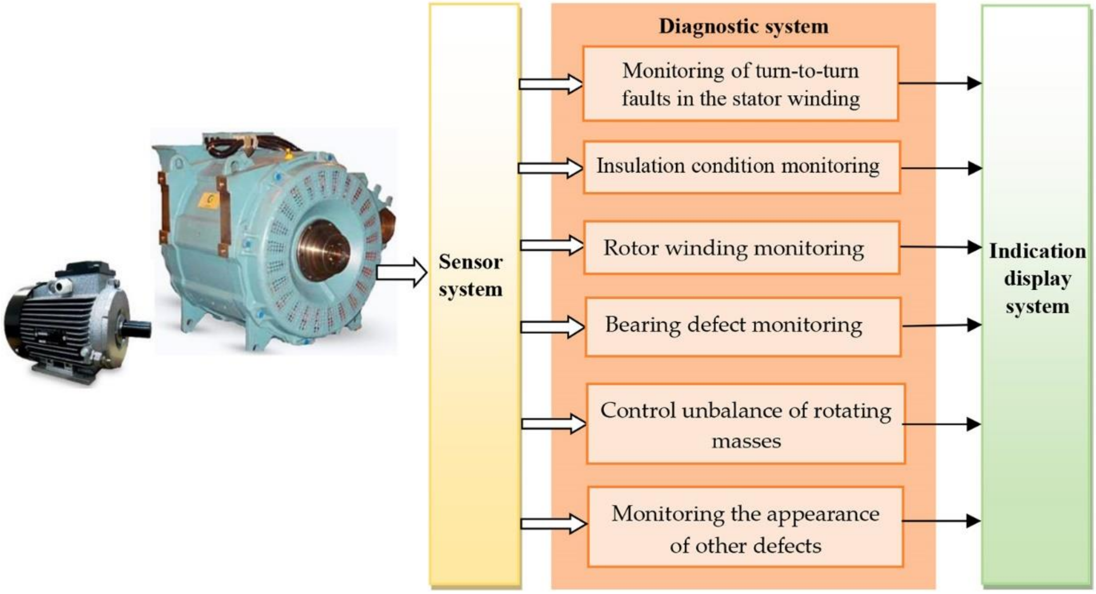


Fig. 5. Diagram of the on-board vehicle diagnostics system (author's development)

The diagnostic system for vehicle induction motors includes units for monitoring the following damage:
- inter-turn short circuits in the stator windings;
- contact failure in the short-circuited rotor winding;
- violation of the winding insulation properties;
- mass unbalance of the rotating mechanism;
- damage to bearings;
- appearance of "other defects".

To ensure the functioning engine damage monitoring units, appropriate algorithms are used, which receive the necessary signals from sensors from the "sensor system" unit (Fig. 5). After determining the type and quantitative analysis of the defect, the information is displayed on the "display unit".

4.1. Methods and algorithms for monitoring short circuits in the stator winding and damage to the integrity of the rotor winding

Methods for diagnosing the main types of damage, in particular inter-turn short circuits in the stator winding and the integrity of the rotor winding structure, should provide diagnostics of induction motors that can operate with both static (fan motors, pumps) and dynamic (compressor drive) loads [34]. When the load changes during operation, the values of the engine parameters change, which complicates monitoring their condition [50]. In addition, the operation of the electrical equipment of vehicles, especially on the railway, is characterized by the appearance of asymmetric voltage, which affects the accuracy of determining damage to the stator or rotor winding.

The indicator that characterizes the degree of damage to the stator winding and provides the necessary information for predicting the accident-free period of operation is the number of closed phase turns. For a short-circuited rotor winding, such an indicator is the establishment of a contact violation in the structure of the "white cell" and the determination of the number of broken rods.

Turn-to-turn faults in the stator winding phase are difficult to diagnose, especially in the initial stages. The difficulty in diagnosing turn-to-turn short-circuits is the similarity of the external manifestations of this type of damage with a number of other defects. Turn-to-turn short-circuits cause asymmetry of the rotation of the stator field and, accordingly, vibration [26]. When inter-turn short circuits occur, an increased current flows in the damaged section of the coil, which causes significant heating of both the closed turn itself and the adjacent turns of the winding.

Among the most common methods of functional diagnostics of induction electric motors according to electrical parameters, the following can be distinguished:
- based on the analysis of the stator current;
- based on the analysis of the external magnetic field;
- based on the analysis of the electromagnetic field inside the motor.

The greatest development for the detection of inter-turn short circuit and control of the state of the rotor of the diagnosis of the state of induction motors was obtained by current methods [52].

There are a number of diagnostic methods that use the current in the winding phases [26] followed by spectral analysis of the signal [42]. Stator currents carry information about turn-to-turn short-circuits of windings, broken rods, misalignment, static or dynamic eccentricity, etc. [9, 46]. Mechanical damage, such as bearing failure, can also be detected by the current spectrum [28, 38]. In addition, motor current monitoring for diagnostic purposes can be carried out directly at the terminal box while the motor is running. This connection is very convenient for use in on-board diagnostic systems. Compared to other methods, the current spectral analysis method has a number of advantages and to the greatest extent meets the criteria of accuracy and efficiency of diagnosing the condition of electric motors.

Current diagnostic methods use data from the spectral analysis of various signals. Spectral analysis of induction motor currents consists of using the fast Fourier transform algorithm and obtaining the values of the first harmonics of the current to determine the parasitic frequencies that correspond to various defects. The modern innovative spectral methods investigated for the diagnosis of various damages of electrical machines include such as the fast Fourier transform, the Hilbert method, the Park’s vector approach method, the wavelet transform, and the Multisignal Classification (MUSIC) method [1, 46].

Of the existing methods, the most promising for use in embedded diagnostic systems for induction motors is Park`s vector method [18]. Park's vector approach method makes it possible to detect inter-turn short circuits of the stator winding and damage to the short-circuited rotor winding when the engine is operating under load and in systems with a poor-quality power supply system. This method can be used to automate the diagnostic process.

Research on the application of the Park’s vector for motor diagnostics requires the use of simulation tools, which has already become an integral part of research in various fields [15, 23, 37, 42]. Park's vector method is based on the transformation of phase currents of a three-phase motor power supply system (I_A, I_B, I_C) into a two-phase current system (I_d, I_q) of a moving *d-q* coordinate system [16]:

$$I_d = \sqrt{\frac{2}{3}} I_A - \sqrt{\frac{1}{6}} I_B - \sqrt{\frac{1}{6}} I_C \quad (1)$$

$$I_q = \sqrt{\frac{1}{2}} I_B - \sqrt{\frac{1}{2}} I_C \quad (2)$$

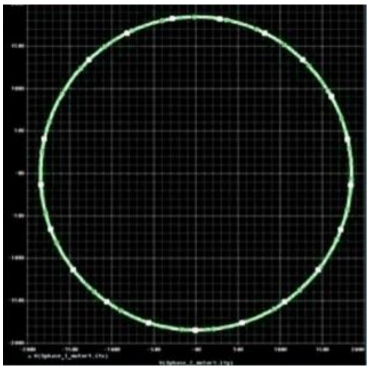
A vector describing the process figure in the dq coordinate system:

$$\vec{I_p} = I_{sd} + J \cdot I_{sq} \quad (3)$$

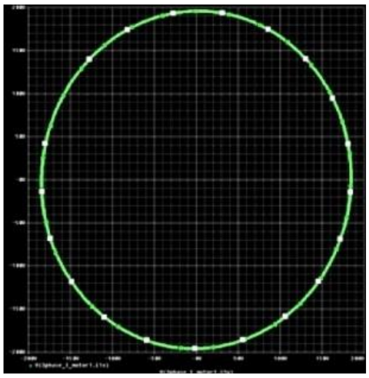
Fig. 6 shows the figures of the Park vector obtained by modeling an induction motor of the AIR132 M4 series with a power of 11 kW for a symmetrical power system. In Fig. 6, a is a vector drawing of Park for an undamaged engine, and In the presence of interturn short circuits in the stator, a vector picture is obtained, shown in Fig. 6, b.

Thus, a two-dimensional vector image of three-phase currents with a high-quality power supply system for an intact motor describes a regular circle of constant radius as the angular frequency ω changes (Fig. 6, a).

The study [18] found that in the presence of short circuits in the stator winding, the circle of the Park vector takes the shape of an ellipse (Fig. 6, b). Fig. 7 shows the scheme of current designations and angles of the hodograph figure. The researchers also established that when the number of short-circuited turns increases, the angle of ellipticity ε decreases (Fig. 7).



(a



(b

Fig. 6. Park`s vector figures for: a – undamaged motor; b – if the stator winding is damaged

When an asymmetry appears in the motor power supply, the resulting ellipse deviates from the I_{sd} axis by an angle θ, which affects the change in the ellipticity angle in the new basis and the values of the projections of the Park`s vector currents on the *d* and *q* axes (Fig. 7).

In [18] it was established that the decrease in the ellipticity angle depends proportionally on the number of closed turns in the stator winding. However, it is impossible to obtain accurate damage parameters when powered from an asymmetrical voltage system. It is necessary to recalculate the values of the projections of Park`s vector currents from the orthogonal-elliptic basis to the orthogonal-circular one.

When developing an algorithm for determining stator damage using Park's vector approach, the following notations were used (Fig. 7):

θ – the angle between the 0-I_{sd} axis and the main semi-axis of the ellipse;

ε – the angle of ellipticity (the angle between the main semi-axis of the ellipse and the diagonal of the rectangle closest to it);

$\vec{I_p}$ – Park’s vector;

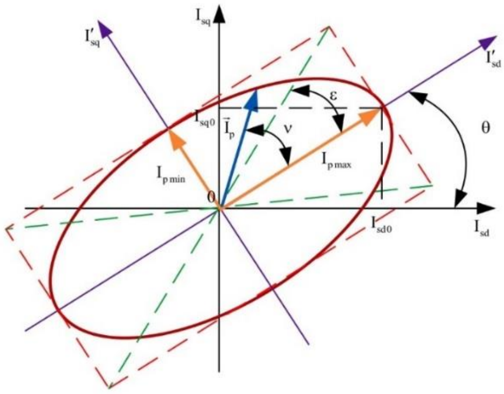


Fig. 7. Scheme of currents on the Park's vector drawing in case of damage to the stator winding and asymmetrical power system

γ – the angle between the semi-major axis of the ellipse and the instantaneous position of the Park's vector;

I_{pmin} – the minimum value of the Park's vector (when it coincides with the q axis);

I_{pmax} – the maximum value of the Park's vector (when it coincides with the d axis);

I_{sd0} – the projection of the Park's vector on the d axis;

I_{sq0} – the projection of the Park's vector onto the q axis.

The process of diagnosing the motor stator winding takes place in the following sequence. During the operation of the induction motor, the currents of each phase are measured from the power supply system using current sensors: I_A, I_B, I_C.

Using the Fourier transform algorithm, their first harmonics are obtained from phase currents. They are used to convert to a moving d-q coordinate system. On the two-phase coordinate plane with the I_{sd} and I_{sq} axes, when the power supply frequency ω changes, the shape of the Park's vector is constructed. Using Park's vector drawing, the values of the currents of I_{sd0}, I_{sq0} and the maximum value I_{pmax} (for I_{sq}) and the minimum value I_{pmin} (for I_{sd}) are determined (Fig. 7).

To determine the stator damage and the symmetry of the power system for further calculations, it is necessary to calculate the following angles: (Fig. 7) [18, 22]:

- ellipticity angle for a symmetric power system (orthogonal-circular basis)

$$\varepsilon = \operatorname{arctg}\frac{I_{pmin}}{I_{pmax}}, \tag{4}$$

- the angle of inclination of the ellipse in case of asymmetry of the power supply system

$$\theta = \arccos\frac{I_{sd}}{I_{pmax}}, \tag{5}$$

- ellipticity angle for an asymmetric power system (orthogonal-elliptic basis)

$$\gamma = \operatorname{arctg}\frac{I_{sq0}}{I_{sd0}}, \tag{6}$$

The value of the angle θ≠0 indicates the asymmetry of the power system and it is necessary to recalculate the values of the projection of the Park`s vector currents. The remaining angles are also used when establishing the exact values of currents in another basis.

Further calculation using the deviation values of the phase current amplitudes or the displacement of the current phase angles allows us to determine the degree of damage to the stator winding at any time during its operation with poor quality power system.

Using the calculation algorithm given in [18], it is possible to establish the accuracy of damage down to one turn of the winding.

The method of determining the exact number of damaged turns of the stator winding implemented in this way during the operation of motors with a static load mode with the presence of an asymmetric supply voltage system provides a wide opportunity to use the Park's vector method in the modern on-board diagnostic system of induction motors of vehicles.

For motors operating in a dynamic mode with a constant change in load, for example in a compressor drive, damage to the stator winding is diagnosed using the method in the work [26], using voltage sensors.

Based on the method in the work [26], from the values of the first harmonics of the currents, the second derivative of the phase shift between phase currents and voltages is calculated depending on the engine speed.

A comparison of the obtained and experimental results allows us to determine the exact number of damaged turns in each phase of the stator winding when the load changes.

Thus, to ensure the monitoring of the motor stator winding taking into account the fast Fourier transformation, the following sensors are required:

D_ω – angular velocity sensor (for selecting the control mode: static or dynamic);

D_{sIA}, D_{sIB}, D_{sIC} – current sensors;

D_{sUA}, D_{sUB}, D_{sUC} – voltage sensors.

The general view of the algorithm for determining the number of damaged turns of the stator winding is shown in Fig. 8.

The considered principle of using Park`s vector method also allows us to determine the condition and degree of damage to the rotor winding.

For ease of use and optimization of the diagnostic system, it is advisable to also use Park method to diagnose the condition of the rotor. The same data and sensors as for the stator are used to diagnose the rotor using Park's vector approach. The works [29, 49] present the results of studies on diagnosing the condition of the rotor using the Park vector. An established sign of a violation of the structural integrity of the windings of a squirrel-cage rotor for the motor is an increase in the thickness of the vector pattern.

Figure 9 shows the difference in the Park's vector pattern of an intact AIR132 M4 motor with a power of 11 kW and with a broken rod with a symmetrical power system, which was obtained by means of mathematical modeling.

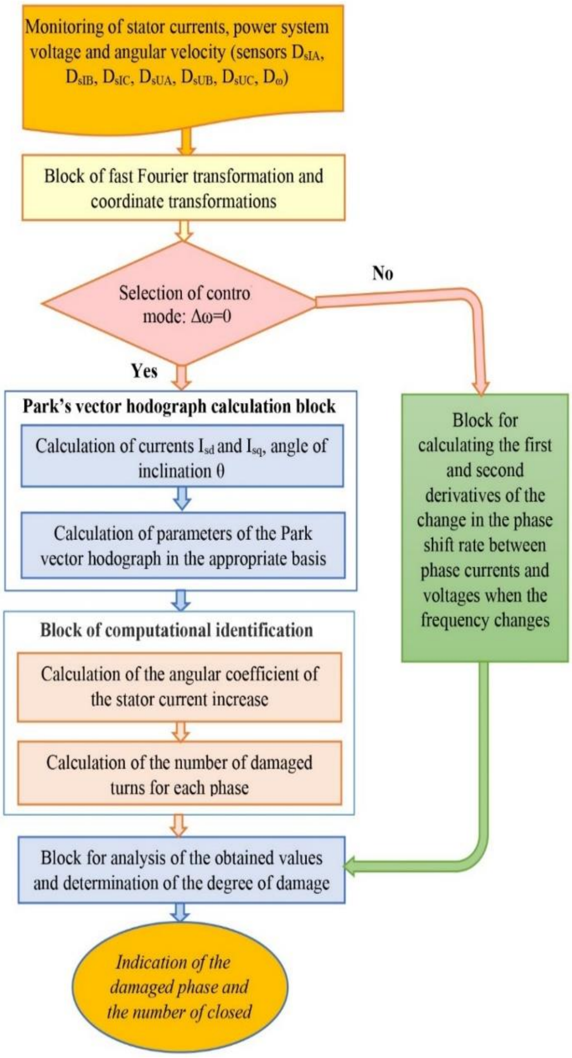


Fig. 8. Algorithm of the stator damage determination unit (author's development)

There are a number of methods for estimating the signal signature of the resultant vector of stator currents through the determination of specific spectral components associated with a rotor fault. However, the methods under consideration are given for a symmetrical power system to calculate damage in an orthogonal-circular basis. The main use of the Park's vector at present is the possibility of detecting a rod defect when comparing the created hodograph with a standard obtained in the case of a working motor with a high-quality power supply, that is, for bench tests.

Considering that when operating transport systems in real conditions, the power supply system is not ideal, this method has not received practical development.

Work [25] presents studies on adapting Park's vector method to determine damage to the rotor winding under an asymmetrical power supply system.

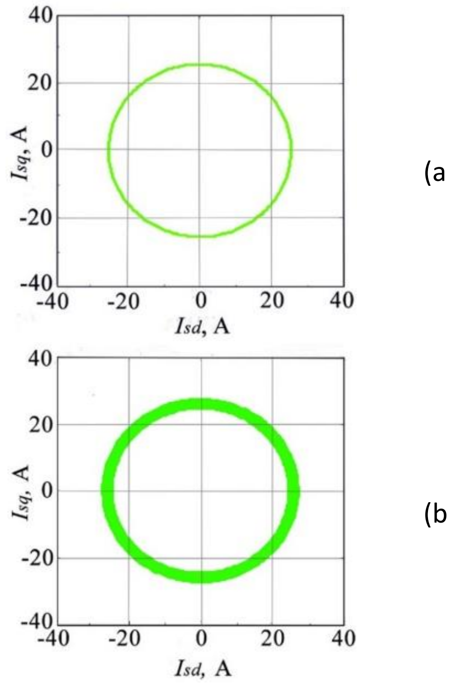


Fig. 9. Park`s vector figures for: a – undamaged motor; b – if there is damage to the rotor

When developing an algorithm for determining the degree of rotor damage in the presence of an asymmetrical power supply system, it is also necessary to use recalculation to convert values for currents from a vector diagram from an orthogonal-elliptical basis to an orthogonal-circular one. Fig. 10 shows a scheme of currents on the Park's vector drawing in case of damage to the rotor winding and asymmetrical power system.

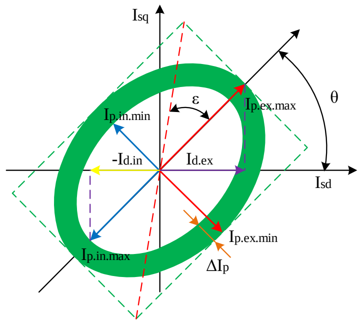


Fig. 10. Scheme of currents on the Park's vector drawing in case of damage to the rotor winding and asymmetrical power system

The following notations are used in Figure 10:

$I_{p.ex.max}$ – the maximum value of the Park's vector for the outer circle;

$I_{p.ex.min}$ – the minimum value of the Park's vector for the outer circle;

$I_{p.in.max}$ – the maximum value of the Park's vector for the inner circle;

$I_{p.in.min}$ - the minimum value of the Park's vector for the inner circle;

$I_{d.ex}$ – the projection of the Park's vector of the outer circle onto the d axis;

$I_{d.in}$ – the projection of the Park's vector of the inner circle onto the d axis;
ε – the ellipticity angle;
θ – the inclination angle of the ellipse.

Calculation of the line thickness of the Park`s vector figure, which shows the degree of damage to the rotor, is determined by:

$$\Delta I_p = I_{s\max} - I_{s\min}, \tag{7}$$

where I_{smax} – the maximum instantaneous value of the stator phase current;
I_{smin} – the minimum instantaneous value of the stator phase current.

When the value ΔI_p=0, the thickness of the Park vector figure (Fig. 7) is absent. It follows from this that the rotor winding is not damaged. If the value ΔI_p>0 this indicates damage to the short-circuited rotor winding. The greater the degree of damage to the rotor winding structure, the higher the value of ΔI_p.

Just as for calculating damage to the stator winding, the angle of inclination of the ellipse θ (Fig. 10) should be determined. If asymmetry of the voltage system is established (at $\theta \neq 0$), then to determine the exact value of ΔI_p it is necessary to recalculate the current values from an orthogonal-elliptical basis to an orthogonal-circular one [25].

As with stator diagnostics, after the Fourier transformation with the determination of the first harmonics of the stator currents, in order to construct a vector pattern of the Park's vector, the phase currents of the three-phase motor power supply system (I_A, I_B, I_C) are converted to the two-phase system of currents (I_d, I_q) of the moving dq-coordinate systems according to (1) and (2). In the case of using the rotor diagnostic module together with the stator diagnostic module discussed above, the signals from the transformations received from the current sensors are also used to control both elements.

According to relations (1) and (2), the maximum (I_{pmax}) and minimum (I_{pmin}) values of the circle of the Park's vector drawing are determined, corresponding to the outer (ex) and inner circle (in) (Fig. 9). After determining the projection of the maximum value of the Park's vector I_{pmax} on the d axis marked $I_{d.ex}$ (Fig. 10), the inclination angle of the ellipse is calculated

$$\theta = \arccos\frac{I_{d.ex}}{I_{p\max}}. \tag{8}$$

The resulting projections for phase currents from Park's drawing , after transformations, can be used both for diagnosing the rotor and for determining damage to the stator. A detailed method for determining rotor defects from a vector drawing of the Park is given in [25]

Thus, when comparing the calculated width of the Park`s vector figure with the reference value for a given type of engine, the degree of development of rotor damage is monitored. The rotor condition can be monitored during operation under an asymmetrical voltage system.

An indicator of the development of a rotor defect is the calculated value of ΔI_p (7).

In accordance with the above studies in Fig. 11 an algorithm is proposed for the practical use of this method when diagnosing the rotor of an induction motor.

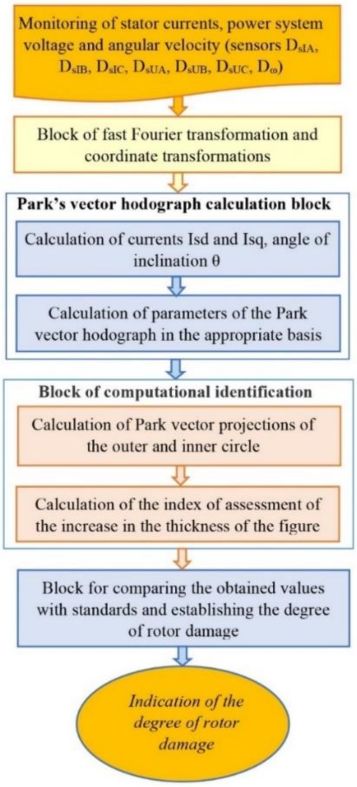


Fig. 11. Algorithm of the rotor damage determination unit (author's development)

The results of studies on the use of Park's vector approach in stator and rotor diagnostics demonstrate the convenience and perspective of using the method in on-board systems of vehicles to monitor the condition of the main elements of the induction motor during operation.

4.2. Justification of the method and algorithm of control of mechanical damage by vibration parameters

The main mechanical damages of electric motors that cause vibration during the operation of the electric motor include: damage to bearings, imbalance of rotating masses, misalignment, increased eccentricity, weakening of the rotor package and mechanical weakening of the structural elements of the electric motor.

Bearings are among the most common damages, according to operational statistics (Fig. 2), which require constant monitoring in the on-board diagnostics system. Manifestations of bearing damage include increased vibration, noise, and an increase in housing temperature. Bearing failures can be caused by excessive loads, sudden braking and starts, long-term operation of transport equipment in

conditions that do not correspond to the calculated ones. The most typical causes of bearing failure include:
- high loads,
- ineffective seals,
- excessive tension when landing (too small working gap),
- overheating of the bearing,
- excessive wear,
- destruction of bearing parts,
- natural fatigue.

In most cases, damage to the bearings of vehicles occurs as a result of wear and tear of bodies and raceways, the formation of increased clearance and cracks during operation. Monitoring the state of bearings as part of the diagnostic system to improve motor reliability is an urgent task. The most convenient and informative means of bearing diagnostics are methods based on the analysis of vibration signal spectra, for which contact vibration sensors are used [35].

Control of the condition of the bearings in the conditions of the built-in diagnostic system can be carried out by one of the following main methods [10, 56]:
- peak factor;
- by the spectrum of the envelope of the vibration signal;
- by spectral analysis of vibration signals.

The peak factor method (PIK) consists in monitoring two vibration parameters: the root mean square value (RMS) of the vibration acceleration and the peak amplitude of the vibration acceleration. The ratio of these two PIK/RMS parameters is the PIK factor. With the development of the defect, the peak of the amplitude and the RMS increase monotonically, but with a delay in time. By observing the changes in the RMS level of the vibration signal, a conclusion is made about the presence or development of a bearing defect using the defined limit values for the selected vibration parameters. However, this method is uninformative and inconvenient for use in embedded diagnostic systems. Assessment of the condition of bearings using a pronounced peak factor provides objective information only for a short time before its failure [40]. This method is most commonly used for operational measurement of vibration parameters using a portable vibrometer.

The method based on the spectrum of the vibration signal envelope is based on the analysis of the high-frequency component of the vibration and the detection of its modulating low-frequency signals [8]. When receiving a wide-band signal after the vibration sensor, narrow-band filtering is carried out with the selection of a low-frequency modulating signal from it, that is, the "signal envelope", which is fed to the vibroanalyzer for analysis. To control the condition of the bearings using this method, a vibration spectrum analyzer with the function of analyzing the spectrum of the envelope of high-frequency vibration is required [36]. The results of determining the condition of the bearings using the envelope method have a high degree of reliability, but the signal processing is quite complex, and the equipment has a high cost. Therefore, this method has become widely used in stationary diagnostic systems for condition control during equipment maintenance.

Spectral analysis has become the most widely used in diagnostic systems, as a method that corresponds to the reliable informativeness of equipment defects due to the unambiguous identification of damages, due to the connection of dependencies between the mechanical processes taking place and the presence of harmonics in the spectrum, characteristic of specific defects. The degree of development of a specific defect is observed by the amplitude bursts of harmonics that have appeared. To detect and identify the type and degree of development of the defect, the obtained values of the quantitative assessment of the diagnostic parameters are compared with standards of defect-free machines and their components. This method fully meets the requirements for use in diagnostic systems during operation and allows automating the diagnosis process.

Piezoelectric and eddy current vibration sensors are used from all known types of vibration sensors to remove the vibration signal during vibration diagnostics of rotating machines. Piezo sensors have higher measurement accuracy and sensitivity, have high stability, and at the same time have miniature dimensions and mass, which is convenient for use.

The direct measured value of the piezoelectric sensor is vibration acceleration (a), which can be converted to vibration velocity (V) and vibration displacement (s) using integrators, which are related by the equations:

$$V = 2\pi f s = \frac{a10^3}{2\pi};\ s = \frac{V}{2\pi f} = \frac{a10^3}{2\pi f};\ ^3 \quad a = (2\pi f)^2 s10^3 = 2fV10, \tag{9}$$

where f – the frequency of complete oscillation cycles of the body per second: f = 1/T,
T – the repetition period of each variable value.

When passing the signal after the vibration sensor, which performs the functions of a vibration converter of mechanical vibrations into electrical signals, through a spectrum analyzer with the required bandwidth. an amplitude spectrum is obtained at the output. Thus, the physical characteristics of mechanical oscillations in the frequency domain are the frequency distribution of their amplitudes, i.e., their frequency spectrum.

The following mathematical methods are used to decompose a complex signal received from a vibration sensor with the determination of harmonic components of the spectrum:
- fast Fourier transform;
- wavelet transform;
- Wigner-Will transformation.

The most common use in diagnostic tasks was the fast Fourier transform algorithm [25, 46]. In addition, in order to optimize the diagnostic system in which this method is used in the rotor and stator diagnostic modules, it is advisable to also use a fast-discrete Fourier transform algorithm when performing signal decomposition.

Decomposing a complex signal using the fast Fourier transform allows to determine the components of the spectrum, which are the harmonic components of the complex signal during narrow-band analysis. Knowing the frequencies at which mechanical malfunctions of the motor are manifested, it is possible to assess their condition by the amplitude of the spectrum components, that is, to detect an increase in the vibration amplitudes at frequencies that coincide with the frequencies of possible damage and to identify the defects that arise at an early stage of nucleation.

To monitor the state of the bearings of the electric motor, sensors are installed one on each bearing shield or bearing inner cover in the immediate vicinity of the bearing, as shown in fig. 12.

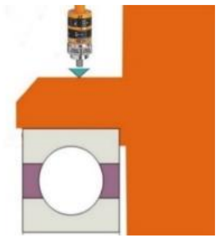


Fig. 12. The location of the vibration sensor

Defects of bearing assemblies, mass imbalance, eccentricity and a number of other damages that cause the appearance of vibration can be determined by one pair of sensors located as in fig. 12. The vibration pattern of the mass imbalance of the rotating mechanism is established in two bearings of the controlled mechanism at once, therefore, when creating a module for monitoring this defect in the engine diagnostic system, it is enough to enter only the controlled characteristic frequency.

Unpredicted for individual identification and determined by the on-board vibration system, an increase in the level of vibration of the induction motor is transmitted to the corresponding control unit – "other damage" (see Fig. 5). As a diagnostic criterion for establishing the level of other mechanical defects to ensure general vibration monitoring of the current state of the electric motor, it is possible to use the amplitude values at characteristic frequencies for several defects according to the expression [35]:

$$\Delta k = \sum_{k=1}^{n} 10lg \frac{A_{iCur}(\varphi)}{A_{iLim}(\varphi)}, \quad (10)$$

where $A_{iCur}(\varphi)$ – the current value of the amplitude of the spectral signal of the i-th motor defect for the frequency φ, which is characteristic of its occurrence; $A_{iLim}(\varphi)$ – the limit value of the amplitude of the spectral signal of the i-th motor defect for the frequency φ, which is characteristic of its occurrence; n – the number of controlled defects.

When defects occur, when the control parameter Δk takes the value: $\Delta k > \delta$, the signal is transmitted to the corresponding on-board display. As a control for "other damage" to simplify the diagnostic system, it is also possible to use the overall limit or acceptable level of vibration of the entire unit.

Thus, the principle of control of mechanical damage selected in the on-board system is a comparison of the received and converted signal of the marked frequency band, indicating the type of defect, with one of the prescribed limit levels with the transfer of information to the display unit.

In the process of identifying defects of the electric motor, which cause an increase in the level of vibration, the main role is played by the selection of the correct number of characteristic frequencies. For a real diagnostic system, it is possible to expand the number of modules for determining specific defects, currently classified as "other damages". The determined frequencies of defects can be used in the future, for example, as training material for a neural network, when automating the diagnostic system. In addition, it should be taken into account that the too large number of selected characteristic frequencies for determining a number of damages may affect the quality of recognition of motor defects and the time of their identification.

Four main stages are used in the construction of the vibrodiagnostic algorithm: signal conversion from mechanical to electrical, pre-processing of the signal, selection of necessary features and classification of the level of damage based on the system of features.

The operating algorithm of the diagnostic unit for detecting damage to the mechanical units of the induction motor is shown in Fig. 13.

To ensure monitoring of mechanical defects, vibration sensors D_{v1} and D_{v2} are used.

4.3. Current control of the state of insulation

On-line insulation condition monitoring in electric motors is a very important option for predicting the failure-free period of operation and provides lower costs compared to invasive monitoring during the maintenance period, which is associated with related problems.

There are a number of methods for monitoring the condition of the insulation to diagnose the stator windings, which in turn can be classified according to the measured or calculated parameter, electrical or non-electrical quantities [27, 54]. The wide availability of different methods is related to the nature of occurrence and type of damage, where the

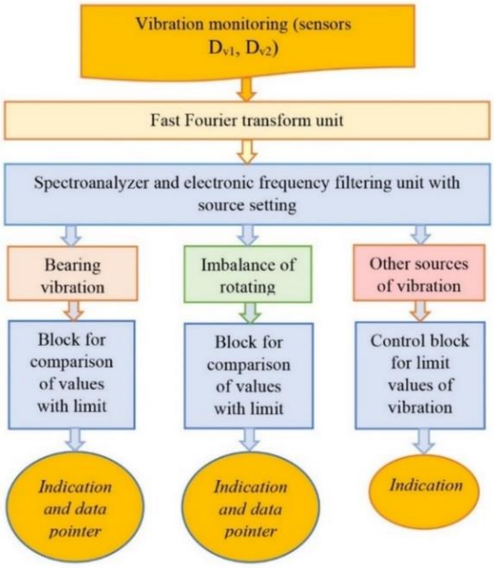


Fig. 13. Algorithm of the unit for determining the state of mechanical defects of the induction motor (author's development)

causes can be not only operational, but also technological defects. Most of the insulation condition monitoring methods require stationary conditions of use and rather complex and specific equipment that cannot be applied to electric motors directly during operation [12, 27].

The main manifestation of the decrease in the insulating properties of the motor winding materials is the appearance of partial discharges. Under normal operating conditions, insulation defects (which are almost always present) do not lead to complete insulation breakdown. However, during further operation of the equipment, these defects develop and their activity increases. The activity of partial discharges, which continues continuously for some time, leads to the local destruction of the insulation due to thermal processes and its catastrophic breakdown with equipment failure. According to existing observations, in the absence of extreme effects such as emergency overvoltages, the process of defect development from the embryonic stage to complete breakdown lasts from several months to several years [14]. Thus, the appearance of partial discharges indicates the presence of an insulation defect, and partial discharges can be detected already at the earliest stage of the development of the defect. Diagnostics of the occurrence of partial discharges also makes it possible to monitor the state of insulation of motor windings during operation, especially of high power, due to their high cost and more severe accidents. In addition, winding monitoring using partial discharge analysis is essential to implement proper maintenance planning. The method of partial discharges, as the most effective and demonstrative, has been used for post-repair or acceptance tests of the motor after manufacturing, with increased voltage, for quite a long time.

The method of monitoring partial discharges under operating voltage during normal operation for use in the monitoring system of electric motors of vehicles is the most promising and effective for this task. This method allows detecting insulation defects at the earliest stages of their occurrence and monitoring the dynamics of their development online.

Monitoring and measuring the frequency and intensity of partial discharges to assess the condition of the motor winding can be carried out during normal operation of the equipment without decommissioning it. In addition, the characteristics of partial discharges allow for a multifaceted assessment of the properties of defects and the nature of the process development.

A partial discharge causes signals of three types: electrical, electromagnetic, and acoustic, which can be measured using electrical, thermal, mechanical (acoustic and inertial), magnetic, optical, and chemical means [31, 12, 57].

The electrical method, which allows measurements to be taken in normal operating mode (without applying increased voltage) with completeness of data for assessment and forecasting of the objective state of insulation, has been most widely used in diagnostic systems for monitoring the state of insulation [33].

The use of the partial discharge method to monitor the technical condition of the insulation of the stator windings of high-voltage generators and powerful electric motors is implemented in the MDR-3/HF (Motor and Generator Diagnostics Relay) and MDR-S20 brand monitoring systems. In these systems, sensors operating in the HF/UHF frequency range are used to measure partial discharges in the insulation of the stator windings. They are high-voltage communication capacitors or electromagnetic sensors-antennas of various types, which are mounted directly in the stator of an electric machine.

Determination of the technical condition of the insulation is carried out under the operating voltage of the motor based on the analysis of the intensity and distribution of pulses of partial discharges using a pulse recorder. Antenna-sensors (D_{a1}, D_{a2}) are installed for these purposes on the front parts of the electric motor during production or during repair, as shown in fig. 14. At the moment, this method is the most studied and promising for use in embedded diagnostic systems.

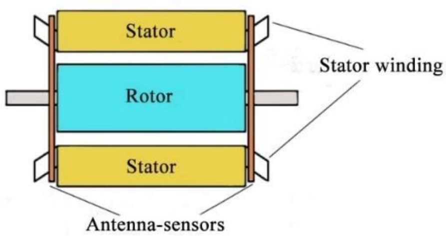


Fig. 14. Installation of sensors-antennas for monitoring partial discharges

In the general case, the quantitative assessment of partial discharges can be carried out by measuring directly the charge (Cl), the frequency (intensity) of the pulses, the average current of the discharge and the power loss per discharge. The lack of a regulatory framework with standards of normalized values does not make it possible to formalize the operation of automatic systems for diagnosing the state of insulation according to the level of defined characteristics of partial discharges. However, the quantitative assessment of the state of insulation of electric machines according to the parameters of partial discharges can be carried out only by comparison with the results of previous measurements performed on this equipment or, most often, by analyzing the change in the characteristics of partial charges by frequency and power in the corresponding unit of the on-board diagnostic system.

At present, special attention is paid to the issue of the development of diagnostics of the state of insulation of electric motors by partial discharges. Partial discharge methods are the most widely used and commercially studied. The works of a number of researchers are devoted to the study of means of estimating the intensity of partial discharges of electrical equipment based on modern advanced technologies [54, 31].

When controlling one intensity of partial discharges for a set time, it is possible to ascertain the correct and stable period of operation of the stator of the electric machine. An increase in the intensity of discharges several times over a controlled period of time indicates the presence of dangerous defects developing in the insulation with the possibility of dangerous consequences.

It follows from this that the presence of an insulation condition control module in the diagnostic system increases the guaranteed level of detection of defects in the early stages, which contributes to increasing the efficiency of the used diagnostic system and ensuring the trouble-free operation of vehicles.

4.4. Functional diagram of the on-board diagnostics system

The proposed diagnostic system includes six modules for determining the type and degree (for the stator and rotor) of damage to the elements of the induction electric motor (see Fig. 5) considered in the work. When choosing diagnostic methods, modern approaches and research are used to determine the condition of important and most damaged motor elements. Based on the developed algorithms of each control module, a functional diagram of the on-board diagnostic system (Fig. 15) is proposed, which is ready for practical implementation.

The following sensors are required to ensure the operation of the on-board diagnostic system:

D_{ω} – angular velocity sensor;

D_{sIA}, D_{sIB}, D_{sIC} – current sensors;

D_{sUA}, D_{sUB}, D_{sUC} – voltage sensors;

D_{v1}, D_{v2} – vibration sensors;

D_{a1}, D_{a2} – sensors-antennas.

The functioning of each module is completely autonomous and depends only on sensors monitoring specific parameters for its operation. The current, voltage and speed sensors are located externally. The module for controlling the degree of damage to the stator winding for the static mode and the state of the rotor winding, in order to optimize the system, it is advisable to perform it with general units of fast Fourier transformation, calculation of Park's vector parameters and recalculation of currents from an orthogonal-elliptic to an orthogonal-circular basis. In the case of a dynamic load detected by the angular velocity sensor, i.e. when $\Delta\omega \neq 0$, further diagnosis of the stator takes place through another channel.

For this, a corresponding unit is installed in the scheme to ensure the switching of diagnostic channels depending on the type of load (Fig. 15).

After establishing the type and degree of damage to the stator or rotor, the data is provided to the display unit.

After the signal from the vibration sensor is transformed and decomposed into a Fourier series in the mechanical damage control module, it is frequency filtered and transferred to the corresponding unit for determining the motor element. After calculating the parameter characterizing the amount of vibration, a control signal is generated, which, when the vibration reaches the limit level, is transmitted to the display unit. The presence of an indicator of vibration parameters serves to control and monitor the development of the magnitude (level) of vibration. In addition, it is possible to use the vibration indicator to eliminate imbalances with the help of portable devices (or built-in functions of monitoring systems) for balancing rotors in their own supports (bearings), etc. At the same time, the disassembly of the equipment is performed in the minimum volume sufficient to access the balancing planes. The presence of a vibration indicator also makes it possible to eliminate such defects as a violation of the centering of the connection of the electric motor and the mechanism driven by it.

The implementation and implementation of the proposed on-board diagnostic complex built into the electric drive will allow not only to reduce the failure of transport equipment of an emergency nature, but also to reduce economic costs by planning the terms of technical inspections and repairs and their volumes.

In addition to the on-board diagnostic system, the standard configuration of some types of induction motors, for example traction in AC electric locomotives, includes temperature control sensors for the stator winding and bearings, which provides additional diagnostic indicators of the condition. In combination with the received indicators of the on-board diagnostic system, additional equipment sensors make up the maximum information level for reliable forecasting of the fault-free period of operation of induction motors of vehicles.

5. RESEARCH RESULTS

On the basis of the most frequent failures and operational requirements, a structural diagram of the built-in diagnostic system of transport equipment with induction electric motors is proposed. Taking into account the increasingly widespread and promising further use of induction electric motors in the transport industry, the presented development is a solution to an urgent modern issue to ensure an increase in the efficiency of transport.

The induction motor diagnostics system includes the following modules for monitoring electric motor defects: the presence of an inter-turn short circuit in the stator winding phase; damage to the condition of the "white cell" of the rotor winding; winding insulation breakdown; the occurrence of mass imbalance of the rotating mechanism; damage to bearings and control of appearance of "other defects".

The proposed structure of the diagnostic system covers the main types of electric motor damage, including preventive monitoring of the insulation condition and the general vibration condition of the electric motor. To control the occurrence of turn-to-turn short-circuits in the stator winding phase and damage to the rotor winding, the modern method of Pack's vector approach is used.

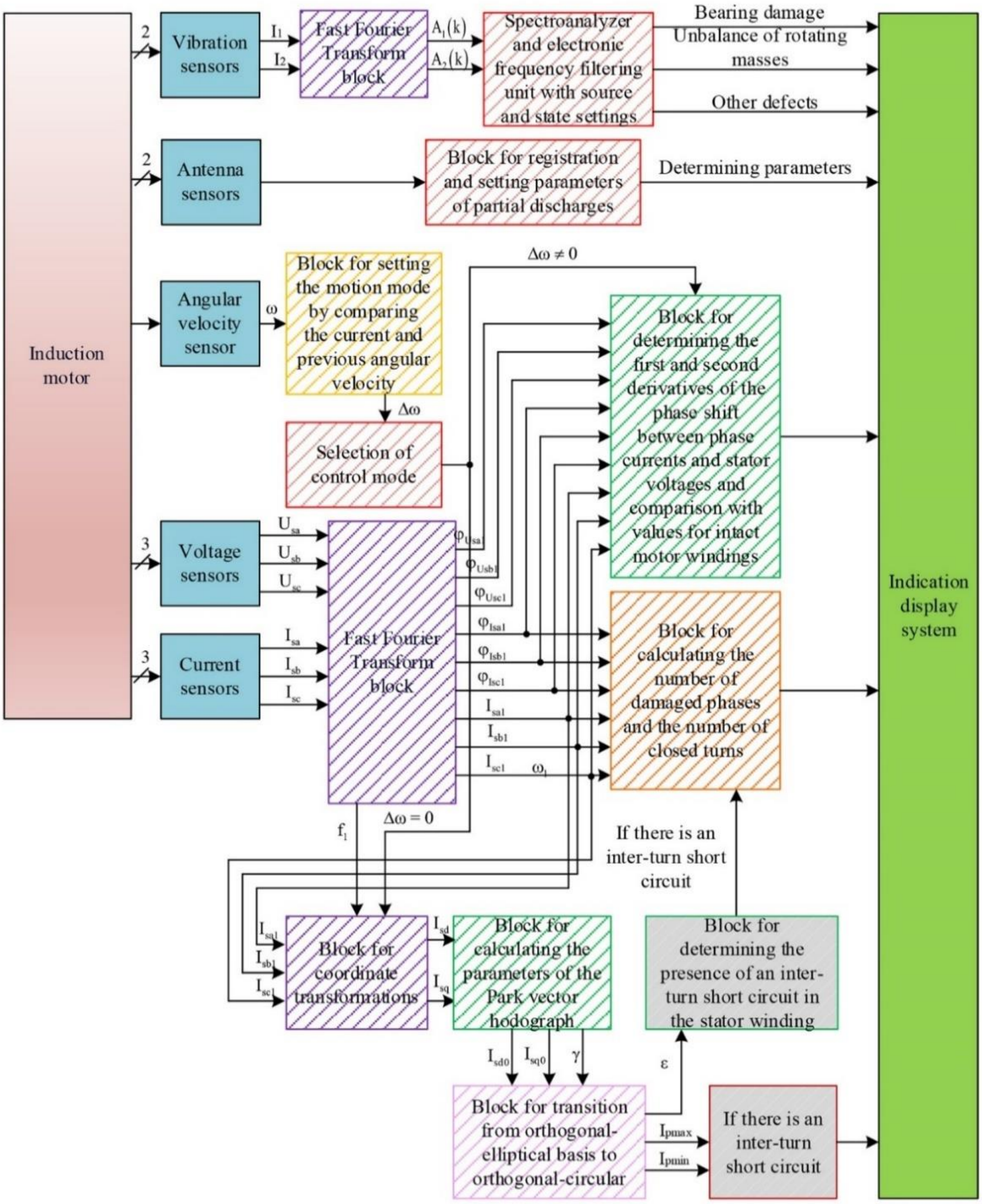


Fig. 15. Functional diagram of the on-board diagnostics system (author's development)

This method allows to obtain reliable diagnostic results when the motor is operating under load and with a poor-quality power supply voltage system. To control the condition of bearings and other defects that cause vibration, the method of spectral analysis with preliminary decomposition of the signal using the fast Fourier transform is used. This makes it possible to differentiate the type and degree of damage to mechanical elements by frequencies that coincide with the frequencies of possible damage and to identify defects. The work draws attention to the need for a module for monitoring the condition of the insulation, which provides control and prediction of the time of trouble-free operation in advance of the occurrence of damage to the stator winding.

Algorithms are provided for the operation of each module, which are synthesized in the general functional scheme of the diagnostic system. The proposed scheme of the diagnostic built-in system is idealized, but the system architecture allows the use of a reduced set of selected modules. In addition, it is possible, if necessary, to expand the "other damage" unit with the creation of additional units of individual defects that cause vibration for specific industries and conditions of use of electric motors.

Ensuring constant monitoring of the condition of induction electric motors in real operating conditions with the detection of early stages of failures is a complex and most important task, the solution of which is a more effective and economical alternative to scheduled maintenance and creates greater safety of transportation with timely fulfillment of logistical tasks.

The developed diagnostic system, unlike well-known systems for monitoring the condition of asynchronous motors, allows you to simultaneously monitor both electrical and mechanical faults when the motor is operating under load with a poor-quality power supply system.

6. CONCLUSIONS

In this comprehensive study, the concept and structural diagram of the on-board system of diagnostics of induction electric motors with the development of algorithms for the operation of unit monitoring units of its main structural elements are proposed. During the development of the diagnostic system, the peculiarities of the construction of diagnostic systems for rotating electric machines were investigated in the real conditions of their operation, and modern current and vibration diagnostic methods were implemented.

Algorithms for the operation of each module are presented in the functional scheme of the general diagnostic board diagnostic system and cover important defects of induction motors. The diagnostic system integrates methods that use various diagnostic principles and criteria and are adapted for use in the built-in diagnostic system. The use of Park's vector approach allows determining the number of damaged turns in the stator winding and the degree of damage to the rotor under the load of a motor with a poor-quality power supply system, which creates a condition for more accurate prediction of the state of trouble-free operation. The used principle of vibration diagnostics allows developing a system for detecting damage to mechanical components.

The developed functional diagram of the diagnostic system can be used for practical implementation in physical form. The use of the proposed system of on-board diagnostics will provide continuous information about the state of the main elements of induction motors of vehicles in accordance with modern requirements and real operating conditions.

A continuation of research may be the expansion of the use of Park's method to identify mechanical defects in the diagnostic system of asynchronous motors.

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