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MODULAR UNIT FOR MONITORING OF ELEMENTS OF ASYNCHRONOUS MACHINE FOR IMPROVING RELIABILITY DURING OPERATION

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Abstract

To ensure the reliable operation of asynchronous machine, the most effective is to use modern monitoring systems for current monitoring of the state of the main engine elements. This work presents research and developpment of a structural diagram of a modular unit for monitoring the appearance and development of the most frequent and difficult to diagnose types of defect to the main structural elements of the engine. The developed modular unit allows simultaneous monitoring of the presence of inter-turn short-circuits of the stator winding and the integrity of the structure of the short-circuited rotor winding. In the work of the monitoring unit Park's vector approach is used. When conducting research and developing algorithms for the operation of the modular unit, the possibility of accurately determining the degree of damage to the specified defects in the event of a violation of the quality of the engine power supply system was taken into account, which is very important for real-life conditions of use. The obtained results are ready for practical use in the development of new or improvement of existing monitoring systems for monitoring the condition of asynchronous machine under load with a possible poor-quality power supply system.

Keywords: condition monitoring system, asynchronous machine, operational reliability, Park's vector method

1. INTRODUCTION

Considering the growth in the number of industries using asynchronous machine, increasing the reliability of their operation is a priority task for increasing the efficiency of work even in individual branches of industry. This is especially relevant for enterprises and technologies where the price of a sudden failure can lead to significant losses in the event of violation of technological or logistical tasks [1, 2]. Thus, in vehicles, asynchronous machine are used as traction or drives of various auxiliary mechanisms [3, 4, 5]. In addition, in complex precisions productions, the requirements for each technological process determine the need to set and maintain with high accuracy at a given level the operating parameters of asynchronous machine during their use [6]. Asynchronous machine with a short-circuited rotor, which have significant advantages over other types of electric machines due to low cost, ease of maintenance and sufficient reliability, have become the most common in modern times. The share of asynchronous machine with a short-circuited rotor is 70% of the machines used in the drives of modern industries of the world [7, 8].

One of the main ways to prevent sudden failures of asynchronous machine is timely diagnosis and monitoring of their main elements during operation with the establishment of the current state and forecasting of the period of trouble-free operation [9, 10]. Many researchers pay attention to the development of modern methods of diagnosing the state of individual elements of asynchronous machine, which ensure their operability and reliability [11, 12].

Since the main manifestations of defect to the elements of asynchronous machine are increased vibration, noise, heating and changes in electrical parameters, most modern monitoring methods use the appropriate principles for their determination. Currently, the following methods for diagnosing asynchronous electric machines are known as the most common [13, 14, 15]:

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- analysis of electrical parameters of the machine;
- monitoring of insulation condition;
- monitoring vibration signals of engine elements;
- acoustic control;
- change in magnetic flux in the engine air gap;
- analysis of the thermal state of individual machine elements.

When developing methods for diagnosing asynchronous machine, operational data are taken into account to determine the main elements of asynchronous machine that affect performance and require monitoring and timely diagnosis. According to the results of operational statistics, fig. 1 shows the distribution of defect to asynchronous electric machines by the main structural elements of the machine [16, 17, 18].

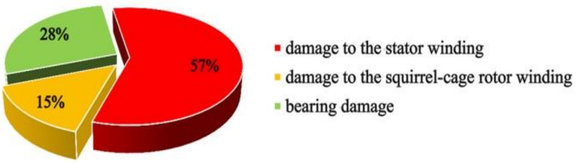


Fig. 1. Distribution of failures according to the main structural elements of an asynchronous machine

As can be seen from fig. 1, the largest share of failures is caused by defect to the stator winding, where inter-turn short circuits are the main cause. Interturn short circuits in the phase of the stator winding are the most complex and difficult to diagnose type of defect. At the same time, there is an increase in the current and an excess of temperature in the short circuits part of the phase, the creation of vibration due to the occurrence of an asymmetric rotating field of the stator, which contributes to the further development of defects and emergency failures of the engine during its continued operation [19].

Current, thermal, and vibration methods have become the most widely used for diagnosing inter-turn short circuits. The works [20, 21] present the method of early diagnosis of inter-turn shorting in the phases of the stator winding of an asynchronous machine based on the convolution of a neural network the wavelet kernel. At the same time, the phase currents are registered by the data collection system of various defects. Recorded current signatures are used to identify defects. Experimental studies of asynchronous machine using signal processing methods for early detection of inter-turn short-circuits are given in [22]. The presented methods are divided into power spectral density estimation methods and time-frequency methods using the Welch periodogram and the Hilbert transform. In works [23, 24, 25], the authors cite research on the identification with a high probability of machine winding defect based on vibration characteristics. However, in [26], results were obtained regarding the impossibility of using vibration parameters in the determination and diagnosis of a number of defects that may occur during operation. This limits the use of vibration methods in determining defect caused by defects in engine elements of electrical origin. Current methods were most effective in determining defect to electrical elements of engines. Among them, Park's vector approach method received a special place as the most promising method for use in systems for assessing the condition of various engine elements. [27, 28, 29]. According to Park's vector method, defect is determined by the shape of the ring of the vector pattern. In work [30], the authors obtained practical results for the use of the Park`s vector method in embedded defect detection systems.

Monitoring the condition of the short-circuited rotor winding is also a relevant issue when monitoring the condition of asynchronous machine. Rotor failures make up a smaller proportion of failures than defect to the stator winding (fig. 1), but for engines operating under significant loads, for example, traction in transport or in lifting systems, they can reach up to 35-40% in certain industries [31, 32]. The main manifestations of rotor defect are the violation of the integrity of the " squirrel cage " of the rotor winding structure and the separation of the rods [33]. With increased loads on the engine with a violation of the short-circuited rotor winding, further destruction of the rods occurs during long-term operation of the engine until the emergency stop occurs. This is facilitated by the increased current in the rods of the intact part of the rotor and increased vibration.

To diagnose the condition of the rotor of an asynchronous machine, modern methods and approaches are also used, as for diagnosing the stator. The works [34, 35] present research on the detection of a broken rotor core fault based on an artificial neural network using the Hilbert transform and on the analysis of the transient starting current. In [36, 37], the article investigates the possibility of detecting broken rotor rods in asynchronous machine using current signatures and vibration analysis methods. However, as in the case of stator winding monitoring, the most effective and convenient to use in monitoring systems are the current methods based on the analysis of machine current characteristics when determining defect of short-circuited rotor winding [38, 39, 40, 41]. In these works, spectral studies on the determination of defects using the Fourier transform, using the wavelet transform and the observation of the current vector with fuzzy logic are presented.

A separate place in the studies of rotor defect detection methods is also occupied by Park's vector approach together with its variations and is one of the most common methods for diagnosing electric machines [42, 43, 44]. Diagnosis of rotor defect in asynchronous machine, according to the generally accepted practice based on the results of research by many authors, is to control the increase in the width of the figure of the circle of the Park's vector. Various methods of signal processing are used in studies to determine the change in the width of Park ring. Thus, traditionally, an increase in the thickness of the Park's vector figure is taken as an indicator of rotor defect. Among the common defects, according to the existing statistics (fig. 1), there is a violation of the condition of the bearings of asynchronous machine. According to research by the Japanese Electromechanical Manufacturers Association (JEMA), bearing failure is the cause of defect from 30% to 40% of all equipment failures [45]. Bearing failures can lead to the most serious accidents, and in some cases, to the impossibility of restoring the product. Therefore, monitoring and controlling the state of engine bearings during operation is an important task for increasing the reliability of the equipment in use.

Manifestations of bearing defect include increased vibration, noise, and an increase in housing temperature. It is the primary mechanical vibration caused by a bearing defect that affects the torque output, machine speed, and finally the very nature of the bearing vibration, the failure frequency of which is directly proportional to the machine speed. The most widely used methods in bearing condition monitoring systems for detecting the level of their defect are those based on the spectrum of the vibration signal envelope. [46, 47].

From the analysis it follows that to effectively determine the current state of bearings, there are modern means and methods of practical use as part of operational monitoring systems based on vibration characteristics. These methods fully meet modern requirements for monitoring systems and have practical implementations.

Current methods, in particular the Park's vector method, are the most promising for determining defect to the stator and rotor windings. However, further research is needed to accurately identify and determine the degree of defect to the main structural elements of the engine, taking into account the poor-quality power supply system and the practical application of this method in monitoring systems.

These issues are resolved in this work, where the theoretical developments regarding the use of the Park`s vector method to determine the degree of defect to the stator winding and rotor winding are given. In addition, the method of recalculating indicators for determining the degree of defect in case of a poor-quality power supply system is given, which is of great relevance for engines that are used in transport equipment or at large industrial enterprises. The recalculation of the parameters of the Park's vector contributes to the accurate determination of the degree of defect of the selected elements to increase the reliability of predicting accident-free operation and, accordingly, reliability.

2. A MODULAR UNIT FOR MONITORING THE CONDITION OF ASYNCHRONOUS MACHINE ELEMENTS USING PARK'S VECTOR METHOD

2.1. Block diagram of the monitoring system for asynchronous machine elements

In fig. 2 shows the proposed block diagram of the monitoring system, taking into account the statistics of defect to the main elements of the asynchronous machine. (fig. 1).

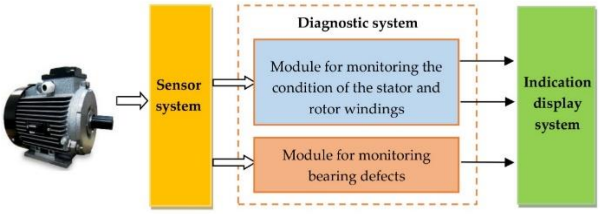


Fig. 2. Block diagram of the monitoring system for asynchronous machine elements (author's development)

The main purpose of this monitoring system is to determine the types and degree of defect to the main structural elements of the engine, which contribute to the performance and require monitoring during operation. According to modern requirements for monitoring systems, the main task is to determine the appearance of defects at the initial stages with the possibility of controlling their development for timely planning of restoration or repair works without prejudice to the performance of technological tasks.

The system for operational monitoring of the condition of the main elements of an asynchronous machine includes two modules:

- the inter-turn short-circuit control module in the stator winding phase and control of the condition of the "squirrel cage" of the rotor;
- module for monitoring the state of bearings.

To optimize and simplify the monitoring system, it is proposed to use the same methods for monitoring the state of the stator winding and the rotor winding, in particular, Park's vector method. In this case, in addition to general current sensors, from which preliminary information is obtained for the operation of the module from the "sensor system" (fig. 2), the main part of the general structural blocks of the algorithm of the entire module is also used. Therefore, the status control module of the stator and rotor windings is represented by one block on the structural diagram (fig. 2).

When identifying the degree of defect to the stator winding, that is, establishing the number of defectd turns of the winding and the degree of violation of the design of the “squirrel cage” of the rotor winding, the data is sent to the in the "indication display system". When recalculating the parameters of the Park`s vector in the monitoring system, in case of detection of a violation of the quality of the engine power supply system, information about the state of the power supply system is also displayed on the " indication display system".

The operation of the module for determining the condition of the bearings can be ensured by two vibration sensors installed on the bearing assemblies on each side of the engine, providing the necessary data to the " indication display system" (fig. 2).

Thus, in the proposed system for monitoring the current state of the electric machine, modules for defect control are presented, which at the initial stage do not lead to sudden failure. However, the identified defects have the prospect of worsening their further development with the creation of secondary failures and emergency shutdowns.

Therefore, the reliable establishment of the type and degree of defect to the elements of the electric machine allows to increase the accuracy of forecasting the period of its trouble-free operation and thereby ensure reliability during its operation.

2.2. Using the Park`s vector method to detect defect to electric machine elements

According to the research experience of modern authors, there are a number of disadvantages in the use of Park's method in the diagnosis of defect to electric machines in the presence of important advantages over other methods. The main disadvantage of this method is the difficulty of detecting defect in idle mode, their accurate interpretation and identification of the degree of defect in the case of a poor-quality power supply system. Such shortcomings have limited the development of the use of this method both in stationary systems and in monitoring systems in industrial operation where there may be an asymmetric power supply system.

Research on the use of the Park`s vector to identify defect to engine elements requires the use of modeling tools, which are an integral part of the study of technical systems in various industries [48, 49]. Simulation models of asynchronous electric machines are actively used in the improvement of defect detection systems and the study of processes that occur with various degrees of defects, including the use of Park's method [27, 28, 30].

Park's vector method consists in identifying defect from the shape described by the end of the vector, which is created from the three-phase currents of the machine power system on a two-dimensional moving coordinate plane. The two-dimensional representation of three-phase currents by a vector rotating with an angular frequency ω is a circular pattern, which under ideal conditions of power supply and a working machine has the form of a regular circle with a constant radius. To build a vector circuit, a mathematical model of an asynchronous machine with the addition of a Park's vector block is used. In the presence of defect to the stator winding, rotor winding, and even defect to the mechanical structure or symmetry violations of the power supply voltage system, a modified form of Park's vector drawings obtained. In fig. 3, *a* the resulting shape is described by the end of the Park's vector for an intact electric machine with a symmetrical power system.

To construct a picture of the Park vector from the values of phase currents of a three-phase system I_A, I_B, I_C obtained from the power supply system of an electrical machine, their first harmonics are preliminarily calculated using the fast Fourier transform algorithm. The transformation of a three-phase current system into a two-phase moving *dq*-coordinate system when constructing a vector drawing occurs with the determination of the corresponding currents by expressions:

$$\begin{cases} I_d = I_A \cdot cos(\omega \cdot t + \varphi) - \frac{1}{\sqrt{3}} \cdot (I_B - I_C) \cdot sin(\omega \cdot t + \varphi), \\ I_q = I_A \cdot sin(\omega \cdot t + \varphi) + \frac{1}{\sqrt{3}} \cdot (I_B - I_C) \cdot cos(\omega \cdot t + \varphi), \end{cases} \quad (1)$$

where:

I_A, I_B, I_C – values of phase currents of an asynchronous electric machine, shown in *ABC* coordinates;

ω – angular frequency of the supply voltage of the stator of an asynchronous electric machine;

φ – the phase angle of the projection of the vector rotating in the direction of the main semi-axis of the ellipse;

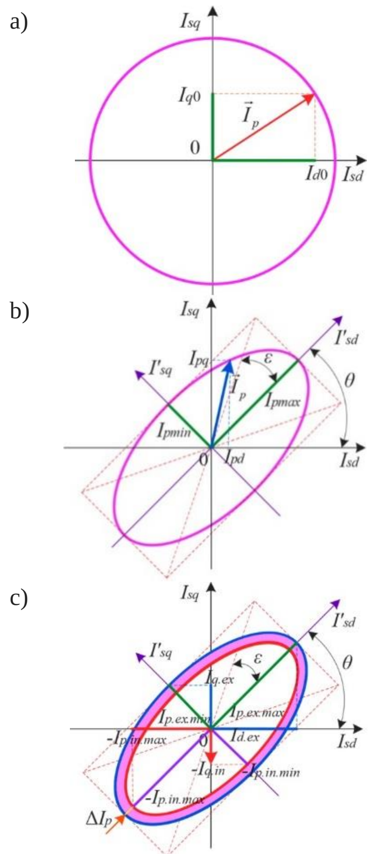


Fig. 3. Figure of the Park's vector: *a* – for an intact machine and a symmetrical system of supply voltages, *b* – with inter-turn shorting of the stator winding and asymmetry of the supply voltages; *c* – in case of defect t o the structure of the short-circuited rotor winding and asymmetry of the supply voltages

For the convenience of further consideration in fig. 3 the following notations are introduced:

$\vec{I}_p$ – Park's vector;

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

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

I_{pmin}, – the value of the Park's vector when it coincides with the axis *q*;

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

θ – the angle of inclination of the ellipse from the orthogonal-circular base;

ε – angle of ellipticity (for an orthogonal-circular basis without defect to the stator ε=45°);

$I_{p.ex}$ – the Park`s vector of the outer ellipse;

$I_{p.in}$ – the Park`s vector of the inner ellipse;

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

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

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

$I_{p.in.min}$ – the minimum value of the Park's vector for the inner ellipse (fig. 3, *c*);

$I_{d.ex}$ – projection of the Park's vector of the outer ellipse onto the axis *d* (fig. 3, *c*);

$I_{d.in}$ – the projection of the Park's vector of the inner ellipse onto the axis *d* (fig. 3, *c*);

ΔI_p – the difference of the modules of the Park's vectors describing the outer and inner ellipse.

To determine the symmetry of the power supply system, the angle θ is entered, by which the figure of the vector drawing deviates (fig. 3). With a symmetrical supply voltage system, the angle of inclination of the ellipse θ=0.

If there is defect in the stator winding, the circle of the Park's vector figure, depicted in the orthogonal-circular basis, takes the form of an ellipse. For this case, according to the markings in fig. 3, *b*:

$$\begin{cases} I_{pmax} = I_{d0}, \\ I_{pmin} = I_{q0}. \end{cases} \quad (2)$$

The angle of ellipticity obtained due to defect to the stator winding, the shape of the Park's vector, is calculated by the formula:

$$\varepsilon = arctg \frac{I_{pmin}}{I_{pmax}}. \quad (3)$$

Based on the results of studies carried out using mathematical modeling in the *MATLab* software environment, the dependence of the influence of the number of closed turns in the stator winding on the ellipticity angle of the vector pattern was established. This can be used to determine the extent of winding defect in electrical motor component monitoring systems.

In the case of defect to the structure of the "squirrel cage" of the rotor winding, the shape of the created ring of the Park`s vector spreads through the thickness. To further consider the thickness of the resulting vector drawing in fig. 3, *c* with the designations of the external and internal contours of the created figure are introduced. The angle of ellipticity for the case of a symmetrical supply voltage system and the presence of defect in the rotor winding (fig. 3, *c*) of Park's vector drawing is also calculated according to (3). Since the angle of inclination of the ellipse is θ=0, the drawings of the Park's vector describing the outer and inner ellipse are also obtained in the orthogonal-circular basis. Calculation of vectors for this case:

$$\begin{cases} I_{p.ex.max} = I_{d.ex}, \\ I_{p.ex.min} = I_{q.ex}, \\ I_{p.in.max} = I_{d.in}, \\ I_{p.in.min} = I_{q.in}. \end{cases} \quad (4)$$

The value of the ellipticity angle for this case is calculated by:

$$\varepsilon = arctg \frac{I_{p.ex.min}}{I_{p.ex.max}} = arctg \frac{I_{p.in.min}}{I_{p.in.max}}. \quad (5)$$

With an asymmetrical supply voltage system, the value of the angle of inclination of the ellipse (fig. 3, *b*) is calculated by:

$$\theta = arccos \frac{I_{pd}}{I_{pmax}} = arcsin \frac{I_{pq}}{I_{pmin}}, \quad (6)$$

and:

$$\theta = arccos \frac{I_{d.ex}}{I_{p.ex.max}} = arcsin \frac{I_{q.ex}}{I_{p.ex.min}} = arccos \frac{I_{d.in}}{I_{p.in.max}} = arcsin \frac{I_{q.in}}{I_{p.in.min}}. \quad (7)$$

After determining the angle of ellipticity and establishing a low-quality supply voltage system based on it (when the angle of inclination of the ellipse is $\theta \neq 0$), it is necessary to recalculate the values of the projections of the Park`s vector obtained in the orthogonal-elliptical basis (fig. 3, *b*) to the orthogonal-circular one in accordance with the expressions [30]:

$$i'_{sd0} = (cos\varepsilon_0 \cdot cos\theta_0 - j \cdot sin\varepsilon_0 \cdot sin\theta_0) \cdot I_{sd0} + j(cos\varepsilon_0 \cdot sin\theta_0 + j \cdot sin\varepsilon \cdot cos\theta_0) \cdot I_{sq0}; \quad (8)$$

$$i'_{sq0} = \left(\cos(-\varepsilon_0) \cdot \cos\left(\theta_0 + \frac{\pi}{2}\right) - j \cdot \sin(-\varepsilon_0) \cdot \sin\left(\theta_0 + \frac{\pi}{2}\right)\right) + +j\left(cos(-\varepsilon_0) \cdot sin\left(\theta_0 + \frac{\pi}{2}\right) + +j \cdot \sin(-\varepsilon_0) \cdot \cos\left(\theta_0 + \frac{\pi}{2}\right)\right) \cdot I_{sq0}, \quad (9)$$

where

ε_0 – the angle of ellipticity of the basic ortho along the *d* axis in the new basis. Along the *q* axis, the value of the angle ε_0=0. For an orthogonal-circular base without defect ε_0=45°;

θ_0 – is the angle of ellipse inclination of the basic ortho along the *d* axis in the new basis. Along the *q* axis, the value of this angle is θ_0=90°. For an orthogonal-circular basis θ_0=0.

After recalculating the obtained values of vector projections for the orthogonal-circular basis, the amplitude values of the I'_{sd0} and I'_{sq0} for this basis are calculated using the expressions:

$$\begin{cases} I'_{sd0} = \sqrt{\left(Re(i'_{sd0})\right)^2 + \left(Im(i'_{sd0})\right)^2}, \\ I'_{sq0} = \sqrt{\left(Re\left(i'_{sq0}\right)\right)^2 + \left(Im\left(i'_{sq0}\right)\right)^2}. \end{cases} \quad (10)$$

To determine the quantity of short-circuited turns in the phase of the stator winding, it is possible to use the deviation of the amplitudes of the stator phase currents (10) or the displacement of the phase shift angles of the stator currents. The obtained results of the quantity of short-circuited turns will be the same. Angles of phase shifts of the stator current for each phase are determined by:

$$\begin{cases} \varphi_{IsAm} = arctg(tg\varepsilon \cdot tg\varphi_{snom}), \\ \varphi_{IsBm} = arctg\left(tg\varepsilon \cdot tg\left(\varphi_{snom} - \frac{2\cdot\pi}{3}\right)\right), \\ \varphi_{IsCm} = arctg\left(tg\varepsilon \cdot tg\left(\varphi_{snom} + \frac{2\cdot\pi}{3}\right)\right), \end{cases} \quad (11)$$

Where: φ_{snom} – value of the phase shift angle of the stator currents with undamaged stator windings.

The instantaneous values of the amplitudes of the phase currents of the stator are determined by:

$$\begin{cases} I_{sAm} = \sqrt{(I'_{sd0} \cdot cos(\Delta\varphi_{sIAm}))^2 + (I'_{sq0} \cdot sin(\Delta\varphi_{sIAm}))^2}, \\ I_{sBm} = \sqrt{\left(I'_{sd0} \cdot cos\left(\Delta\varphi_{sIAm} - \frac{2\cdot\pi}{3}\right)\right)^2 + \left(I'_{sq0} \cdot sin\left(\Delta\varphi_{sIAm} - \frac{2\cdot\pi}{3}\right)\right)^2}, \\ I_{sCm} = \sqrt{\left(I'_{sd0} \cdot cos\left(\Delta\varphi_{sIAm} + \frac{2\cdot\pi}{3}\right)\right)^2 + \left(I'_{sq0} \cdot sin\left(\Delta\varphi_{sIAm} + \frac{2\cdot\pi}{3}\right)\right)^2}. \end{cases} \quad (12)$$

During research, it was established that the dependence of the deviations of the amplitudes of the stator phase currents and the angles of phase shifts of the stator current is a function of the quantity of damaged turns of the stator windings and has a linear character, ie: $\Delta I_s = k_{Is} \cdot n$ та $\Delta\varphi_{Is} = k_{Ism} \cdot n$ [30]. Then the following ratios are valid for establishing the quantity of short-circuited turns of the stator winding:

$$n = \frac{\varphi_{Is} - \varphi_{Isnom}}{k_{\varphi Is}} \quad (13)$$

$$n = \frac{I_s - I_{snom}}{k_{Is}} \quad (14)$$

where

φ_{Is} – the value of the phase shift angle of the stator current of the controlled phase;

φ_{Isnom} – the nominal value of the shiftphase angle of the stator current.

I_s – value of the stator phase current of the controlled phase;

I_{snom} – the value of the stator phase current in the absence of an interturn short circuit.

$k_{\varphi Is}$ – angular displacement coefficient of the angle of the phase shift of the stator current;

k_{Is} – angular coefficient of increase of the stator current.

For getting to obtain the absolute number of damaged turns at any moment of machine operation according to (13)-(14), it is necessary to have experimental values of the deviations of the amplitudes of the phase currents or the displacement of angles the phase shift of the stator currents for one case of defect. This will allow you to determine the angular coefficients for this type of engine. Angle coefficients should be calculated for the same mode both in the absence and presence of interturn shorting.

Thus, if there are deviations of the amplitudes of the phase currents or shifts of the angles of the phase currents, even for one turn of the stator winding of the controlled machine, it is possible to determine the quantity of damaged turns of the stator winding at any time of its operation with a poor-quality power supply system.

To determine the degree of defect to the rotor of an engine with a symmetrical power system (fig. 3, *c*), use the thickness of the vector pattern of the Park circle according to:

$$\Delta I_p = I_{p.ex} - I_{p.in} \quad (15)$$

where

$I_{p.ex}$ – the Park's vector of the outer ellipse;

$I_{p.in}$ – the Park's vector of the inner ellipse.

Since, with the symmetry of the supply voltage system, the modulus of the Park's vector is the instantaneous value of the phase current of phase *A*, then expression (15) takes the following form:

$$\Delta I_p = I_{sAmax} - I_{sAmin} \quad (16)$$

where

I_{sAmax} – the maximum instantaneous value of the phase current of the stator for phase *A*;

I_{sAmin} – the minimum instantaneous value of the stator phase current for the phase *A*.

When ΔI_p=0 the rotor has no defect. ΔI_p>0 indicates defect to the rotor, and as ΔI_p increases, a greater degree of defect occursto the structure of the short-circuited rotor winding.

In the presence of asymmetry of supply voltages and defect in the rotor, the value of the projections of the external and internal projections of the Park's vector should be transferred from the orthogonal-elliptical basis to the orthogonal-circular basis according to the ratios (8)-(10).

To calculate the external values of the ring of the Park's vector drawing, in expressions (8)-(12), the values I_{sd0}, I_{sq0}, I'_{sd0}, I'_{sq0}, i'_{sd0}, i'_{sq0} should be replaced by $I_{d.ex}$, $I_{q.ex}$, $I'_{d.ex}$, $I'_{sq.ex}$, $i'_{sd.ex}$, $i'_{sq.ex}$, respectively. For the inner ring in expressions (8)-(12), the values I_{sd0}, I_{sq0}, I'_{sd0}, I'_{sq0}, i'_{sd0}, i'_{sq0} should be replaced by $I_{d.in}$, $I_{q.in}$, $I'_{d.in}$, $I'_{sq.in}$, $i'_{sd.in}$, $i'_{sq.in}$, respectively (Fig. 3, *c*).

Then it is possible to distinguish the following criteria for assessing the state of the asynchronous machine elements according to Park's vector drawing:

- in case of equality $I'_{d.ex}=I'_{q.in}$ та $I'_{d.ex}=I'_{q.in}$ (the outer and inner trajectories of Park's vector drawing describe circles), it follows that the engine is not defectd;
- when $I'_{d.ex}\neq I'_{d.in}$ та $I'_{q.ex}\neq I'_{q.in}$ (the outer and inner trajectories of Park's vector drawing describe ellipses), then only the short-circuited rotor winding is defects for the machine;
- when $I'_{d.ex}\neq I'_{q.in}$ та $I'_{d.ex}\neq I'_{q.in}$ і $I'_{d.ex}\neq I'_{d.in}$ та $I'_{q.ex}\neq I'_{q.in}$ – the stator winding and rotor winding have defects;
- when $I'_{d.ex}\neq I'_{q.in}$ та $I'_{d.ex}\neq I'_{q.in}$ (the outer and inner trajectories of Park's vector drawing describe ellipses), and $I'_{d.ex}=I'_{d.in}$ і $I'_{q.ex}=I'_{q.in}$ (the outer and inner trajectories of Park's vector drawing are equal) – only the stator winding has defects.

Since in case of defects only the rotor winding of an asynchronous machine $I'_{d.ex}=I'_{q.in}$ and $I'_{d.ex}=I'_{q.in}$, then the thickness of the Park's vector pattern is determined by:

$$\Delta I_p = I'_{d.ex} - I'_{d.in} \tag{17}$$

or by the expression:

$$\Delta I_p = I'_{q.ex} - I'_{q.in} \tag{18}$$

The value ΔI_p according to (17) and (18) can be used to quantify the degree of defect to the rotor winding of an asynchronous electric machine with sufficiently high accuracy and also to monitor the development of rotor defect during operation.

Based on the presented studies, it has been established that the Park`s vector method allows for online monitorings of the stator and rotor windings of an asynchronous machine in the presence of an asymmetrical power supply system. This confirms the prospects of using this method in online monitoring systems for the condition of asynchronous machines during operation.

2.3. Algorithm for the operation of a modular unit for determining defects in the stator and rotor windings for technical condition monitoring systems

In accordance with the conducted research on the use of Park's vector approach, a technique was developed, which is the basis of the algorithm of the modular unit for determining defects to the stator winding and rotor winding during operation. In fig. 4 presents the algorithm of the modular unit, which is ready for practical implementation in monitoring systems for the condition of asynchronous machine in industrial operating conditions with a possible low-quality power supply system.

The development of the methodology and algorithm for determining the exact number of closed turns in the stator winding using the Park's method is based on studies of the effect of the number of closed turns on the change in the amplitude instantaneous values of the stator current in each phase and the increment of the stator current in each phase. These values are used during operation of the entire modular unit. The studies were conducted on a mathematical model for symmetrical and asymmetrical supply voltage systems of an asynchronous machine.

Table 1 shows the obtained values for an undamaged winding (100%) and for stator windings with varying degrees of damage to one phase - A. The values in Table 1 correspond to different numbers of undamaged turns: 95, 90, 85, 80% for a symmetrical power supply system.

The calculation of the angle of ellipticity ε and the angle of inclination of the θ of the Park figure is carried out using the formulas (3) and (6).

Since the Park's vector method is current, current sensors D_{1sA}, D_{1sB}, D_{1sC}, which are externally located in the engine power supply system, are needed to ensure the operation of the monitoring system. Since the monitoring system must be universal, it is necessary to take into account the possibility of supplying power to the machine from a voltage inverter.

The algorithm for determining rotor damage is performed according to the algorithm in Fig. 4 also based on the data in Table 1.

In this case, the supply voltage will have a non-sinusoidal character, therefore, to determine the necessary values for further application of the Park's method, it is necessary to use the Fourier fast transformation algorithm [50]. After determining the values of the amplitude and phase of the first harmonics of the phase currents and phase shifts between the phase voltages and currents, the coordinate transformation of the three-phase coordinate system to the two-phase moving *dq* coordinate system is performed in accordance with expressions (1) and the parameters of the Park figure are calculated. The next step is to determine the angle of inclination of the vector pattern figure θ and establish the symmetry of the supply voltage system. Depending on the value of θ, the calculation and determination of the type and degree of defects in the corresponding windings is carried out through separate channels.

Table 1. Values of amplitudes and increments of currents in all phases of the winding in case of damage in phase A of the stator winding

Obtained parameter values for the Park`s vector algorithm	Undamaged part of phase A of the stator winding w_A, %				
	w_{A1}=100	w_{A2}=95	w_{A3}=90	w_{A4}=85	w_{A5}=80
Current value Isd0, at Isq=0, A	30.946	31.183	31.398	31.66	31.854
Current value Isq0, at Isd=0, A	30.946	30.685	30.418	30.192	29.897
Instantaneous value of the phase A stator current I_A, A	30.942	31.191	31.398	31.66	31.9
Phase A stator current increment ΔI_A, A	0	0.228	0.456	0.718	0.958
Instantaneous value of the phase B stator current I_B, A	30.942	30.788	30.634	30.48	30.326
Phase B stator current increment ΔI_B, A	0	-0.154	-0.308	-0.462	-0.616
Instantaneous value of the phase B stator current I_C, A	30.942	30.808	30.674	30.54	30.406
Phase C stator current increment ΔI_C, A	0	-0.134	-0.268	-0.402	-0.536
Ellipticity angle ε, deg.	45.0	44.539	44.092	43.64	43.185
Ellipse tilt angle θ, deg.	0	0	0	0	0

The algorithm for determining rotor damage is performed according to the algorithm in Fig. 4 also based on the data in Table 1.

In this case, the supply voltage will have a non-sinusoidal character, therefore, to determine the necessary values for further application of the Park's method, it is necessary to use the Fourier fast transformation algorithm [50]. After determining the values of the amplitude and phase of the first harmonics of the phase currents and phase shifts between the phase voltages and currents, the coordinate transformation of the three-phase coordinate system to the two-phase moving *dq* coordinate system is performed in accordance with expressions (1) and the parameters of the Park figure are calculated. The next step is to determine the angle of inclination of the vector pattern figure θ and establish the symmetry of the supply voltage system. Depending on the value of θ, the calculation and determination of the type and degree of defects in the corresponding windings is carried out through separate channels.

When θ=0, the defect is determined for an orthogonal-circular basis, otherwise – with a preliminary recalculation of the values from orthogonal-elliptical to orthogonal-circular according to the expressions considered above. After establishing the type and degree of defects to the stator or rotor winding, the data is indicationdisplayed on the indication display unit and, depending on the calculation channel, information on the quality of the power supply system is provided.

The developed algorithm for monitoring the state of the main structural elements of the asynchronous machine according to the main types of their defect can be used in built-in industrial or on-board transport monitoring systems to increase the level of reliability during operation. The presented modular unit can be used both separately and as part of any monitoring system for monitoring the current state of asynchronous machine with the possible presence of an asymmetric power system.

3. A CURRENT SENSOR FOR A MODULAR MONITORING UNIT FOR DETECTING DEFECT TO AN ASYNCHRONOUS MACHINE

Different types of current sensors are used to control and diagnose circuits, starting protection schemes, detect malfunctions of electrical equipment and emergency states of various types, which are divided into invasive and non-invasive according to their design and principle of operation.

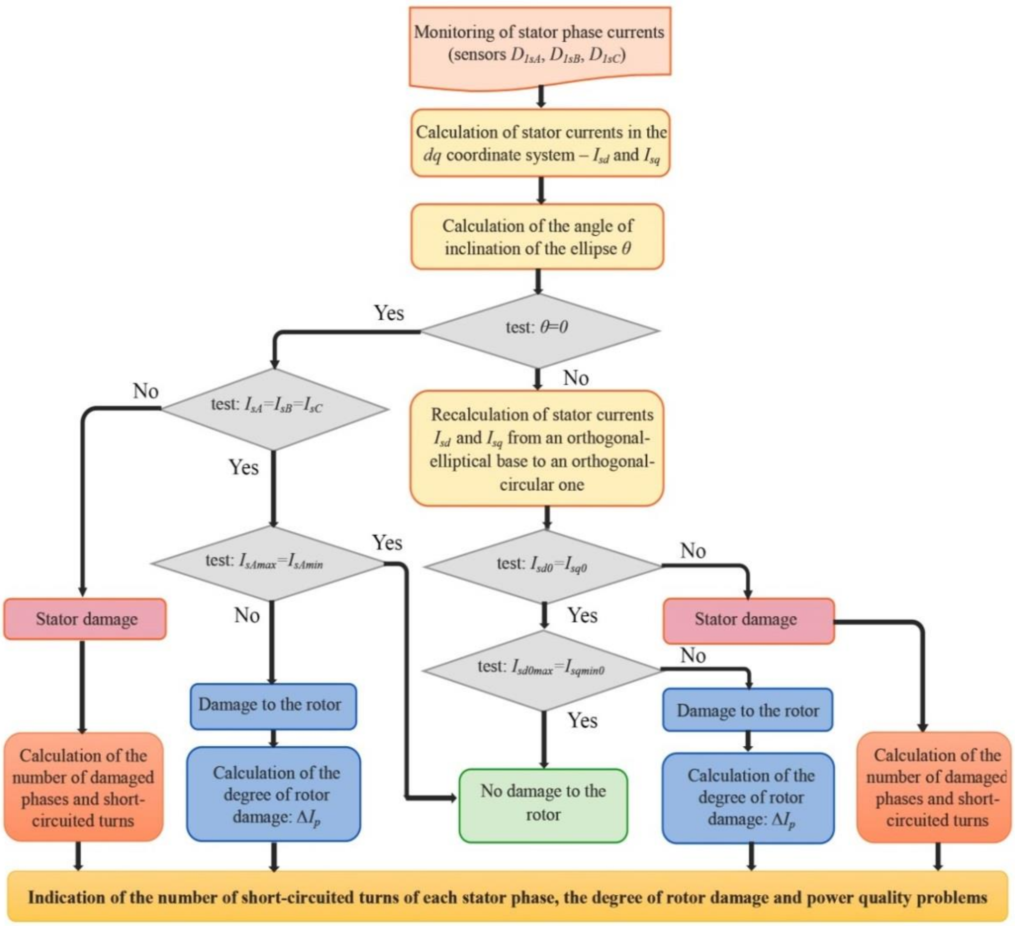


Fig. 4. Algorithm of the modular unit for monitoring the state of the stator and rotor windings of asynchronous machine (author's development)

According to the principles of current measurement, the following are most widely used to solve monitoring tasks in industry:

- resistive sensors (current shunts);
- based on the Hall effect;
- current transformers.

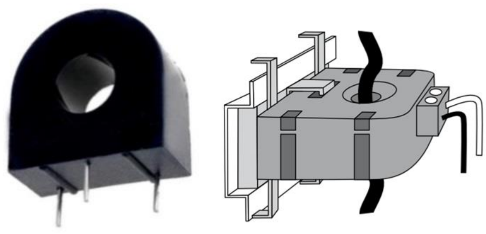
The advantages and disadvantages of various types of current sensors determine their application areas [51]. Transformer current sensors and resistive current sensors have a wide range of measured currents, but the resistive current sensor has advantages expressed in low cost and the ability to measure both alternating and direct currents. The main disadvantage of the resistive current sensor is the need to connect the sensor directly to the gap of the phase wire to the measuring circuit, which is very inconvenient for industrial use and the impact of noise and impulse interference on the measuring circuit. In addition, resistive sensors create heating of the shunt and a change in its resistance, which affects the accuracy of measurements and increases energy consumption.

The current transformer has a non-invasive connection, which is relevant for the industrial use of the entire monitoring module. The disadvantage of a current transformer is the ability to measure only industrial frequency alternating currents, but this disadvantage is not important for the tasks of monitoring alternating current machines. A current sensor based on the Hall effect has a number of advantages, which are the ability to measure both direct and alternating current in small dimensions. However, a significant disadvantage is the need for an external power source and the dependence on temperature, which reduces the areas of its use. This type of sensor is used to measure the speed of rotation of wheels and shafts, for example, to synchronize the ignition of an internal combustion engine, tachometers and anti-lock braking systems, as well as in DC valve electric machines to detect the position of a permanent magnet.

Transformer current sensors are the most appropriate for use in the system of monitoring the status of asynchronous machine in industrial conditions. The main advantages when using them in monitoring systems are as follows:

1. They work during input voltage drops and consume practically no electricity.
2. Due to non-invasiveness, they provide galvanic isolation between the windings, so the measuring circuit is not under a high potential.
3. The parameters practically do not change over time and do not depend on temperature.
4. The transformation coefficient is easily maintained during production and always remains constant.
5. Impulse disturbances in the measuring circuit are extinguished without the use of additional filters.
6. They provide a minimum phase shift between voltage and current measuring circuits, because the measuring signal is filtered due to the transformer's own inductance.
7. Ease of measurement of 3-phase current signals due to galvanic separation of current wires and the measuring part.

The appearance and connection diagram of the current transformer is shown in fig. 5a.



a *b*

Fig. 5. Measuring current transformer:
a – appearance; *b* – scheme of the design of use

The conductor of each phase is placed in the middle of the transformer and then the system works like a normal current transformer. The primary winding is a current-carrying conductor, the secondary winding is directly a transformer sensor, from which a voltage proportional to the current flowing through the conductor is removed (fig. 5b). To increase the accuracy of measurements, it is necessary that the conductor through which the measured current flows is wound on the transformer (one turn through the central hole is sufficient).

To use a transformer current sensor as part of a modular unit for monitoring defect of an asynchronous machine to increase the accuracy of the entire system, it is suggested to use the connection diagram shown in fig. 6.

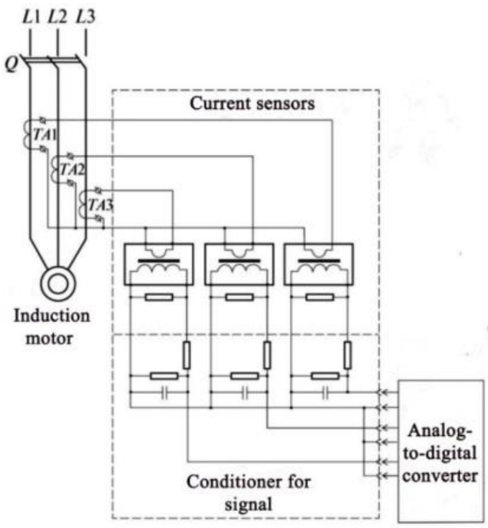


Fig. 6. Current transformer sensor connection scheme

A transformer sensor is located on each phase of the engine power supply system, after which the received signals are sent to the signal conditioner for normalization and filtering. After the conditioner, the signals are sent to the analog-to-digital converter, which has a *USB* interface for connecting to the monitoring system unit for further processing (fig. 6).

The proposed option of using transformer sensors and their connection to the monitoring system completes the preliminary construction of the modular unit for monitoring defects to the stator and rotor windings of the asynchronous machine.

4. RESULTS AND DISCUSSION

A study of the use of Park's vector approach for current control of the condition of the main structural elements of the engine, in particular the stator winding and the short-circuited rotor winding as part of the monitoring system, was conducted. According to the given statistics of failures during the period of operation, a structural diagram of the monitoring system is proposed, which includes current control of the most common types of defect, which include inter-turn short circuits in the stator winding, violations of the structural integrity of the short-circuited rotor winding, and bearing defects. To control the degree of defect to the stator and rotor, the use of the current method of the Park's vector in one modular installation is proposed. The Park's vector method is the most promising and convenient method for monitoring the state of various types of defect to asynchronous machine elements, but it has not received practical development in monitoring systems due to the impossibility of clearly interpreting the types and degree of defect, and especially when used in conditions of poor quality power supply system. These issues are resolved in this work, where the methodology is researched and an algorithm is developed for determining the quantity of defectd turns of the stator winding and the degree of defect to the short-circuited rotor for asynchronous machine in case of possible asymmetry of the power of supply system.

When powering the machine through an inverter with a non-sinusoidal signal, to determine the amplitude and phase of the main harmonic of the phase currents in the modular unit, the use of the fast Fourier transformation algorithm is provided, which makes the monitoring system independent of the type of supply voltage signals.

The main disadvantage of Park's vector method remains the difficulty of detecting defects in engine idle mode. However, for a modular unit for monitoring the state of engine elements during operation, i.e. operating under load, this drawback is insignificant.

5. CONCLUSIONS

This paper presents a set of studies on the development and practical implementation of Park's vector method for diagnosing and monitoring the most common defects in the main structural elements of an asynchronous machine. The research examines the diagnosis of defect to the stator winding and short-circuited rotor winding in one modular unit. In the course of research, a methodology for establishing the degree of defect to the elements that are monitored during operation, with a recalculation of monitoring parameters in the event of a violation of the quality of the engine power supply system, is proposed. This makes it possible to obtain reliable indicators for predicting the accident-free period of operation in real industrial conditions. Based on the method of defect detection, an algorithm and a structural diagram of the modular unit have been developed. The presented structural scheme is ready for practical implementation as a separate block in the monitoring system. Using one method in a modular unit to monitor two machine elements simultaneously has a number of advantages, which include a significant proportion of common units in the monitoring system and current sensors. For the complete completion of the construction of the modular monitoring unit, the option of using transformer current sensors and their connection to the monitoring system is proposed.

Thus, the authors have developed a general scheme and an algorithm for the operation of the module for monitoring the state of the most damaged elements of an asynchronous motor - the stator winding and the rotor winding. The developed scheme uses a general method for diagnosing damage and a number of common blocks, which makes the use of the proposed scheme the most rational. The proposed diagnostic scheme is ready for practical implementation in built-in diagnostics systems.

The use of the developed monitoring system will provide ongoing monitoring to control the development of the main defect of asynchronous machine in accordance with modern requirements and industrial operating conditions. Ensuring continuous monitoring of the appearance and development of defect, which can develop into emergency failures, contributes to a significant increase in the reliability of asynchronous machine in the relevant systems and mechanisms.

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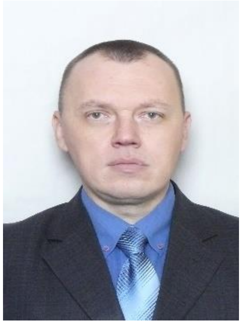

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