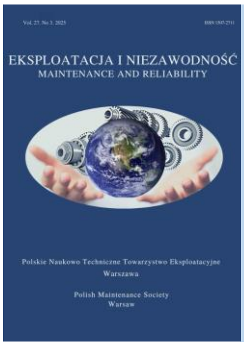

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Increasing the accuracy of calculated indicators of operational reliability of industrial electric motors

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Highlights

- Analysis of types and causes of failures of the main types of electrical machines.
- Taking into account the hazard rate when assessing the reliability of electrical machines.
- Equivalent hazard rate for real operating conditions of electrical machines.
- Using hazard rate when planning maintenance schedules for electrical machines.

Abstract

To ensure reliable operation of electric motors and their efficient use during operation, data from modern modeling tools and calculated reliability indicators. The obtained modeling and calculation results are necessary to adjust the existing or create a new strategy for technical system equipment maintenance. The paper offers practical recommendations for increasing the accuracy of reliability indicators by taking into account real operating conditions when calculating the hazard rate of an electric motor during its normal operation. For this purpose, when calculating the hazard rate of an electric motor, λeq is used, where individual coefficients take into account the influence of possible external and operational factors and modes during the operation period. Clarified data on the hazard rate values allow us to obtain values of a number of reliability indicators close to the actual ones, and to plan rational terms for performing maintenance of an electric motor or its individual elements. This is important to ensure reliable operation of equipment using electrical machines.

Keywords
reliability indicators, probability of failure-free operation, hazard rate, electric motor

1. Introduction

In modern industry, a more pressing issue is ensuring continuous and reliable operation of drives of systems and devices during the period of their performance of production tasks. Continuous operation of drives depends primarily on electric motors that provide the creation of mechanical energy. An electric machine as an energy converter is one of the main elements of each installation and is widely used in electrical stations, industrial installations, transport, aviation, automatic

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control and regulation systems, wired communications and in a number of other industries and systems.

There are many types of electric rotating machines, which cover a wide range of capacities and operating modes. However, any electric machine is subject to the risk of failure, which can lead to damage and material damage. Creating conditions for increasing the reliability of individual elements and units of electric motors, which are characterized by increased failures, is the basis for increasing the reliability of all electromechanical equipment. In [1,2] a classification and overview of possible failures of electric motors during operation is given. Electric motors are a complex design in terms of reliability, since they have both electrical and mechanical units and elements, reflected by the nature of damage [3] and the principles of control and methods for determining them [4,5]. In works [6] and [7] the authors reviewed and analyzed the causes and methods of diagnostics and detection of damage in asynchronous motors and DC machines, respectively. This implies the need for careful monitoring of the condition of many individual elements of motors during operation using modern diagnostic systems [8,9]. A number of authors in their studies use a comprehensive approach based on diagnostic data of faults that are just emerging using the example of DC motors [10]. In [11] studies of an adaptive method for diagnosing multiple faults of an asynchronous motor for a comprehensive assessment of the condition are presented.

However, given that a significant number of electric motors used in the drives of most mechanisms do not have built-in diagnostic systems for current condition monitoring, the tasks of maintaining the working condition are performed by the maintenance system [12]. In order to optimize the frequency and minimize the costs of maintenance with a reduction in the risk of failure for various types of equipment, separate studies are conducted to determine the strategy and plan the maintenance of technical systems [13,14]. A number of authors consider issues of technical equipment in combination with conditions or impacts during their use or maintenance. Thus, in [15] the optimal maintenance policy and the assessment of the remaining resource for a slowly deteriorating system are studied. Of interest are studies on the issues of preventive maintenance in conjunction with the inventory policy [16] and life cycle cost analysis taking into account multiple dependent processes of decomposition and environmental impact [17]. Determination of the strategy of maintenance and minimization of downtime for waiting for spare parts using the prediction of failures of individual elements is considered in works [18] and [19], where data on the reliability of key elements of the device and degradation processes are taken into account [20]. Issues of reliable and efficient operation of electric motors can be solved by using an intelligent system for supporting decision-making and assessing the quality of operation [21], optimizing the efficiency of motor control systems in the drive system [22] or by determining the rational parameters of individual elements of the technical system [23].

The most effective remains maintenance planning based on the forecasting of the condition and analysis of streaming data during the operation of the equipment, as, for example, in railway transport systems [24,25]. However, this path is appropriate for a narrow segment of controlled electric motors that perform critical functions with a high cost of failure.

To develop a strategy for the planned maintenance of electric motors operated in various conditions and industries where there is not always provision of diagnostic systems for the current state, personal reliability indicators obtained in the study by means of mathematical modeling taking into account specific conditions are actively used [26,27]. The design reliability 0criteria primarily include hazard rate, mean time between failures, and service life. A common quantitative indicator is the probability of failure-free operation of equipment or individual elements. The obtained indicators can be used in developing a new design and designing individual types of equipment [28].

In addition to general issues of maintenance planning, modeling is also used to solve problems of diagnosing individual elements of electric motors. In [29,30], models were developed for assessing the states of operability and predicting the mean time between failures of an electric motor bearing, and in [31], a method for determining the state of the stator and rotor was developed using modeling. An important stage of mathematical modeling is checking and maintaining the adequacy of the model and its compliance with real processes [32,33].

Based on the conducted research on the use of mathematical models, new diagnostic methods for various engine components are also being developed. Thus, in [34], an original non-destructive testing method for interturn short circuit diagnostics was developed, and in [35], methods for direct diagnostics of electrical machine winding insulation, taking into account the negative impact of operating conditions, were developed.

The accuracy of the calculated quantitative reliability indicators and the conclusions of the organization of the equipment maintenance process or forecasting the timing of repairs depend on the accuracy of the model for each case or situation. It is well known from the experience of using many theoretical models that the calculated reliability indicators can actually differ by several orders of magnitude, and the adoption of a more appropriate theoretical model with the establishment of a close time of failure-free operation of the test object turns out to be a difficult task. Therefore, the task of increasing the accuracy of theoretical models for calculating reliability indicators for assessing the state of electric motors is one of the main issues of the theory, practice of design, production and operation to ensure a high level of operational reliability.

The purpose of this work is to improve the accuracy of calculation of reliability indicators taking into account individual operating conditions of an electric motor and negative external conditions of industrial use, operating modes and degradation processes of its main elements. This approach contributes to the accuracy of forecasting a trouble-free state, timely planning of maintenance and reduces the risk of unexpected failures that can lead to economic losses and danger of equipment operation. In addition, the refinement of the calculation of reliability indicators makes it possible to obtain more accurate reliability models when solving various issues of operation of electromechanical equipment.

The presented article has the following structure. Section 2 provides an analysis of the most damaged units of electric motors of different types. Section 3 provides the characteristics and principle of calculating the main quantitative indicators of the reliability of electric motors. Section 4 contains the proposed methodology for taking into account harmful factors when calculating the hazard rate and when calculating other quantitative indicators of reliability.

2. Analysis of causes of damage to electric motors of different types during operation

When developing a model and calculating reliability indicators, it is important to analyze damage to the main elements of different types of motors. It is advisable to consider operational damage for three types of electric motors of industrial drives that are fundamentally different in design and operating conditions. The most common and used type of motors in modern industry are asynchronous motors with a squirrel-cage rotor. According to operational statistics, the main causes of damage to the elements of asynchronous motors are electrical, mechanical, thermal and operational factors. According to average operational statistics, the distribution of damage by elements and units of asynchronous motors is shown in Fig. 1 [1,2,4].

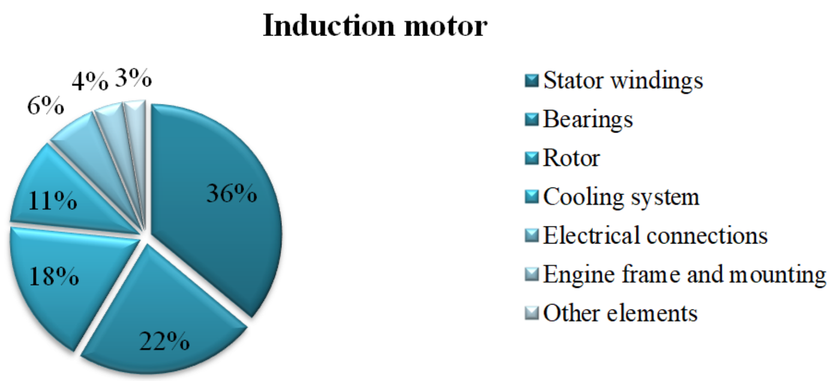

Fig. 1. Distribution of damage by elements and components of induction motors.

The main design elements of an asynchronous motor that have the greatest impact on its running characteristics are the stator, rotor and bearings. The most damaged element of an asynchronous motor is the stator winding (Fig. 1). The main cause of stator damage is insulation damage due to overload, accompanied by thermal overheating of the winding, and damage to the stator package due to mechanical vibrations. The second most frequent cause of failures are bearings, which are the most influential element for ensuring normal operation of the motor (Fig. 1). The main causes of bearing failure are mechanical overloads leading to wear of the rolling races and rolling elements, as well as elevated temperatures, which affect a decrease in the viscosity of the lubricant and lead to increased friction and wear. Operational reasons contributing to increased bearing wear include operating conditions associated with frequent starts and stops, overloads or operation at low speeds, which increase the load on the bearings. Damage to the rotor winding is not a very common cause of operational failures and accounts for up to 20% of all motor failures. Rotor damage can occur due to significant overloads of high-power motors or the development of process cracks and cavities under the influence of increased vibration and load.

Other causes of damage are not controlled during the period of use of asynchronous motors and can be eliminated during scheduled maintenance or control.

Thus, the main factors affecting the damage of asynchronous electric motors during operation are:

- *overheating*: the main cause of damage to windings and bearings;
- *overload*: leads to mechanical wear and electrical overloads;
- *vibrations*: cause damage to bearings, rotor, destruction of the housing and fasteners;
- *dust and moisture*: reduce the efficiency of cooling, damage insulation and promote corrosion.

The next type of motors used in drives of various systems where there is a need to create a high starting torque and a flexible speed control system are DC machines. This type of motors is distinguished by increased requirements for operating conditions and maintenance [36]. According to the average operational statistics, the distribution of damage by motor elements is shown in Fig. 2 [37,38,39].

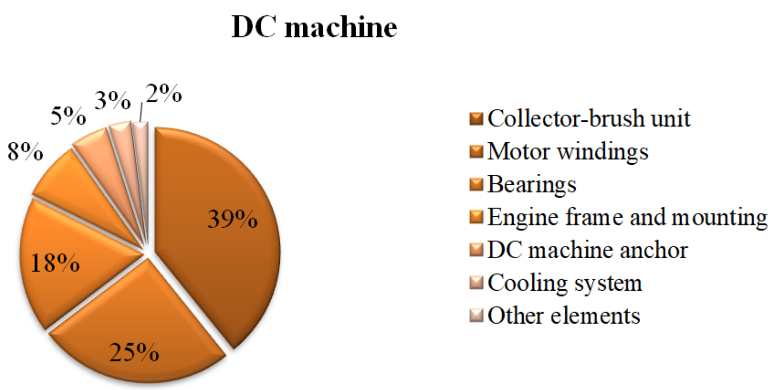

Fig. 2. Distribution of damage by elements and components of DC machines.

In DC motors, the main faults and damages occur due to mechanical, electrical or thermal effects. The main design elements of a DC electric motor are the collector-brush unit, windings and bearings [36]. The most damaged element of the motor is the collector-brush unit, where the main causes of damage are motor overload with the creation of increased sparking and overheating, as well as operating modes associated with frequent starts and stops. Contamination of the collector surface with dust particles, grease or brush residues disrupts contact, causing uneven current distribution and contributes to disruption of commutation and increased wear of the collector and brushes. Increased humidity or condensation contributes to corrosion of the copper plates of the collector structure and deterioration of commutation processes. Increased vibration of the motor during operation can cause contact disruption and brush displacement, which also affects the deterioration of commutation and accelerated wear of the entire unit. Failures of the collector-brush unit account for up to 40% of all failures of DC electric motors (Fig. 2).

The next vulnerable element of a DC machine is the armature windings and excitation. Damage to the windings can occur as a result of burnout or damage to the insulation due to overheating or electrical breakdowns. The main reason for this is frequent starts and stops, which increase the thermal and mechanical load on the windings or operation in an overload mode. Increased humidity also has a destructive effect on the insulation, which leads to a loss of electrical strength of the insulation and short circuits [38]. Failures due to damage to the motor windings account for 25% of all failures of a DC machine. The causes of damage to bearings, as for AC motors, are violation of operating conditions, overload, increased temperature and vibration. Other types of damage can also be eliminated during scheduled technical inspections and surveys. Thus, the factors that affect damage to DC motor components during operation include:

-*overheating*: affects damage to windings and insulation.

-*vibrations*: disruption of commutation and operation of the collector-brush unit and wear of bearings;

-*mechanical loads*: lead to wear of bearings and collector.

-*operating conditions*: high humidity and dustiness affect the housing, bearings and cooling system.

Traction electric motors represent a separate group among electric motors, combining operating conditions, significant power and type of load. Statistics of traction electric motor failures show that the most frequent problems arise due to mechanical damage, wear of key components and thermal effects. Bearing failure in traction electric motors is one of the main causes of mechanical failures. According to statistics, bearing failures can account for the majority of all mechanical failures of motors [40]. Overheating can be caused by motor overload or faults in cooling systems. Failures of electric traction motors can occur for various reasons, and their distribution among elements depends on the specific motor design and operating conditions. The classification and specific distribution of failures can vary depending on the motor type and its purpose (railway transport, industrial installations, etc.). Conventionally common causes of failures are shown in Fig. 3 [40,41].

Damage to traction electric motors of railway transport is mainly associated with wear of critical units, such as the collector-brush unit (for DC machines), burnout of rotor bars (for AC machines), winding insulation and bearing destruction. Failures in power supply systems and malfunctions with controllers during operation make up an insignificant percentage of failures (Fig. 3).

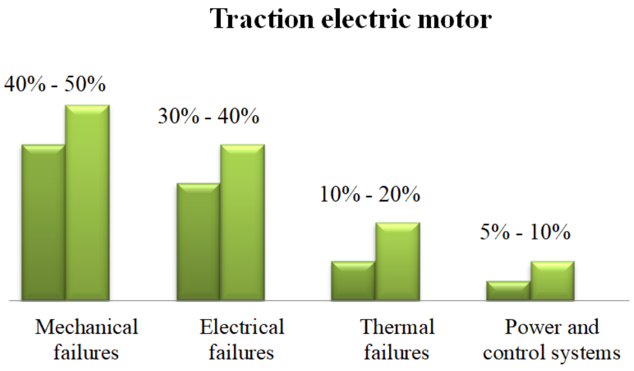

Fig. 3. Causes of failure of traction electric motors.

Based on the analysis of electric motor failures, the influence of operational factors on motor failure, such as increased load, operating mode and physical wear occurring throughout the entire period of operation, was determined. The listed factors should be taken into account when calculating reliability indicators to obtain more accurate results. Reducing the number of damages is possible if operating modes are observed and technical maintenance is carried out in a timely manner.

3. Reliability indicators during the period of electric motor operation

The reliability level of electric motors is assessed using quantitative indicators and characteristics with the use of modeling to identify damage and make decisions [42]. The main quantitative characteristics of the reliability of technical objects include: the probability of failure-free operation $P(t)$, the probability of failure $Q(t)$, the failure rate $a(t)$, the hazard rate $\lambda(t)$ and the average time of its operation until the first failure T_{av}. The most frequently used quantitative indicators of reliability for decision-making in the production or maintenance of electric motors are: the probability of failure-free operation during the time $P(t)$, the hazard rate $\lambda(t)$ and the average time of its operation until the first failure T_{av} [43].

An electric machine, like any technical system, consists of individual elements (blocks) that have their own reliability values and a specific connection diagram. The reliability of the entire system is calculated depending on the connection diagram of the elements included in the motor design. Electric machines of different types have a sequential connection diagram, in which the failure or deterioration of each element affects the failure or deterioration of the entire system (Fig. 4).

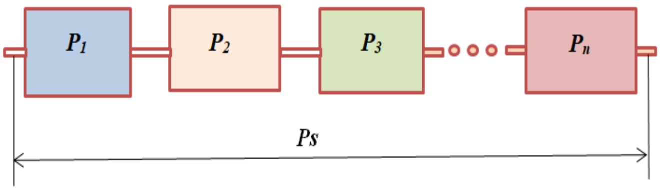

Fig. 4. Serial connection of elements on a reliability logic diagram.

The overall reliability of an electric motor, consisting of n elements with reliability p_1, p_2 … p_n and independent of each other with known values of the element reliability [41]:

$$P_{e.m.} = p_1 \cdot p_2 \cdot p_3 \cdot p_3 \cdot \ldots p_n = \prod_{i=1}^{n} p_i. \quad (1)$$

To calculate the probability of failure-free operation of motor elements, various distribution laws and the hazard rate value $\lambda(t)$ of each element for the time under consideration are used. The hazard rate values of elements or the entire product are specified in reference literature or calculated according to statistical data on operation. The obtained values represent the average statistics of operation in the nominal mode under the same ambient and load conditions.

To analyze the reliability of the motor and make decisions on its maintenance during the period of use, with a known hazard rate, the period of normal operation of electrical equipment is usually selected - *II*, which corresponds to the section ($t_1 – t_2$) according to Fig. 5, curve 1.

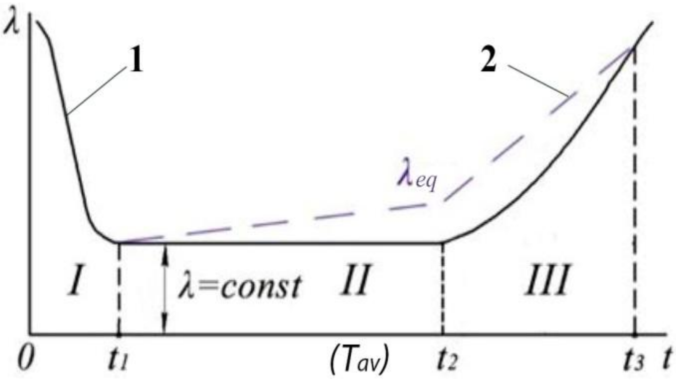

Fig. 5. Dependence of the hazard rate of an electric motor. from the time of operation:

1 – without taking into account operational factors;

2 – taking into account operational factors

As is known, the dependence of the hazard rate on the operating time has three characteristic sections (Fig. 5, curve 1). I is the running-in period of the electric motor, which begins immediately after its initial commissioning ($0 – t_1$). This period is characterized by a high level of gradually decreasing failures as restoration and adjustment work is carried out. Failures during this period are caused by design and technological omissions and errors, including defects in components and materials, as well as storage and transportation conditions of the finished product.

To reduce failures during this period, before release, electric motors undergo adjustment of bearing assemblies, insulation control, vibration control, checking of the balance of rotating masses, running-in of brushes, etc. Sometimes, the end of this period is associated with warranty service of the motor, when the elimination of failures is carried out by the manufacturer.

Upon completion of the running-in period, when the hazard rate becomes minimal and in most cases the manifestation of hidden defects or random factors due to non-compliance with operating conditions is gradual, the period of normal operation begins – *II* ($t_1 – t_2$) in Fig. 5, curve 1. The period of normal operation is the main and longest period of use of an electric motor, which is subject to separate analysis and study to create conditions for increasing the reliability of the equipment during operation.

The end of the normal operation period is determined by a sharp increase in the hazard rate $\lambda(t)$. Starting from a certain point, conventionally corresponding to the duration of operation $t_2<t<t_3$, the elements and parts of the motor begin to age and wear out more intensively, which corresponds to the final period (*III*), the period of aging and wear (Fig. 5, curve 1). The increase in the hazard rate of electric motors in this period is due to the aging processes of insulating materials and wear of mechanical elements due to irreversible physical and chemical processes occurring during long-term operation.

The normal operation period (*II*, Fig. 5, curve 1) is used to calculate the probability of failure-free operation of the motor depending on its operating time with the determination of quantitative reliability indicators. Based on the results of the calculated probability values $P(t)$, it is possible to compare different designs and types of motors by quantitative indicators when selecting an electric drive for industrial systems.

Of greatest practical importance is the precise determination of the hazard rate λ(t) and the calculation of the associated mean operating time of the electric motor before the first failure T_{av}. The values of the mean time between failures are taken into account when establishing the terms for performing technical maintenance of the entire technical system or monitoring its individual elements or units during the operation of the motor.

Failures occurring during the normal operation period (t_1 – t_2) (Fig. 5, curve 1) are random in nature with an accepted constant hazard rate throughout the entire period. To describe the failure process and the probability distribution of failure-free operation from the time of operation in this period, the exponential probability distribution law *P*(t) is used [44].

The exponential distribution law is single-parameter and depends only on the hazard rate λ(t), the value of which remains constant throughout the normal operation period and does not depend on the motor operating time:

$$P(t) = e^{(-\lambda t)}, \tag{2}$$

where λ – hazard rate of electric motor (element).

Mean time to first failure, *h*:

$$T_{av} = \int_0^\infty e^{-\lambda t} dt = \frac{1}{\lambda}\,. \tag{3}$$

Probability of failure:

$$Q = 1 - P(t) = 1 - e^{(-\lambda t)}. \tag{4}$$

For an object consisting of *n* series-connected elements, the overall hazard rate is determined by:

$$\lambda(t) = \sum_{i=1}^{n} \lambda_i(t), \tag{5}$$

where *n* – is the number of sequentially connected basic elements.

Considering (3) the mean time to first failure of an electric motor:

$$T_{av} = \left(\sum_{i=1}^{n} \frac{1}{T_i}\right)^{-1}, \tag{6}$$

where T_i – time to first failure of the *i*-th element of the system.

Consequently, the accuracy of determining the main quantitative indicators of the reliability of an electric motor and any other technical system depends on the accuracy of calculating the probability of failure of the system or its individual elements.

4. Consideration of operational factors when calculating reliability indicators

The most well-known reference for the analysis and prediction of reliability of electronic and mechanical components and systems, in particular for predicting the probability of failure in military and other critical applications, is the MIL-HDBK-217F (Military Handbook 217F) standard [45]. This standard contains methods for calculating the mean time between failures and corrected values of hazard rates for electronic and mechanical components. One of the purposes of the MIL-HDBK-217F standard is to correct the reliability calculation using mathematical models. In [46,47], practical studies of the reliability prediction method based on the MIL-HDBK-217F reference book are conducted, where predictions are made from the methods given in the standard based on the hazard rate of individual components. A similar standard is GJB/Z 299C-2006 Reliability prediction handbook for electronic equipment (China), which is also used in assessing the reliability of various elements of technical systems, in particular, using statistical methods, hazard rates, and reliability models created on their basis for predicting the failure-free operation of systems [48]. Therefore, determining and refining the calculation of the hazard rate of individual elements or systems is an important step in determining the reliability and failure-free operation of any technical systems.

The hazard rate is determined, if possible, on the basis of the operating statistics of each type of electric motor. However, the hazard rate values used in the subsequent calculation of quantitative reliability indicators are quite approximate, so the calculated indicator of the operating time before the first failure T_{av} (3) does not correspond to the actual time of the first failure.

The exponential distribution used for the normal operating period has a characteristic property: the probability of failure-free operation does not depend on how long the motor has been operating in the time interval $t_1 - t_2$. It follows that the conditional probability for the time period (t_0+*t*) following the interval t0, in which the device has already operated without failure, will be:

$$P\left(\frac{1}{t_0}\right) = \frac{e^{-\lambda(t_0+t)}}{e^{-\lambda t_0}} = e^{-\lambda t}. \tag{7}$$

This means that when operating an electric motor for a period of time ($t_1 - t_2$), the aftereffect property is absent, that is, the reliability indicators of the motor depend only on its condition at the beginning of the time interval $t_1<t>t_2$ and will have the same values as at the time of the previous operation, that is, without any change in the technical condition.

This approach may be valid for electrical or electronic devices, but for electric motors, the absence of wear and tear during normal operation does not correspond to the actual situation, which actually begins from the beginning of operation, and their failure due to these processes occurs throughout the entire period. In addition to wear and tear and aging processes, the hazard rate is also affected by operating conditions and loading modes, which are not taken into account in the usual calculation of the intensity value.

A number of modern sources provide studies of the influence of individual external factors (temperature, humidity, vibration, etc.), which, if data on the degree of their impact are available, must also be taken into account when calculating the probability of failure-free operation [16,35,45].

To take into account the complex impact of all possible influences of external factors during the operation period, when determining quantitative indicators of the reliability of electric motors, it is proposed to use the equivalent hazard rate λ_{eq}.

The equivalent value of the intensity can be obtained as the product of the hazard rate under steady-state conditions (nominal) λ_0 by the coefficients of various influential factors – $k_1, k_2, \ldots k_n$:

$$\lambda_{eq} = \lambda_0 \cdot \prod_{n=1}^{N} k_n. \quad (8)$$

The coefficients taken into account in (8) may differ for different elements or objects, taking into account the type of equipment and operating conditions.

Taking into account external factors and impacts

For elements or types of equipment that are exposed to mechanical factors during operation, the following coefficients are taken into account:

k_{vl} – vibration loads;

k_{sl} – shock loads.

Table 1 shows approximate values of the coefficients of impact of the main mechanical factors on the hazard rate of equipment elements.

Table 1. Values of coefficients of influence of mechanical factors.

Equipment operating conditions	Vibration loads, k_{vl}	Shock loads, k_{sl}	Total impact, k_{mech}
Stand (indoors)	1,0	1,0	1,0
Stationary (outdoors)	1,04	1,03	1,07
Water transport	1,3	1,05	1,37
Automobile transport	1,35	1,08	1,46
Railway transport	1,4	1,1	1,54
Air transport	1,46	1,13	1,65

For specific operating conditions of the equipment, the influence of humidity and temperature of the – k_{hum} according to Table 2 and air pressure depending on the altitude of the operating location of the – $k_{o.l.}$ according to Table 3 are also taken into account.

Table 2. Value of the coefficients of impact of humidity and temperature $k_{hum.}$

Humidity, %	Temperature, C^0	Value of the coefficient, k_{hum}
60–70	20–40	1,0
90–98	20–25	2,0
90–98	30–40	2,5

Table 3. The value of the air pressure impact coefficients at the altitude of the operating location $k_{o.l.}$.

Height, *km*	Value of the coefficient, $k_{o.l.}$	Height, *km*	Value of the coefficient, $k_{o.l.}$
0–1	1,0	8–10	1,25
1–2	1,05	10–15	1,3
2–3	1,1	15–20	1,35
3–5	1,14	20–25	1,38
5–6	1,16	25–30	1,4
6–8	1,2	30–40	1,45

Accounting for operational factors

For a number of electrical equipment elements, operating factors k_{exp} are used, which depend on the operating temperature of the technical system and the electrical load factor $K_{e.l.}$. The value of the load factor $K_{e.l.}$ is determined by the ratio of the operating values of voltage, current or power of the element during the operating period (operating value) to the maximum permissible values of these quantities. For various equipment elements, the most influential parameters are used in determining the value of the electrical load factor and the corresponding ratio:

$$K_{e.l.} = \frac{I_{o.v.}}{I_{m.p.}}, \quad K_{e.l.} = \frac{U_{o.v.}}{U_{m.p.}} \quad \text{or} \quad K_{e.l.} = \frac{P_{o.v.}}{P_{m.p.}}.$$

Table 4 shows the values of the operating factors k_{exp} for calculating the hazard rate of transformer windings and electrical machine windings depending on the loading factor and the operating temperature of the technical object.

Table 4. The value of the operating factors coefficients k_{exp} for transformer windings and electrical machine windings.

Temperature, C^0	**Electrical load factor $K_{e.l.}$**							
	0,3	**0,4**	**0,5**	**0,6**	**0,7**	**0,8**	**0,9**	**1,0**
20	0,1	0,1	0,1	0,2	0,3	0,6	0,8	1,0
25	0,1	0,1	0,2	0,3	0,5	0,8	1,2	1,3
30	0,1	0,1	0,2	0,3	0,6	1,0	1,4	1,6
35	0,1	0,1	0,2	0,4	0,9	1,3	1,9	2,5
40	0,1	0,2	0,2	0,5	1,2	1,8	2,4	3,0
45	0,2	0,2	0,3	0,6	1,4	2,3	3,2	4,2
50	0,2	0,2	0,3	0,8	1,8	2,8	4,0	5,2
55	0,2	0,2	0,3	1,0	2,2	3,5	5,2	6,9
60	0,2	0,3	0,4	1,2	2,5	4,1	6,4	8,6
65	0,2	0,3	0,5	1,6	3,4	5,7	8,5	11,5
70	0,3	0,4	0,6	2,0	4,2	7,2	10,7	14,0

Accounting for frequent load changes

The operating modes of most electric motors in industry, depending on their purpose, have frequent load changes, which is especially relevant for transport systems. Frequent load changes accelerate the wear and aging of motor materials during its operation, which is advisable to take into account a separate coefficient $k_{нав}$.

To carry out a quantitative accounting of frequent load changes, we assume that the periods of such motor operating cycles are the same during the normal operating period and are equal to T, then for an exponential distribution the hazard rate can be represented as:

$$\lambda(\omega) = \begin{cases} \lambda_c(\omega), \ z \cdot T \le \omega \le z \cdot T + t_0 \\ \lambda_n(\omega), \ z \cdot T + t_0 \le \omega \end{cases}, \tag{9}$$

where $\lambda_c(\omega)$– motor hazard rate under cyclic load operation;

$\lambda n(\omega)$ – hazard rate under nominal motor operating conditions;

t_0 – duration of transient processes;

z – number of cycles in the interval under consideration.

The probability of failure-free operation of the motor for z cycles can be imagined:

$$P(t/z) = e^{-z\int_0^{t_0} \lambda_c(\omega)d\omega - z\int_{t_0}^{t} \lambda_n(\omega)d\omega}. \tag{10}$$

Then the exponent of expression (10) under the condition:

$$\int_0^{t_0} \lambda_c(\omega)d\omega = \int_{t_0}^{t+\sigma} \lambda_n(\omega)d\omega. \tag{11}$$

It is possible to write:

$$z \cdot \lambda_n(t_0 + \sigma) + z \cdot \lambda_n(1 - \sigma) = \lambda_n(t + z \cdot \sigma) = \lambda_n(1 + f \cdot \sigma) \tag{12}$$

where σ– conventional time equivalent to one complete cycle of load increase and its subsequent decrease. For transport systems, this can be considered as a mode of acceleration and subsequent braking, h;

$f = \frac{z}{t}$ – frequency of load change cycles, $1/h$.

From equation (12), it is possible to determine the coefficient of accounting for the variable load $k_{v.l.}$ during the motor operation period, which will be used in calculating the hazard rate of technical systems operated in such modes:

$$k_{v.l.} = (1 + f \cdot \sigma). \tag{13}$$

Accounting for aging and wear since the start of equipment operation

The processes of aging and wear of elements begin almost immediately from the start of operation of the electric motor and continue until the moment the motor enters in critical state. The most susceptible motor elements to aging and wear are the bearing assemblies and stator winding. Thus, the wear and tear processes operate from the start of putting the motor into operation and during the following period of normal operation, which also affects the hazard rate and the calculation of the mean operating time to first failure T_{av} in section *II* (Fig. 5, curve 1).

To take into account the processes of mechanical wear and gradual change in the properties of materials and the increase in the hazard rate, the Weibull distribution is used in reliability theory:

$$P_w(t) = e^{-\lambda t^m}. \tag{14}$$

The Weibull distribution is a two-parameter distribution and includes, in addition to the hazard rate λ another parameter m, depending on which the characteristics of the distribution law change.

When $m = 1$, the Weibull distribution becomes exponential (λ = const), when m > 1, the hazard rate increases, when m < 1, the hazard rate decreases according to a law close to hyperbolic.

To take into account the aging and wear processes of motor elements, the Weibull distribution with an increasing hazard rate function is used, where the shape parameter m>1.

In the form presented in (14), the Weibull distribution for m>1 is used to assess the hazard rate in the final *III* period of motor operation (Fig. 5, curve 1), where aging and wear have a decisive influence on motor failure.

To take into account wear and aging processes during normal operation, when calculating the hazard rate, it is proposed to use the corresponding coefficient k_w :

$$k_w = \frac{1}{P_w(t)} = \frac{1}{e^{-\lambda_0 t^m}} = e^{\lambda_0 t^m}. \tag{15}$$

Thus, a coefficient of influence of physical wear processes occurring during normal operation and affecting the change in hazard rate was obtained.

When calculating the hazard rate of an electric motor during its normal operation according to (8), an equivalent hazard rate value λ_{eq} is obtained, including the influence of all possible operational factors with the corresponding coefficients.

Fig. 5, curve 2 shows an example of changing the type of hazard rate in the normal period of the motor with clarification of λ_{eq}.

Taking into account various additional factors during the operating period allows us to bring the value of the average time to first failure closer to more actual indicators, on the basis of which the maintenance time is planned, h:

$$T_{av} = \frac{1}{\lambda_{eq}}. \tag{16}$$

In addition, refining the calculation of the hazard rate allows us to obtain a more accurate value of the main reliability indicator – the probability of failure-free operation:

$$P(t) = e^{-\lambda_{eq} t}. \tag{17}$$

The refined value of the probability of failure-free operation for a certain period of time $P(t_1,t_0)$ obtained in (17) also influences the value of one of the most important process engineering coefficients, as well as a complex reliability indicator - the operational readiness coefficient A_0.

The operational readiness coefficient shows the probability that an object in standby mode will be operational at an arbitrary point in time, and, starting from this moment, will operate without failure for a given time interval (t_1–t_0) and is related to the probability of failure-free operation by the expression:

$$A_0 = A \cdot P(t_1,t_0), \tag{18}$$

where A – is the readiness factor coefficient, characterizing the property of the object to be in working condition and capable of performing the required functions for its intended purpose at time t or during a specified time interval.

The readiness factor can be calculated as follows:

$$A = \frac{T_{wf}}{T_{wf}+T_{sm}} , \tag{19}$$

where T_{wf} – time without failure (period without failures);

T_{sm} – scheduled maintenance time.

The specifics of operation of electrical machines, which often work in difficult conditions, failures occur randomly and for reliability assessment the most objective is to use the operational readiness coefficient A_0. The operational readiness coefficient, in addition to the time of failure-free operation and the time for scheduled maintenance, also takes into account the time of restoration of the operability of the electrical machine after a sudden (emergency) failure.

$$A_0 = \frac{T_{wf}}{T_{wf}+T_{sm}+T_{ur}}, \tag{20}$$

where T_{ur} –unplanned time to recover from failure (emergency failure).

Taking into account unplanned failures and the time for their restoration during the operation of electric machines is the main difference between the availability factor and the operational availability factor. Taking into account planned and unplanned equipment downtime is an important and most objective criterion for assessing the operational readiness of equipment for analysis. The operational availability factor is used to predict equipment failure or the need for its maintenance and shows the real availability of equipment taking into account all possible downtimes.

Clarification of the value of the operational availability factor (A_0) has many practical advantages, including the possibility of more effective management of the reliability and operability of the system with electric machines, where the main aspects are a more accurate forecast of the operability time, assessment of the probability of failure in a given period of time, minimization of maintenance costs, ensuring safety and improving the quality of service. To increase the reliability and efficiency of electric machines during operation, it is necessary to fully develop the following factors that affect the increase of the operational availability factor:

-increasing the reliability of engine structural elements using materials resistant to external influences;

-timely maintenance and replacement of individual elements and units;

-compliance with normal operating conditions;

-minimization of technical service costs based on the balance between the frequency of scheduled maintenance and the risk of emergency failures;

-reduction in the number of overloads and starting modes;

- widespread implementation of control systems and automatic motor condition monitoring systems with the introduction of various types of protection.

The coefficient of operational readiness A_0 is one of the important coefficients of process engineering and a complex indicator of reliability, and its clarification is a necessary condition for use in assessing various types of technical equipment during operation.

Thus, taking into account the actual operating conditions with the corresponding coefficients allows us to bring the value of a number of parameters and reliability models closer to the real ones, which can be used at all stages of design, creation and maintenance of industrial equipment with electric motors.

5. Conclusions

The article focuses on the importance of increasing the accuracy of reliability process modeling for use in decision-making on technical equipment maintenance strategies. A refined approach to calculating hazard rate is proposed, taking into account possible factors and processes that may arise during the industrial operation of electric motors.

Among the factors taken into account, the influence of external operating conditions (humidity, temperature, pressure), load conditions, as well as the processes of wear and aging of equipment elements during the period of normal operation is highlighted. Each of the proposed factors is taken into account by a separate coefficient when calculating the equivalent value of the hazard rate, taking into account the nominal value of the intensity λ_0, which is obtained for stationary operating conditions: $\lambda_{eq} = \lambda_0 \cdot \prod_{n=1}^{N} k_n$.

Practical calculation relationships are proposed for taking into account changes in load and wear and aging processes during the normal period of operation of electric motors with a general concept for taking into account accompanying factors during operation. Taking into account operational factors and obtaining more accurate reliability indicators, including the mean time to first failure, increases the accuracy of predicting the trouble-free operation of electric motors and planning the time for maintenance, taking into account actual operating conditions.

Timely and optimal maintenance helps to improve the economic performance and efficiency of using equipment with electric motors. The obtained refined value of the operational readiness coefficient allows managing the reliability, efficiency and productivity of equipment, which includes electrical machines, primarily due to the prediction of the operating time without failure and optimal planning of maintenance while minimizing costs.

Further work will be aimed at developing a Markov's model and establishing the frequency of restoration and maintenance of the main elements of electric motors to prevent emergency failures during operation using refined hazard rate values.

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