Тягові електродвигуни, що використовуються на міському електричному транспорті, забезпечують ефективність роботи електропривода, тому надійність визначає працездатність рухомого складу у цілому. Проаналізовано умови експлуатації тягових електродвигунів, проведено оцінку надійності та визначено шляхи підвищення. Встановлено закономірності зміни параметрів елементів тягових електродвигунів у процесі експлуатації. Розроблено математичну модель оцінки надійності елементів тягових електродвигунів

Ключові слова: електричний транспорт, тяговий електродвигун, експлуатаційна надійність, діагностування, імовірність безвідмовної роботи

Тяговые электродвигатели, используемые на городском электрическом транспорте, обеспечивают эффективность работы электропривода, поэтому надежность определяет работоспособность подвижного состава в целом. Проанализированы условия эксплуатации тяговых электродвигателей, проведена оценка надежности и определены пути повышения. Установлены закономерности изменения параметров элементов тяговых электродвигателей в процессе эксплуатации. Разработана математическая модель оценки надежности элементов тяговых электродвигателей

Ключевые слова: электрический транспорт, тяговый электродвигатель, диагностирование, эксплуатационная надежность, вероятность безотказной работы

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WAYS TO IMPROVE OPERATION RELIABILITY OF TRACTION ELECTRIC MOTORS OF THE ROLLING STOCK OF ELECTRIC TRANSPORT

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1. Introduction

The integrated transport system of Ukraine includes public transport, along with city electric transport. It carries out an important social function of passenger transportation.

Improvement of transport services for population relates to the efficient work of city electric transport. It depends on capabilities and quality of individual units and rolling stock aggregates. In addition, power supply and traffic control systems play an important role.

An important technical and economic indicator of quality for each technical system of electric transport or product is the concept of reliability, which characterizes a level of operational conditions of main elements and characteristics of traction electric motors (TEM).

One of the main criteria for the reliability of traction electric motors is a no-failure operation.

The experience of operation of a rolling stock of city electric transport shows that a significant number of its failures occurs due to technical damage of electrical equipment. A share of failures of traction electric motors makes up about 20 %. This leads to a halt of the functioning of rolling stock, as well as the violation of traffic schedules, deterioration of the quality of passenger service. The combination of failures in the operation of such electric machines leads to significant material losses at enterprises of electric vehicles [1, 2].

A number of factors determine reliability and efficiency of traction electric motors and electric drives in general [3]:

– technical condition of rolling stock;

– level of personnel training of an electric transport company (drivers, repairmen, etc.);

– climatic conditions, etc.

Thus, consequences of failures in the operation of a rolling stock increase the relevance of this direction. This contributes to the need for the development of further technical solutions and related activities on a scientific basis.

Therefore, an increase in the operational reliability of traction electric motors of rolling stock of electric transport, organization of control of parameters in the process of operation is a relevant issue.

2. Literature review and problem statement

Various physical processes occur during the operation of a traction electric motor. They lead, ultimately, to the following negative consequences [4]:

– degradation of parameters for a number of TEM elements;

– loss of efficiency of a traction electric motor;

– presence of voltage on a TEM body, which is dangerous for passengers and maintenance staff;

– growth of wear of separate elements of TEM;

– increase in TEM vibrations with negative influence on a comfort of a trip and reliability of other elements of rolling stock.

In addition, it is known that the main part of failures, which occur due to increased vibration and preventive technical influences, falls on the collector brush assembly of TEM, as well as bearings, insulation of armature windings and poles.

The emergence of such undesirable consequences leads to dismantling of traction electric motors, which causes material costs for a transport company.

Thus, ensuring the reliability of traction electric motors to overcome negative consequences is a relevant problem. Effective achievements of studies solve similar problems in the modern world. This contributes to increase in the reliability of TEM and rolling stock as a whole.

Various methods help to diagnose some parameters and characteristics in the directions of studies on parameters of electric motors. For example, paper [5] presents a method for evaluation of electrical parameters of engines and a rotor flow. This method is based on the approach of a model reference adaptive system and can only be used for asynchronous motors. The specificity of the operation of traction engines and a change in their parameters in real time makes not possible to use this research method.

Paper [6] also shows the study of parameters of asynchronous motors and uses a method for estimation of the speed and rotation angle of a rotor. Analysis of the article also shows that this method of parameters study is not universal.

Authors of work [7] use a method of monitoring of a condition of electric machines and changes in parameters during their operation. The disadvantage of this method is that it diagnoses only some of parameters associated with engine start up processes. There is no information about studies and diagnostics of parameters of failures of engines during their operation.

Paper [8] shows a method of estimation of parameters of asynchronous motors in real time [8]. This method can be used for drives that use an automatic setting of required parameters in a wide range of loads. But the use of such a method to evaluate parameters and to increase the reliability of traction electric motors is impossible, because it does not take into account a number of failures or their probability during operation.

Results of analytical and experimental studies determined structural schemes of a traction electric motor and a functional relationship between parameters of motor elements at loading in papers [9, 10]. In addition, it was substantiated that statistical data, as well as analytical methods, do not give a complete evaluation of the operational reliability of traction electric motors. Therefore, we need methods of mathematical modeling with the evaluation of reliability levels.

Paper [11] considers a method of determination of damage in electric machines and diagnosis of failures. This method is popular and effective, but for asynchronous motors only. A paper does not reveal results of studies on parameters of reliability of traction electric motors and diagnosis of damages of their elements.

Thus, analysis of the shown works proves that the improvement of methods for evaluation of the reliability and failures in operation of traction electric motors is relevant. Problems of reduce in failures of traction electric motors practically have not been solved up to now.

Authors of some works attempt to solve certain issues of increasing the reliability of traction electric motors by using physical-statistical methods for estimation of TEM parameters.

For example, papers [12–15] present diagnostics and research of characteristics of electric machines. Papers [16–18] show directions of resource saving on transport. Works [19, 20] present studies on parameters of reliability and efficiency of traction electric motors.

However, it is almost impossible to fix parameters of failures of parts and units under conditions of operation of a traction electric motor. Because a load mode and parameters of strength of elements change in time. Thus, there is no practical implementation of the task of registering modes and parameters at load at the moment of failure.

External and internal factors influence elements of TEM during operation. The influence leads to an increase in the intensity of wear of components and units, which changes characteristics of TEM and durability of its elements. Therefore, an important step is to establish the influence of physical factors and laws of physics of failures.

Operating conditions determine stability of TEM characteristics. In addition, a TEM element base has a significant number of different types of structural joints between parts. Parts form units, their quality is determined by conditions and technology of manufacturing. Therefore, it is necessary to use other ways and to take into account the specified requirements.

Also, we should remember that TEM rolling stock operates under different conditions, that is why well-known study methods give ambiguous estimate of failure parameters, estimation has a systematic error.

Reliability testing and evaluation of TEM elements do not include non-damaged components and units. It also produces a systematic error in study results.

Thus, analysis of literary data showed that literary sources consider general questions of the research on characteristics of electric machines, reliability parameters and efficiency of traction electric motors. But they are not studied enough and require a more detailed study on links between systems for diagnostics of rolling stock and processing of information.

Therefore, there is a need to find new ways to increase the reliability of TEM elements in operation and to improve research methods taking into account physical factors, a system of control of a technical state of rolling stock, external and internal influences, etc. We must base such a need on the consideration of structural and functional properties, as well as on links between TEM elements and characteristics of each rolling unit at load during operation.

3. The aim and objectives of the study

The aim of present study is to improve a diagnostic system of operating parameters of traction electric motors of the rolling stock of electric transport during operation. This will make it possible to increase the operational reliability of traction electric motors.

The following tasks were set to achieve the objective:

– analysis of operation conditions of traction electric motors, evaluation of the reliability and determination of ways to increase the reliability;

– establishment of regularities of change of parameters of elements of traction electric motors during operation;

– development of a mathematical model for evaluation of the reliability of traction electric motor elements and getting the results of calculation of required parameters.

4. Methods of study of indicators of reliability of elements of traction electric motors during operation

A procedure of control of a technical state of parameters of traction electric motors during operation is a base for solution of the scientific problem. The following methods [3, 21] are used in this case:

– statistics and probability theory for the analysis of the operation characteristics of traction electric motors;

– mathematical modeling for the development of mathematical models for evaluation of the reliability of elements of traction electric motors.

Such study methods include collection and analysis of statistical information on failures of traction electric motors, further processing in order to obtain adequate models of reliability.

A step-by-step study of parameters of traction electric motors showed that a mathematical expectation and a mean square deviation of elements of traction electric motors (for example, collector plates and electric board) change in its run time function almost linearly.

We use the following main indicators within the given work [3, 21] for the quantitative evaluation of characteristics of the reliability of elements of traction electric motors, taking into account the statistical data:

– probability of $P(l)$ no-failure operation of traction electric motors;

– parameter of a failure flow $\omega(l)$;

– failure rate $\lambda(l)$;

– average time before failures T_{av}.

Output parameters for studies and calculation of indicators of reliability of elements of traction electric motors are the statistical data given in Table 1.

Table 1

Output data for calculation of the reliability of elements of traction electric motors

No.	Inventory quantity of rolling stock N_i, u	Coefficient of use of rolling stock on release α_u, %	Operating speed of rolling stock V_o, km/h	Average daily stay of the rolling stock on a route t_{av}, h	Number of failures of traction electric motors m_{TEM}
1	151	0.687	15.21	10.04	42
2	148	0.647	15.19	10.05	62
3	129	0.549	15.23	10.06	73
4	123	0.667	15.17	10.1	69
5	115	0.632	15.24	10.4	70
6	108	0.681	15.25	10.5	88
7	155	0.674	15.15	10.2	78
8	147	0.548	15.34	10.1	59
9	144	0.569	15.08	9.8	47
10	129	0.539	15.06	9.7	32

The statistical information given in Table 1 is part of technical and economic indicators of work of the enterprise “Trolleybus Depot No. 3”, Kharkiv (Ukraine). It was collected over 10 years in the period from 2007 to 2016. This information is sufficient for the quantitative evaluation of the reliability of elements of traction electric motors.

5. Results of the study of indicators of the reliability of elements of traction electric motors during operation

Reliability is a complex property. It may include: no-failure (probability of no-failure operation, average running time before failure, parameter of failure flow, failure rate), durability (average resource), reparability (probability of a restoration of an operation condition, an average recovery time of an operation state), preservation (average preservation time), or certain combinations of mentioned properties in dependence on the purpose of an object and conditions of its application [3, 21].

There are two groups of reliability indicators. They characterize non-recoverable (winding of a rotor and stator, brushes and bearings) and recoverable (collector-brush assembly, start-up equipment) objects. Quantitative characteristics for non-recoverable objects are probability of no-failure operation, frequency of failures, failure rate, average running time before a first failure. Quantitative characteristics of recoverable objects include a parameter of failure flow for running time to a failure. Fig. 1 presents the classification of methods for reliability evaluation.

The mentioned classification identifies the main methods used in practice for control of the reliability parameters of traction electric motors. They are: accelerated tests, statistical forecasting (planning of the experiment).

Unlike electric motors of general purpose, traction motors operate in a variety of modes (short-term, re-short-term with frequent start-ups), which are accompanied by a wide change in rotor speed and current load (for example, it can be twice as large as the nominal during a start-up), and are not protected from weather changes.

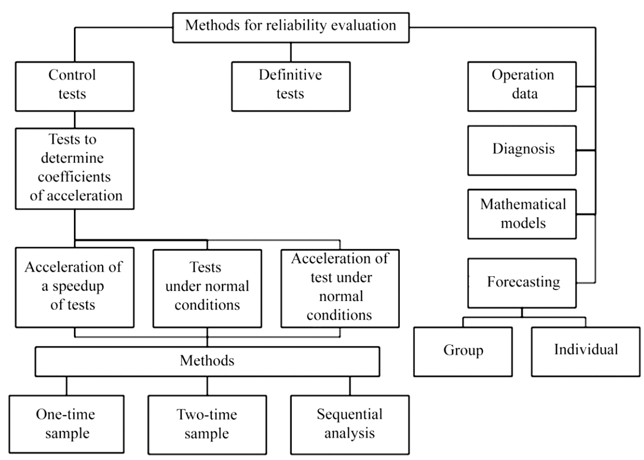

Fig. 1. Classification of methods for the evaluation of reliability

Relating to this, there is a need to develop and implement various methods, techniques, technologies, and diagnostic tools in technological processes of repair. The aim of them is to increase the reliability of traction electric motors and to increase a resource. Table 2 gives actual indicators of the reliability of traction electric motors of city electric transport.

We carried out calculations of indicators of the reliability of elements of traction electric motors on the example of electric machines of DK-210 type.

According to statistical data, taking into account a number of failures, the probability $P(l)$:

$$P(l)=\frac{N-r(l)}{N}=1-\frac{r(l)}{N}, \quad (1)$$

where N is the number of traction electric motors in the estimated aggregate; $r(l)$ is the number of initial failures before the moment of running time l.

Table 2

Indicators of reliability of traction electric motors of city electric transport

Reliability indicators	Types of traction electric motors				
	DK117	DK210	DK211	DK259	DK260
Operation to a failure, thousand km	2000	400	400	1400	1600
Probability of no-failure operation	0,92	0,85	0,88	0,95	0,96
Resource before a first overhaul, thousand km	2000	390	450	280	675
Established operation time before discarding, years	18	14	14	18	18

The parameter of failure flow $\omega(l)$ characterizes a change in the faultiness of traction motors. It is determined by the ratio of a number of all failures of objects of the considered aggregate Δl to a number of objects in the estimated aggregate and a value of the running time interval [3, 21]:

$$\omega(l)=\frac{\Delta r_i}{N\cdot\Delta l},\left[\frac{1}{\text{km}}\right], \quad (2)$$

where Δr_i is the number of failures over considered interval of running time.

The failure rate $\lambda(l)$ characterizes the reliability of elements at each given moment of time and is determined by:

$$\lambda(l)=\frac{\Delta r_i}{N\cdot\Delta l}\cdot\frac{1}{P_i}, \quad (3)$$

where P_i is the probability of no-failure operation of the i-th traction electric motor.

The average running time of no-failure operation T_{av} is the mathematical expectation of the operation time of TEM and we define it as:

$$T_{cp}=\frac{\sum_{i=1}^{N} l_i}{N}, \quad (4)$$

where l_i is the running time of proper operation of the i-th traction electric motor.

Table 3 gives results of statistical evaluation of operational reliability.

Fig. 2 shows results of the study of TEM parameters that have passed the repair stage in dependence on the run time in the form of a histogram.

An analysis of the histogram shows that 20 % of TEM that are out of order falls on the first period of operation – running time. This indicates the imperfection of the technology of elements or the low quality of repairs and imperfections of the previous TEM testing methods by heating. Such tests determine a change in the main parameters of TEM in case of occurrence of a short circuit and, consequently, an increase in the current, which affects the quality of the insulation of armature windings at intense heating.

Fig. 2, 3 show dependence of probability of no-failure operation of TEM and failure rate.

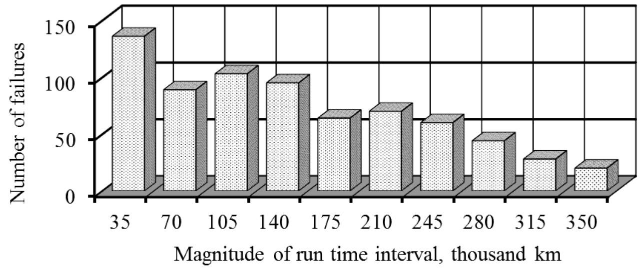

Fig. 2. Histogram of a number of failures Δr_i of traction electric motors in dependence on the run time interval Δl

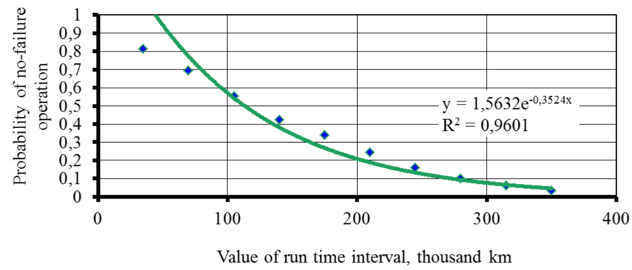

Fig. 3. Chart of probability of no-failure operation $P(l)$ of traction electric motors in dependence on the run time interval Δl

Table 3

Results of statistical evaluation of operational reliability

No.	Value of the run time interval $\Delta l\times10^3$, km	Number of failures in given interval Δr_i	Number of failures by incremental sum $\Sigma\Delta r_i$	Probability of no-failure operation $P(l)$	Parameter of failure flow $\omega(l)\times10^{-6}$	Failure rate $\lambda(l)\times10^{-6}$
1	0–35	136	136	0.815	5.286	5.286
2	35–70	89	225	0.694	3.459	4.245
3	70–105	103	328	0.554	4.004	5.770
4	105–140	95	423	0.424	3.693	6.669
5	140–175	64	487	0.337	2.488	5.860
6	175–210	70	557	0.242	2.721	8.064
7	210–245	60	617	0.160	2.332	9.630
8	245–280	44	661	0.100	1.710	10.65
9	280–315	28	689	0.062	1.088	10.81
10	315–350	20	712	0.031	8.941	14.28

Repairs restore the resource of TEM elements and the reliability of operation increases. The reliability depends on the quality of repairs and conditions of post-repair operation. But sometimes conditions of operation of TEM do not meet the specified technical requirements and, as a rule, are practically not adjusted after the repair of the latter, which leads to an increase in failure rates.

Numerous studies [12–15] showed that improvement of the quality of after-repair tests is one of the ways to improve the reliability of TEM. Increasing the quality of TEM testing, in this case, is to increase the accuracy and sufficient amount of information about the studied object by the use of methods for evaluation of reliability parameters. This will increase the reliability of TEM and reduce the energy and resource costs associated with failures and repairs.

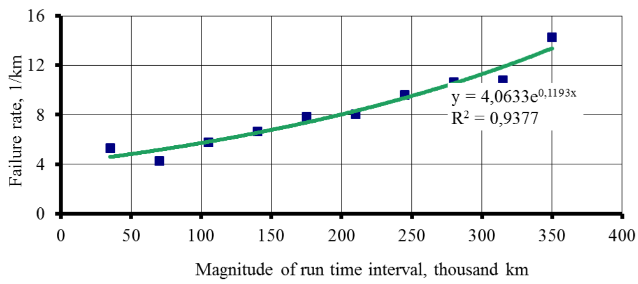

Fig. 4. Chart of failure rate $\lambda(l)$ of traction electric motors in dependence on the run time interval Δl

Mentioned factors substantiate a use of physical-statistical methods. A base of the methods is information on the physics of processes during TEM operation and the statistics on failures [2, 4, 9, 22].

In addition, it is possible to use analytical methods for determination of the reliability of technical systems that have complex internal structures and functional relationships in some cases. This makes possible to create necessary modelling methods that involve assumptions, as well as remove restrictions and accepted conditions.

For example, the aging of insulation determines a service life of an electric part of a motor in dependence on a temperature [11, 20, 22]:

$$t_x = t_0^{-\beta\Delta\tau}, \tag{5}$$

where t_0 is a service life at nominal temperature for a given insulation class; $\Delta\tau$ – parameters, which characterize a given class of isolation; β is excess of the maximum permissible temperature.

In this case, we can determine the parameter of a rate of sudden and parametric failures. However a use of expression (5) does not give possibility to consider structural features of TEM rolling stock and the unevenness of heating of TEM elements. This leads to an increase in errors that can reach significant values.

Taking into account many requirements, a mathematical model for evaluation of the reliability with a use of combined calculation methods is developed [2, 12, 17].

The lack of probabilistic-statistical data on the nature of connection failures of elements complicates the evaluation of reliability parameters of a system as a whole.

It is necessary to keep to established geometric parameters between units and parts according to technical conditions for manufacturing and operation. A deviation of these parameters affects a commutation, operation of a magnetic system, bearing units and isolation significantly and leads to severe types of failures, which require factory repair.

All of the above conditions require careful study, because non-compliance and absence of laws of formation causes severe types of failures in the operation of transport [13, 14, 18].

Analysis of statistical data failures shows that the nature of the occurrence of failures and consequences depends on the complexity of a structure, functional relations of parameters of traction electric motors and the diversity of influences of operational factors. Therefore, we restrict ourselves to the postulates of the basic laws of distribution density of reliability of parameters of elements included to the structural scheme and their evaluation [2, 22].

We can form a data bank that will characterize probabilistic and statistical properties of system elements on this basis. Thus, if we have the distribution density of failures of elements and evaluation, we can determine rational levels of reliability parameters for a system by varying parameters of a model obtained on the basis of the structural scheme.

We can express the probability of no-failure operation of details of a traction electric motor, due to the existing spread of parameters of a load and strength of elements, by such dependence [2, 22]:

$$p(t) = \lambda \int_0^\infty e^{-\lambda t} \mathrm{d}t \left[1 - \frac{1}{\sigma\sqrt{2\pi}} \int_0^\infty e^{-\frac{(t-m)^2}{2\sigma^2}} \mathrm{d}t \right] \times$$

$$\times \frac{1}{\sqrt{2\pi\sigma}} \int_0^\infty \frac{e^{-\frac{(t-m)^2}{2\sigma^2}}}{\int_0^{t_2} e^{t_2 - \frac{U^2}{2}} \mathrm{d}U - \int_0^{t_1} e^{t_1 - \frac{U^2}{2}} \mathrm{d}U}, \tag{6}$$

where m, σ, λ are the statistical parameters, they characterize properties of an element and conditions of its operation; t, t_1, t_2 is the time of run time of parts of a traction electric motor.

Another group of elements is expressed by the exponential and normal distribution laws:

$$p(t) = \lambda \int_0^\infty e^{-\lambda t} \mathrm{d}t \frac{1}{\sigma\sqrt{2\pi}} \int_0^\infty e^{-\frac{(t-m)^2}{2\sigma^2}} \mathrm{d}t. \tag{7}$$

The combination of normal and truncated-normal distribution laws is presented as:

$$p(t) = \left[1 - \frac{1}{(\sigma 2\pi)^2} \int_0^\infty e^{-\frac{(t-m)^2}{2\sigma^2}} \mathrm{d}t \right] \int_0^\infty \frac{e^{-\frac{(t-t_0)^2}{2\sigma^2}}}{\int_0^4 e^{-\frac{U^2}{2}} - \int_0^4 e^{-\frac{U^2}{2}} \mathrm{d}U}. \tag{8}$$

It is also possible to combine parameters of elements with exponential and truncated-normal distribution density. Then the probability of no-failure operation is:

$$p(t) = \frac{1}{\sigma 2\pi} \lambda \int_0^\infty e^{-\lambda t} \mathrm{d}t \int_0^\infty \frac{e^{-\frac{(t-t_0)^2}{2\sigma^2}}}{\int_0^\tau e^{-\frac{U^2}{2}} \mathrm{d}t - \int_0^\tau e^{-\frac{U^2}{2}} \mathrm{d}t}. \tag{9}$$

Having such analytical dependencies, it is possible, to establish the most rational relationships that meet necessary requirements by a way of enumeration of possibilities.

In connection with this, a problem of a more profound study of probabilistic and statistical properties of failures of elements of a system arises. It will be possible to obtain the evaluation of the reliability of a system at rational selection of parameters of the elements reliability based on probabilistic and statistical properties of failures of elements of a system.

Statistical information on the failure of system elements accumulates during the operation of a traction electric motor. On the basis of operational observation data on the operation of system elements and the nature of a load, we can assume that the probability of no-failure operation, in the general case, will be equal to the product of two functions.

We accepted this condition taking into account the independence of sudden failures. Then the general probability of no-failure operation for k-th element [2, 12, 17]:

$$P_k(t)=\left(1-\frac{1}{\sqrt{2\pi\sigma_k}}\int_0^t \exp\left\{-\frac{(x-m_k)^2}{2\sigma_k^2}\right\}\mathrm{d}x\right)\exp(\lambda_k,t), \quad (10)$$

where m_k, σ_k ,λ are the varying parameters; x is the running time.

The probability of no-failure operation is a function of several variables m_k, σ_k, λ_k, which are statistical parameters and characterize properties of an element and conditions of its operation.

Different variations of m_k, σ_k and λ_k change probabilistic and statistical characteristics of failures of a traction electric motor relatively to zero and to each other.

An analysis of properties of m_k, σ_k and λ_k indicates that they are random values distributed at certain intervals. This assumption of the randomness of parameters is obvious, since elements and real operating conditions differ from each other.

Let us suppose that the random variable ξm_k is distrusted on the segment $\left[m_k^{'};m_k^{''}\right]$. The random variable $\xi\sigma_k$ is distributed on the segment $\left[\sigma_k^{'};\sigma_k^{''}\right]$ and the random variable $\xi\lambda_k$ – on the segment $\left[\lambda_k^{'};\lambda_k^{''}\right]$.

In this case, the random variables ξm_k, $\xi\sigma_k$, $\xi\lambda_k$ have a normal distribution function with mathematical expectation for $\xi m_k \to m_k$; $\xi\sigma_k \to \sigma_k$; $\xi\lambda_k \to \lambda_k$; of one variance σ.

The task of determination of the probability P_x of no-failure operation of a traction electric motor at random statistical change in probabilistic characteristics arises.

Let us assume that $P_x=P_k(t, m_k, \sigma_k, \lambda_k)$ is the probability value of a no-failure operation of the k-th element at a given t and with the reliability value of parameters $(m_k, \sigma_k, \lambda_k)$, which is equal to the mathematical expectation of random variables ξm_k, $\xi\sigma_k$, $\xi\lambda_k$. Then, for the accepted conditions of independence of failures, the reliability of a unit or machine as a whole is equal to the product of the probability of no-failure of elements. Let us accept t as a fixed value and parameters $(m_k, \sigma_k, \lambda_k)$ as variables, values of which are in intervals:

$$\xi m_n \in \left[m_k^{'};m_k^{''}\right];\quad \xi\sigma_n \in \left[\sigma_k^{'};\sigma_k^{''}\right]. \quad (11)$$

If $P^{\xi m}$ is a function of the probability of a no-failure operation of an element with m_k equal to ξm and other statistical parameters equal to the mathematical expectation, then we accept the same conditions for $P_k^{\xi\sigma}$ and $P_k^{\lambda\sigma}$.

Values of partial influence of elements on a system in dependence on levels of parameters of reliability characteristics:

$$\Delta m = P_k^{\xi m}-P_k;\quad \Delta\sigma = P_k^{\xi\sigma}-P_k;\quad \Delta\lambda = P_k^{\xi\lambda}-P_k.$$

Let us introduce a new function, which depends on statistical parameters:

$$\Delta P=\frac{\sqrt{\Delta m^2+\Delta\sigma^2+\Delta\lambda^2}}{P}, \quad (12)$$

it characterizes a relative change in the probability of no-failure operation of the system ΔP with the absolute change in statistical parameters $(m_k, \sigma_k, \lambda_k)$. The ΔP function is given in the space $3n$ – measurements, where n is the number of elements of the system. The value of this function is always greater than zero [2, 22].

When a part of the range is set $\varepsilon > 0$, the condition $0<\Delta P(t)<\varepsilon$ is satisfied for the function $\Delta P(t)$. In this case, the inverse problem of finding of the part of those range of the set of the function arises, and the change in the random variables ξm_k, $\xi\sigma_k$, $\xi\lambda_k$ does not lead to a more relative change in the probability of no-failure operation of the system. The range of admissible values ξm_k, $\xi\sigma_k$, $\xi\lambda_k$ if $\Delta P(t)<\varepsilon$ must change when t is changing.

The solution of both the direct and the inverse problem, in an explicit analytical form, is impossible due to the large number of elements of the traction electric motor and complex statistical dependences of parameters on operating conditions. However, derivative solutions for specific values ε, t, m_k, σ_k, λ_k may be obtained using computer software.

Values of the parameters m_k, σ_k, λ_k , as well as limits of the values $\left[m_k^{'};m_k^{''}\right]$, $\left[\sigma_k^{'};\sigma_k^{''}\right]$, $\left[\lambda_k^{'};\lambda_k^{''}\right]$, of the laws of their changes and the calculation formulas are obtained when entering to data bank. A random number generator in a given range generates a value of ξm_k, $\xi\sigma_k$, $\xi\lambda_k$ in a given range, and finally is getting calculated by the formulas $P(t)$ and $\Delta P(t)$ for some fixed t (for example, at t equal to the resource of a machine).

Fig. 4 presents graphical dependences that characterize reliability of the elements taking into account time and quantitative characteristics.

Estimates of parameters for various laws of strength of distribution density make possible to determine quantitative characteristics of sudden and parametric failures of wear of parts of an electric motor.

Graphical dependences of reliability of parts of traction electric motors (Fig. 5, 6), which are constructed on the basis of data of operation, diagnostic methods, and forecasting, are presented as a comparison with the statistical data (Table 3 and Fig. 2, 3).

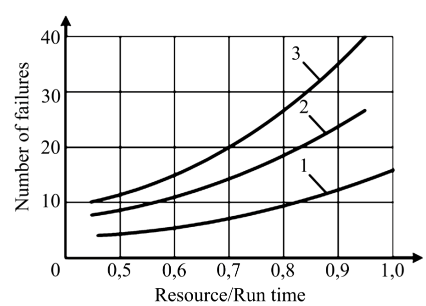

Fig. 5. Dependence of a number of failures (m) on the parameters of the resource and run time (m/N) of elements: 1, 2, 3 — curves that meet the requirements: $\frac{t}{T}<1$; $\frac{t}{T}=1$; $\frac{t}{T}>1$; respectively

Resources of parts of a traction electric motor are significantly different from each other as studies showed. As a result, some parts, which outperform the set running time for repair or replacement, have almost no failures at the given interval and, as a consequence, depends on the distribution law. If one assumes that we know the law of failures distribution and its parameters – $N\{t; T; \sigma\}$, and the running time is set for the repair or repair of a part, the probability that a part will operate more than a given value will be equal to:

$$P\{\xi > t\} = \int_{t}^{t+\infty} f(x)\mathrm{d}x, \qquad (13)$$

where $f(x)$ is the distribution density.

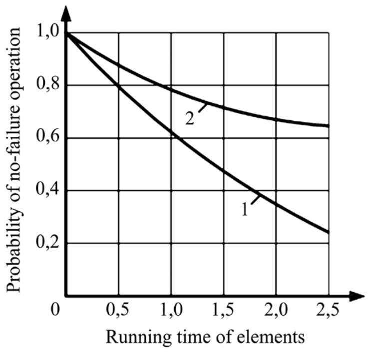

Fig. 6. Dependence of probability of no-failure operation $P(t)$ of a brush holder of the traction electric motor on the running time ($l\times10^6$, km): 1, 2 — elements of a bipolar system

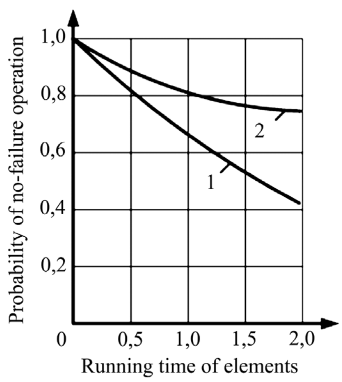

Fig. 7. Dependence of probability of no-failure operation $P(t)$ of a collector of the traction electric motor on the running time ($l\times10^6$, km): 1, 2 — elements of a bipolar system

Thus, a data bank is formed on the basis of theoretical positions and the analysis of probabilistic and statistical characteristics of system elements. Its replenishment will contribute to a realization of the task of obtaining of estimates of the reliability of traction electric motors and ensuring of no-failure operation. In the future, such a solution opens opportunities for the development of an automated diagnostic process.

6. Discussion of results of theoretical and experimental studies into parameters of traction electric motors during operation

On the basis of updated structural and functional schemes of a traction electric motor, taking into account connections between other elements and subsystems, we obtained their models [2, 12, 17]. They make possible to describe the reliability of the entire electric motor as an electrotechnical functional system analytically and obtain a mathematical model (14) of the probability of its failure in general.

The obtained models of subsystems of elements of traction electric motors make it possible to describe the reliability of any system analytically. Based on previously assumed assumptions: a failure of any of subsystems results in the failure of traction electric motors and, after corresponding transformations, it is possible to obtain a model of the probability of failure for any system also:

$$Q(E) = Q\left\{E^{(j)}(T)\right\} + \sum_{i=2}^{5}\prod_{i=1}^{i=1}\left[1 - Q\left\{E^{(j)}(T)\right\}\right]Q\left\{E^{(j)}(T)\right\}, \qquad (14)$$

where $Q\left\{E^{(j)}(T)\right\}$ is a probability of failure of the j-th subsystem [2, 12, 17].

A number of failures significantly decreases in the interval $0-t$ at greater probabilities Q. The flow of failures in a given interval can be considered as stationary at certain values, and this satisfies requirements of the Poisson flow. Then, we can obtain the model of the probability of failure in the interval $0-t$ if to substitute the expression (13) for $f(x)$ and after integration of the left and right sides:

$$P\{\xi > t\} = \begin{cases} 1 - \exp[-\lambda t], & t > 0, \\ 0, & t = 0. \end{cases} \qquad (15)$$

If the expression does not take into account a number of system elements, then the method of determination of the number of failures, which takes into account the total number of N elements that are in use, can be used.

In this case, the elements must satisfy the following other requirements. Let us assume that t is the number of failures for time T_{av} for N operating identical elements. Then:

$$\ln\left(1 - \frac{m}{N}\right) = -\lambda T_{cp}. \qquad (16)$$

In expression (16), the left side is found empirically. We find logarithm for the expression (16) and obtain:

$$\ln\left(1 - \frac{m}{N}\right) = -\lambda T_{cp}. \qquad (17)$$

From the expression (17), we find failure rate λ:

$$\lambda = -\frac{1}{T_{cp}}\ln\left(1 - \frac{m}{N}\right). \qquad (18)$$

Then, we substitute (18) to (15), and obtain:

$$P\{\xi > t\} = 1 - \exp\left[-\frac{1}{T_{cp}}\ln\left(1 - \frac{m}{N}\right)t\right]. \qquad (19)$$

If m is the number of failures for time t for N operating elements:

$$\frac{m}{N} = 1 - \exp\left[-\frac{1}{T_{cp}}\ln\left(1 - \frac{m}{N}\right)t\right]. \qquad (20)$$

After conversion, we have:

$$m = N\left\{1 - \exp\left[-\frac{1}{T_{cp}}\ln\left(1 - \frac{m}{N}\right)t\right]\right\}. \qquad (21)$$

Thus, the determination of mechanisms for obtaining parameters of the reliability of a traction electric motor depends on conditions of its operation and a number of failures of elements in service. Therefore, various methods are used to increase the performance of traction electric motors and reliability during operation. The set of positive conditions reflects the reliability of rolling stock as a whole.

7. Conclusions

1. According to the results of the processing of statistical information of enterprises of electric transport and analysis of conditions of operation of systems and units of rolling stock, we found that electrical equipment has a dynamics of failure growth. We established that failures of traction electric motors make up 20 % of all electrical equipment failures. We analyzed conditions of operation of traction electric motors and estimated their reliability.

2. The study of probabilistic and statistical characteristics of the functions of the distribution density of traction electric motors failure shows that some failures are approximated by an asymmetric distribution. In this regard, it is advisable to use a truncated normal distribution function N $N\{t; T; \sigma\}$, which will make possible tp increase the adequacy of models. We established that the number of failures in the interval $0-t1$ decreases significantly for large probability Q. We can consider the flow of failures in this interval as stationary for certain values.

3. We proposed a mathematical model for reliability evaluation (14), which, unlike existing models, is based on the system analysis of the probabilities of failure of subsystems, which are subjected to diagnosis (brush-holding unit, stator, anchor, collector), on a base of structural and functional diagrams of traction electric motor elements. It makes possible to determine parameters of various elements of traction electric motors during operation. The model differs qualitatively from the existing ones by taking into account structural and electromagnetic characteristics and gibes possibility to optimize parameters of different units in relation to the requirements of the system of planned and preventive repair, when traction motors developed a given resource and continue to operate.

It is possible to estimate parameters of the reliability of traction electric motor of any type according to the results of the study and the above calculations.

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THERMODYNAMIC ANALYSIS OF AIR-COMPRESSION REFRIGERATING MACHINE BASED ON THE EXERGY COST THEORY

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Розроблено методику проведення поглибленого термодинамічного аналізу повітряно-компресійних холодильних машин і теплових насосів на основі теорії ексергетичної вартості. Методика враховує нееквівалентність ексергетичних втрат в різних ланках процесу термотрансформації та їх вплив на споживання ексергії, що підводиться до системи. Сформовано термоекономічну модель, за допомогою якої досліджено вплив внутрішньої незворотності, що зумовлена процесами в компресорі і детандері, на ексергетичну ефективність повітряно-компресійної холодильної машини (ПХМ). Визначено аномалії і дисфункції в елементах технологічної схеми ПХМ

Ключові слова: термоекономічна модель, ексергетична вартість, термодинамічний аналіз, повітряно-компресійні холодильні машини, теплонасосні установки

Разработана методика проведения углубленного термодинамического анализа воздушно-компрессионных холодильных машин и тепловых насосов на основе теории эксергетической стоимости. Методика учитывает неэквивалентность эксергетических потерь в различных звеньях процесса термотрансформации и их влияния на потребление подводимой к системе эксергии. Сформирована термоэкономическая модель, с помощью которой исследовано влияние внутренней необратимости, обусловленной процессами в компрессоре и детандере, на эксергетическую эффективность воздушно-компрессионной холодильной машины (ВХМ). Определены аномалии и дисфункции в элементах технологической схемы ВХМ

Ключевые слова: термоэкономическая модель, эксергетическая стоимость, термодинамический анализ, воздушно-компрессионные холодильные машины, теплонасосные установки

1. Introduction

In recent years, interest in the use of air-compression refrigerating machines (ARM) in air-conditioning systems and air heat-pump installations (AHPI) of heating systems has been reviving worldwide. It is mainly due to prohibitive measures dictated by the need of improving the environmental situation. Imposing restrictions of the Montreal and Kyoto Protocols related to the use of ozone-hazardous freons in refrigeration and heat pump equipment will gradually result in a reduction of the scope of application of vapor-compression refrigerating machines and heat pumps. Obviously, other thermal transformation technologies that are safer for environment will occupy the vacant niche. A special position is occupied by air-compression refrigerating machines and air heat-pump installations operating according to the Brayton reverse cycle in which air is both a source of low-potential heat and a refrigerant.

Aviation turbo-expanders with exhausted engine life can be used as ARM and AHPI equipment. Use of such "conver-