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ЕЛЕКТРИЧНИЙ ТРАНСПОРТ

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METHODOLOGY OF DETERMINING THE PARAMETERS OF TRACTION ELECTRIC MOTOR FAILURES WHEN OPERATING TROLLEYBUSES

Purpose. The work is aimed to study the change in parameters of traction electric motors of trolleybuses during operation and improvement of the technical state control system, using modern diagnostic methods. **Methodology.** Solution of the scientific problem is based on the control of technical state and change in the parameters of traction electric motors in the process of operation. For analysis of operational factors, we used the method of mathematical statistics and probability theory. Mathematical modelling and design of experiment, multifactor regression analysis provides an assessment of the reliability of the electric traction motor elements. Physical and statistical methods provide for research and detection of patterns of influence of the factors that accelerate the wear of parts. This allows us to generate models of system reliability that take into account the influence of operational factors on the reliability. **Findings.** As a result of the studies we obtained quantitative characteristics of the reliability of commutator and established that the failures of traction motors make up 20% of all failures of electrical equipment. We analysed the operation conditions of traction electric motors and determined the failure distribution law $N\{m_x,\sigma_x\}$, which allows assessing the progression between gradual failures. We obtained a mathematical model characterizing the object operation. A generalized equation of the failure rate of elements for traction electric motor (TEM) was found. We improved the estimation methods of reliability of TEM element base that makes it possible to determine the ETM lifetime taking into account the features of each trolleybus. We established the failure rate of commutators using physical and statistical methods. **Originality.** For the first time, the choice of physico-statistical methods of simulation and reliability calculation was substantiated. We determined the regularities of change in parameters of the trolleybus traction electric motor elements, which makes it possible to control the processes of their wear in the operation conditions. We developed a mathematical model for estimating the traction electric motor reliability, based on a system analysis of the probabilities of failures of subsystems to be diagnosed. **Practical value.** Based on the results of the study, we developed practical recommendations for rational choice of diagnostic parameters of traction motors. Their implementation at the enterprises of electric transport will increase reliability of electric motors in general up to 10%. It is proposed to use the results of the work in the educational process and in the research work of students at the Department of Electric Transport of the O.M. Beketov National University of Urban Economy in Kharkiv. The developed methodology for determination of parameters of traction electric motors when operating trolleybuses allows assessing the reliability of any type of trolleybus traction motor.

Keywords: electric transport; traction electric motor; diagnosing; operating reliability; failure rate

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Introduction

Trolleybuses are equipped with traction electric motors of direct and alternating current, which determine the functional purpose of the rolling stock as a whole.

The main task of the operation of urban electric transport, in particular that of trolleybuses, is to ensure uninterrupted process of transportation of passengers, traffic safety on routes, as well as electrical safety.

Providing the appropriate level of reliability of traction electric motors is an urgent task that contributes to the efficiency of urban electric transport in general [1].

It is possible to obtain the solution of the problem by saving resources and controlling parameters in the process of the object operation. This can be achieved by ensuring the quality of maintenance and timely control of the relevant parameters of the traction electric motors while operating trolleybuses on routes. This set of tasks emphasizes the relevance of the work [1, 2].

Purpose

The main purpose of the work is to study the change in parameters of traction electric motors of trolleybuses during operation and improvement of the technical state control system, using modern diagnostic me.

According to the purpose of the work, the following tasks are defined:

– To study the parameters of traction electric motors of trolleybuses in the course of their operation, to obtain quantitative characteristics of the commutator reliability and to define the failure distribution laws;

– To establish the mathematical expectation of the time between failures of the commutator elements;

To define the commutator wear rate distribution law;

To develop the methods of failure prediction for trolleybus traction electric motor elements.

Solving these tasks will increase the operational reliability of trolleybus traction electric motors.

Methodology

The achievement of this purpose is based on the control of technical state and change in the parameters of traction electric motors in the process of operation.

Analysis of operational factors is carried out using methods of mathematical statistics and probability theory. To evaluate the reliability of traction electric motor elements, the method of mathematical modeling and the design of experiment are used.

The history of the development and improvement of methods for assessing reliability allows to distinguish two main stages: the study of statistical parameters and analysis of physico-statistical characteristics.

Comparison of methods in terms of accuracy of the obtained parameters and the adequacy of simulated processes makes it possible to highlight their features.

This allows us to form the system reliability models that take into account the influence of operational factors [1, 2].

The failures of traction electric motors largely depend on the properties of the design, materials, load modes and operating conditions. Quantitatively, they can be estimated by probabilistic-statistical characteristics.

A significant number of works is devoted to the issue of increasing the reliability of traction electric motors (TEM) of trolleybuses [3-5, 9, 12, 13]. However, most of them do not meet the necessary requirements to ensure maximum accuracy of assessment and forecast during the trolleybus operation.

To diagnose electric motors of trolleybuses, we determined the intensity of change in parameters, which contributes to the disturbance of switching of the motors due to the intense wear of the commutator. This phenomenon reflects a deterministic process.

In order to determine the intensity of wear of the traction electric motor commutators, we carried out the studies in the conditions of trolleybus operation in Ukraine. Herewith we took into account the geometry of the commutators and the state of the contact surface. These studies confirmed the well-known provisions on the random nature of the wear intensity of the commutator.

Based on the main property of inconsistent events, the sum of probabilities will be equal to one. If the random variable x is expanded at intervals, then it is possible to obtain probability characteristics, or the failure distribution law.

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According to the statistical analysis, we determined the characteristics of the mathematical expectations and the commutator wear intensity, taking into account the state of the contact surface [9, 12].

Findings

The studies have shown that in most cases, the wear of commutators obeys the Gaussian distribution law $N\{m_x, \sigma_x\}$. But the influence of operational factors on the characteristics can vary with the running time. The form of the distribution of the commutator wear V_c from the probability of scattering of the stagnant failures will be the empirical dependencies shown in Fig. 1, with the corresponding parameters m_x i and σ_x for different commutators.

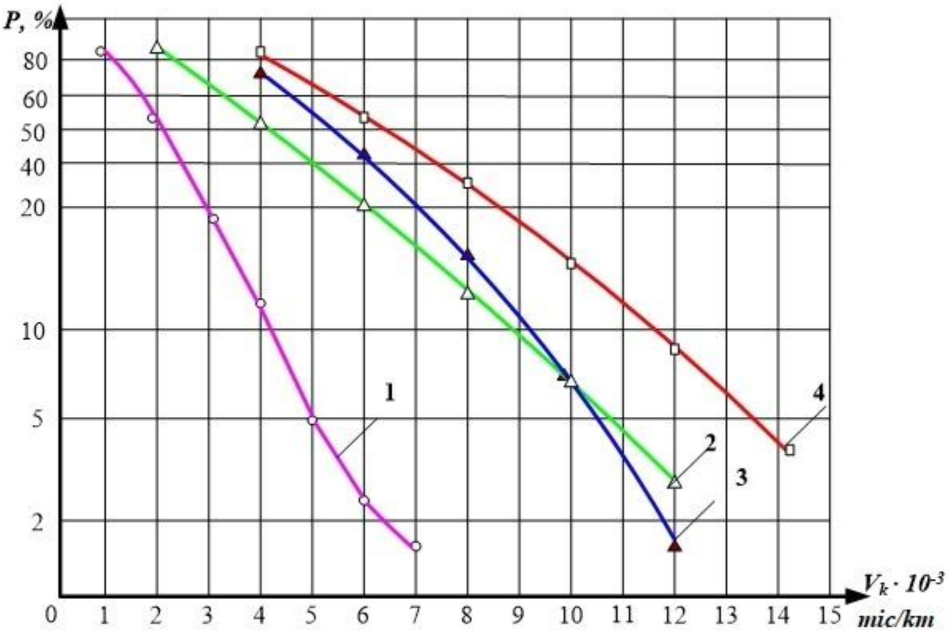

Fig. 1. Empirical dependencies of distribution of the commutator wear rate:
1 – normal palette with black-out of plates; 2 – plate burning;
3 – abrasive destruction of the oxide film;
4 – circular and chaotic burning

If we accept the change in the commutator wear intensity as a diffusion process, then, after the end of the working period (in the stable period), it fluctuates relative to a certain level. The time between failures T in this case is determined by the formula [9, 12]:

$$T = \frac{\Delta H}{\int_0^\infty f(x)dx} \quad (1)$$

where ΔH – allowable value of wear, μm; $f(x)$ – distribution density;

If the wear of the commutator is subject to the Gaussian law, then the formula will have as follows:

$$T = \frac{\Delta H}{\frac{1}{\sigma\sqrt{2\pi}}\int_0^\infty \exp\left[\frac{\left(x-\bar{x}\right)^2}{2\sigma^2}\right]dx}, \quad (2)$$

where σ – mean square deviation; x – a random variable; x – average value of random variable.

Studying the dispersion of the parameter P and the characteristics of the commutator reliability, depending on the state, showed that the contact surface may have a varied colour and composition. The normal palette of plate surfaces has a uniform oxide film without traces of erosion. The plate black-out or chaotic burning shows the destruction of the contact surface by different schemes.

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In the case of plate burning there is oxide film destruction, which affects the commutation process and the reliability of the commutator unit. Results of the study of pre-statistical characteristics of the commutator elements wear are shown in Fig. 2

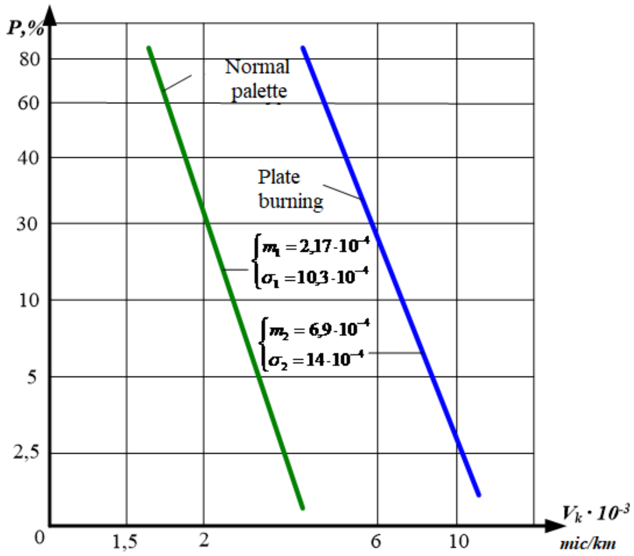

Fig. 2. Dependence of commutator reliability on the nature of its wear

Graphic dependencies demonstrate the significant influence of the plate burning on the dispersion of reliability characteristics.

In case of black-out or the normal state of the oxide film, the dispersion level is almost two times lower than that of commutators with plate burning.

In general, one can note the following: the level of dispersion of the gradual failure of the commutators is high, which requires the turning of the commutators and practically complicates the combination with planned types of technical inspections and repairs.

Practice shows that during TEM operation commutator turning is often performed. This is explained, as was shown earlier, by the magnitude of the spread of the mean time between failures.

The spread of the characteristics of wear is mainly determined by the state of the surface of the plates, the properties of the switching process, vibration. Accelerated wear of commutators requires premature turning, which is performed mainly during unscheduled repairs. Due to frequent grinding, this group of commutators prematurely runs its course.

But there is a group of commutators that has low wear intensity. In this case, grinding occurs during scheduled repairs when the parameters and condition of the commutator allow it to be used until the next scheduled repair, which involves reduction of the resource.

The results of studies are important, which is that the deformation of the commutator during operation is considered as a random process. This gives a qualitative estimate of the change in the commutator geometry under exploitation conditions.

The conducted studies allowed determining the laws of changing the commutator geometry, depending on the operating time and condition of the palette of different types of traction electric motors. This confirms the increase in the life of the commutators without having to be turned in the interval between repairs.

The degree of wear of the brushes depends on the state of the commutator working surface, the armature and pole winding and the insulation (switching stages).

The wear of the brushes is based on the fact that the destruction of individual areas of the friction surface and the separation of the material in the form of wear products is due to repeated interaction of the projections of rough friction surfaces. Interaction of friction surfaces is accidental. Consequently, the microgeometry can be determined only by means of the functions of the distribution of surface areas at the height by the reference curves.

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Since the projections on surfaces have different height and shape, then the magnitude of the stresses and deformations that arise during the interaction will also be characterized by a certain spectrum. This allows us to determine that the process of destruction from weariness can be considered accidental.

The condition of friction pair «commutator-electrical brush» is characterized by a certain set of loads, speeds and other parameters that have a significant effect on their wear. Significant impact on wear is also caused by specific pressure of the brush springs on the brushes. As the practice of exploitation shows, the wear of electro-brushes of different types has significant deviations of pre-statistical characteristics. The fig. 3 shows the graphic dependences of the of wear rate of the brushes of different types *V* on the probability of dispersion of the gradual failure of the brushes.

Taking into account the statistical data, we determined the mathematical expectation, the mean square deviation, and the variance of the intensity of the wear of the brushes [9, 12-14]. This makes it possible to make a comparative analysis of various variants of assembly units of commutators. However, in practice, the combination with planned types of technical inspections and repairs is complicated.

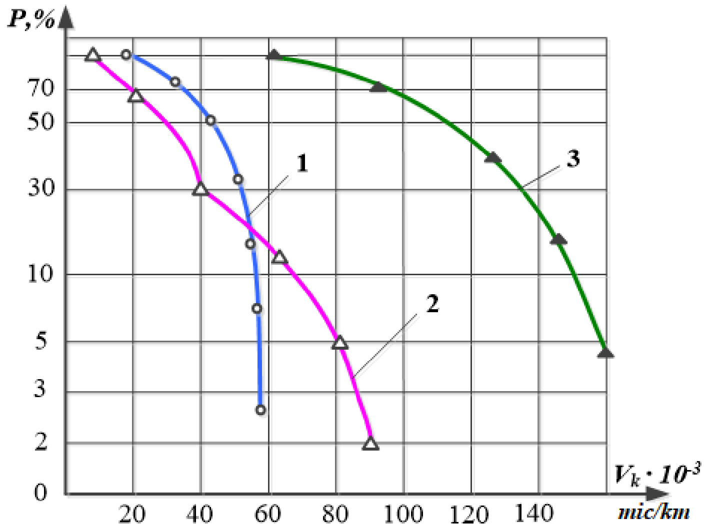

Fig. 3. Dependence of wear rate of the brushes of different types:
1 – wear distribution curve of EG-2A type brushes; *2* – wear distribution curve of EG-62 type brushes;
3 – wear distribution curve of EG-74C type brushes

The value of the mean square deviation of the wear intensity indicates a high degree of dispersion of the reliability parameters (see Fig. 3). From the given data it is seen that the time between failures is characterized by a high level of dispersion for uneven wear. This indicates that the failure of the brushes occurs between the repairs, which creates the preconditions for unscheduled work to eliminate failures and increases operating costs.

Thus, a decrease in the dispersion between failures will allow concentrating the change of brushes of ultimate wear on scheduled repairs.

As the practice of trolleybus traction electric motors shows, the failures of system elements can be caused by the inconsistency of load factors affecting the increased wear. Such influence extends to each element of the system separately or together, and levels can take different values. Temporary and quantitative characteristics depend on operating conditions, under which such factors as ambient temperature, barometric pressure, pollution, frost, snow, etc. operate.

The factors that affect the elements of the traction electric motors include temperature, vibration, current, voltage, power, humidity, frequency of rotation; we denote them as $f_1 \dots f_7$. The part of these factors under operating conditions varies depending on load modes and affects accordingly the elements of traction electric motors.

The failure rate with factors of influence [9–12]:

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$$\lambda_k(f_i) = k_i \exp\{c_i f_i\}, \quad (3)$$

where f_i – variable parameter depending on the operating conditions; c_i – load factor $(c_i = c_1 \ldots c_7)$;

k_i – coefficient with regard to the properties of the design of the traction electric motor, the state of gap in the joints of parts; $i = 1\ldots7$ – influence factors with regard to current, vibration, power, voltage, etc.

The fig. 4 shows the dependence of the failure rate of the insulation for traction electric motors λ on the nominal value of the load mode f_{iH}. Dependencies are constructed for different implementations of the load factor *c* ($c_1 = 0.073$; $c_2 = 0.146$; $c_3 = 0.219$; $c_4 = 0.299$; $c_5 = 0.365$; $c_6 = 0.438$; $c_7 = 0.511$).

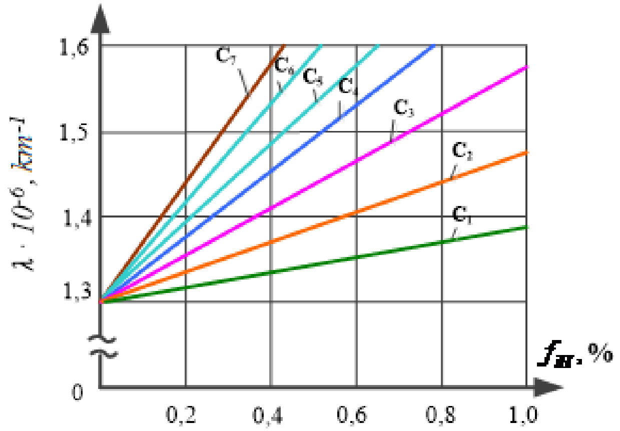

Fig. 4. Dependences of failure rate of the traction electric motor isolation λ on the nominal value of loading mode f_{iH} and various realizations of the load factor *c*

The shown factors are independent and operate simultaneously. Failure of an element due to one of the factors leads to system failure.

The dependence of the failure rate of the traction electric motor element on the failure rate by factors is taken linear and has the form:

$$\lambda(f_1 \ldots f_7) = \lambda_k(f_1)\lambda_k(f_2)\ldots\lambda_k(f_7),$$

or

$$\lambda_k(f_1 \ldots f_7) = \prod_{i=1}^{7} \lambda_k(f_i), \quad (4)$$

Numerous studies [3–8, 10–12] and operational data show the distribution law for the probability of failure-free operation for some elements of the traction electric motor. For relaxation failures in time *t* this is a product with the parameter λ_k , This parameter is determined taking into account the normal law of the distribution of failures $N\{m_k, s_k\}$. $E(\lambda_k;t)$ Then the reliability of $P_k\ (t)$ element for the independence of the parametric and the relaxation $N(m_k;s_k;t)$ failures will be equal to the product:

$$P_k(t) = E(\lambda_k;t) N(m_k;\sigma_k;t), \quad (5)$$

where $E(\lambda_k;t) = exp\{\lambda_k;t\}$

$$N(m_k;\sigma_k;t) = 1 - \frac{1}{\sigma\sqrt{2\pi}} \int_0^{H/T} \exp\left\{-\frac{(x-m_k)^2}{2\sigma_k^2}\right\} dx.$$

$$P_k(t) = E(\lambda_{kH};t) N(t;m_{kH};\sigma_{kH}) \quad (6)$$

Based on the data (see Fig. 4), for the given value of the load factor *c*, the reliability characterristics for the assembly element are calculated:

$m_1 = 3.8 \cdot 10^{-4}$; $\sigma_1 = 5 \cdot 10^{-4}$; $c_1 = 0.776$;

$m_2 = 1.1 \cdot 10^{-4}$; $\sigma_2 = 1.7 \cdot 10^{-4}$; $c_2 = 0.742$;

$m_3 = 1.7 \cdot 10^{-4}$; $\sigma_3 = 2.6 \cdot 10^{-4}$; $c_3 = 0.736$.

From the given dependencies it is clear that the parameters of the composite structure of the model significantly affect the reliability of the traction electric motor.

For $m_k = m_{kH}; \sigma_k = \sigma_{kH}; \lambda_k = \lambda_{kH}$ the equation (5) will look as follows:

Expression of the failure rate for a particular structural scheme of an element will have the form:

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$$\lambda_k\left(f_i,\dots f_m\right)=\lambda(t).$$

By making the appropriate substitution, we can obtain the equation [16–18]:

$$\lambda_k\left(t;\,f_1;\,f_2;\dots f_7\right)=k\frac{1}{M_m}\ln^{-1}\left\{d_3 f_3\right\}\times$$

$$\times\exp\sum_{\substack{i=1\\ j=1\\ i,j\neq 3\\ i<j}}^{7} d_{ij} f_i f_j\left[k-\frac{dN\left(t;m_k;\sigma_r\right)}{dt}\right]\frac{1}{N\left(t;m_k;\sigma_k\right)},\ (7)$$

where k is the coefficient taking into account the properties of the traction electric motor design, namely the state of the gap in the part joints;
M_n is a mathematical expectation;

The obtained dependences for various load factors indicate that the effect on the failure rate for a particular structural scheme of the element λ_k is not the same (Fig. 5). In the general case, the equation that binds the failure rate, the probability of failure-free operation and derivative, depends on the load factors and may have the following form:

$$\lambda_k\left(t;\,f_1;\,f_2;\dots f_7\right)=-\frac{1}{P_k\left(t_0;\,f_1,\dots f_7\right)}\frac{dP_k\left(t_0;\,f_1,\dots f_7\right)}{dt}\quad(8)$$

Thus, we have an important condition under which the expression connects the failure rate with the parameters of the load element.

To diagnose the technical condition of the turn and main insulation we take into account the parameter change processes under the influence of the heating temperature. The combination of changes in the factors influences the level and nature of the TEM load.

During the study of the reliability of the traction motor during operation, it is important to provide an opportunity to analyze the reliability of the insulation, taking into account the number of available factors.

Therefore, it is important to have such a research scheme that would cover, if possible, factors that are not significant, but in aggregate have a great influence on the assessment of reliability parameters.

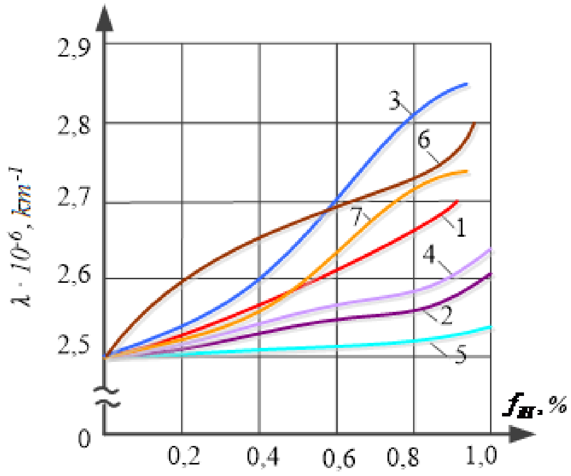

Fig. 5. Influence of load modes on the failure rate of insulation of armature winding for electric motors λ against the nominal value of load mode f_{iH}: the curves *1–7* are load factors

We will show this for the insulation of armature winding when determining the dependence of the probability of failure-free operation of a system element on the base space elements. To do this from the factor space elements we select the base space elements.

Let us suppose: g_1 is the flow rate of the cooling air from 0 to 80 m^3/min; g_2 is the voltage from 0 to 700 V; g_3 is the current of 0 to 720 A; g_4 is the air humidity of 98 %.

In the process of research, there are some difficulties in choosing the main factors. Thus, the temperature depends on the insulation, which depends on the electrical, magnetic, mechanical losses, and they, in turn, depend on the current, air flow, the frequency of the armature rotation, etc. If we take into account that they are correlated with each other to varying degrees, then the formalization of the process will not take place. Therefore, only factors of direct influence are taken into ac-

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count, in particular the temperature of heating of insulation, etc.

The method of multivariable regression analysis in the presence of statistics that characterizes the work of the object, allowed us to obtain a regression model of temperature dependence on the base space elements and load modes, taking into account the effects of pressure:

$$f_1 = d_3g_3 + d_1g_1 + d_1x + d_3g_3 + d_{11}g_1^2 + b^2 +$$
$$+d_{11}x^2 + d_{13}g_3g_1 - d_3g_3 - d_3d_1g_3x + d_1x + b_3, \quad (9)$$

where x is a random variable that has the form of the dependence of the rotational frequency on the voltage g_2 Then there will be an expression:

$$f_1 = d_1g + d_2kg_2 + g_3 + g_1^2 + k^2g_2^2 + g_3^2 +$$
$$+g_1g_3 - g_3 - kg_2g_3 - g_1 - kg_2g_1 + kg_2. \quad (10)$$

By summing the similar and transforming the right side (10) we obtain the equation:

$$f_1 = u_1g_2 + u_2kg_2 + u_3g_3 + u_4g_1^2 + u_5k^2g_2^2 +$$
$$+u_6g_3^2 - u_7g_1g_2 - u_8kg_2g_3 + u_9g_1g_3 + u_0, \quad (11)$$

where $u_0 \ldots u_9$ are the factor space elements.

The equation (11) characterizes the dependence of temperature as an element of the factor space on the strength of current, the flow of cooling air and voltage.

Similarly to the vibration parameter, depending on the frequency of the armature rotation, we have:

$$f_2 = k = k_1kg_2, . \quad (12)$$

Substituting the obtained expressions into the basic equation (7) of the element failures rate, we obtain a generalized equation:

$$\lambda_k\left(t; g_1 \ldots g_4\right) = \frac{k}{M_n}\ln^{-1}\left(1 + d_1g_1^{Б}\right)\exp\left\{\sum_{\substack{i=2\\ j=2\\ i<j}} d_{ij}g_i^{Б}g_j^{Б}\right\}\times$$
$$\times\left[k + \left(-\frac{dN\left(t; m_k; \sigma_k\right)}{dt}\frac{1}{N\left(t; m_k; \sigma_k\right)}\right)\right], \quad (13)$$

From equation (13) we find the characteristics of the failure rate against the factors by solving the differential equations of the form:

$$\lambda_k\left(t; g_1 \ldots g_4\right) = \frac{1}{P_k\left(t; g_1 \ldots g_4\right)}\frac{dP_k\left(t; g_1 \ldots g_4\right)}{dt}. \quad (14)$$

Thus we obtained the dependences of the probability of failure-free operation on the temperature and load modes.

The calculation of reliability made it possible to estimate the level of the system element failure rate, which is $\lambda = 1.29 \times 10^{-6} km$. The failure rate when exceeding the factor levels by 1.5 times gives the magnitude of the failure rate $\lambda = 2.23 \times 10^{-6} km$.

The obtained results show that in the presence of exploitation data, it is possible to predict the failure rate by calculation and, based on the given service life, to predict the probability of failure-free operation.

Consequently, it is possible to predict the failure rate of all elements of traction electric motors without exception and by using compositional models to determine the reliability of the whole system.

Rational choice of diagnostic parameters of traction motors will increase their reliability in general up to 10%.

The conducted researches provide the basis for further development of the calculation-experimental method for estimating the parameters of the maintenance system of trolleybus traction electric motors, which reached the end of their assigned service life.

The proposal for practical use of the method of structural and functional analysis of the reliability of the traction electric motor elements allowed for the particular structural assembly to obtain adequate estimates of the reliability parameters [9, 12].

These methods allow making a calculation of pre-statistical characteristics parameters of failures and damages of parts and units, on the basis of which it becomes possible to adjust the parameters of inter-repair runs of the trolleybus traction electric motor as a whole.

Originality and practical value

For the first time, the choice of physico-statistical methods of simulation and reliability calculation was substantiated. We determined the regularities of change in parameters of the trolley-

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bus traction electric motor elements, which makes it possible to control the processes of their wear in the operation conditions. We developed a mathematical model for estimating the traction electric motor reliability, based on a system analysis of the probabilities of failures of subsystems to be diagnosed.

Based on the results of the study, we developed practical recommendations for rational choice of diagnostic parameters of traction motors. Their implementation at the enterprises of electric transport will increase reliability of electric motors in general up to 10%.

It is proposed to use the results of the work in the educational process and in the research work of students at the Department of Electric Transport of the O.M. Beketov National University of Urban Economy in Kharkiv.

The developed methodology for determination of parameters of traction electric motors when operating trolleybuses allows to assess the reliability of any type of trolleybus traction motor.

Conclusions

1. As a result of the conducted research we obtained the quantitative characteristics of the commutator reliability. It has been established that the failure of traction motors make up 20% of all failures of electric equipment. Conditions of operation of traction electric motors were analysed. We determined the failure distribution law $N\ \{m_x, \sigma_x\}$, which allows assessing the progression between gradual failures.

2. We obtained the mathematical model (9) using the multi-factor regression analysis method in the presence of statistics. This model characterizes the work of the object. We also obtained the generalized equation of the failure rates (13) of the TEM elements. We improved the method of estimating the reliability of the elemental base of traction electric motors. The obtained solution allows to determine the TEM service life taking into account the characteristics of each trolleybus.

3. We established the intensity of commutator wear using the distribution law. The calculation of reliability parameters allowed to estimate the level of the system element failure rate. In case of excess of the wear intensity factors by 1.5 times the parameter $\lambda = 1.29 \times 10^{-6} (km)$ is changed by the value of $\lambda = 2.23 \times 10^{-6} (km)$.

4. The use of composite models and necessary calculation methods will allow to predict the failure of elements of the trolleybus traction electric motors. Practical recommendations, taking into account the research results, will increase the reliability of TEM up to 10%.

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МЕТОДОЛОГІЯ ВИЗНАЧЕННЯ ПАРАМЕТРІВ ВІДМОВ ТЯГОВИХ ЕЛЕКТРИЧНИХ ДВИГУНІВ ПІД ЧАС ЕКСПЛУАТАЦІЇ ТРОЛЕЙБУСІВ

Мета. У роботі необхідно провести дослідження зміни параметрів тягових електричних двигунів (ТЕД) тролейбусів у процесі експлуатації й удосконалення системи керування технічним станом за допомогою використання сучасних методів діагностування. **Методика.** Розв'язання наукової задачі базується на процедурі контролю технічного стану й зміни параметрів тягових електричних двигунів у процесі експлуатації. Для аналізу експлуатаційних факторів застосовано метод математичної статистики й теорії ймовірності. Математичне моделювання й планування експерименту, багатофакторний регресійний аналіз дає оцінку надійності елементів тягових

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електричних двигунів. Фізико-статистичні методи передбачають дослідження й виявлення закономірностей впливу факторів, які прискорюють знос деталей. Це дозволяє сформувати моделі надійності системи, що враховують вплив експлуатаційних факторів на надійність. **Результати.** Авторами у результаті проведених досліджень отримано кількісні характеристики надійності колекторно-щіткового вузла та встановлено, що відмови тягових двигунів складають 20 % від усіх відмов електрообладнання. Проаналізовано умови експлуатації тягових електричних двигунів і визначено закон розподілу відмов $N\{m_x, \sigma_x\}$, що дозволяє оцінити напрацювання між поступовими відмовами. Отримано математичну модель, яка характеризує роботу об'єкта під час експлуатації. Знайдено узагальнене рівняння інтенсивності відмов елементів тягових електродвигунів. Удосконалено методи оцінки надійності елементної бази тягових електродвигунів, яка дозволяє визначити ресурс ТЕД із урахуванням особливостей кожного тролейбуса. Встановлено інтенсивність зносу колекторів із використанням фізико-статистичних методів. **Наукова новизна.** Уперше обґрунтовано вибір фізико-статистичних методів моделювання й розрахунку надійності. Встановлено закономірності зміни параметрів елементів тягових електродвигунів тролейбусів, що дає можливість контролювати процеси їх зношування в умовах експлуатації. Створено математичну модель оцінки надійності тягового електричного двигуна, яка базується на системному аналізі ймовірностей відмов підсистем, що підлягають діагностуванню. **Практична значимість.** На основі отриманих результатів дослідження розроблено практичні рекомендації щодо раціонального вибору діагностичних параметрів тягових двигунів. Їх реалізація на підприємствах електротранспорту дозволить підвищити надійність електричних двигунів у цілому до 10 %. Запропоновано використовувати результати роботи в навчальному процесі та в науково-дослідницькій роботі студентів на кафедрі електричного транспорту Харківського національного університету міського господарства імені О. М. Бекетова. Розроблена методологія визначення параметрів тягових електричних двигунів під час експлуатації тролейбусів дозволяє проводити оцінку надійності будь-якого типу тягового двигуна тролейбуса.

Ключові слова: електричний транспорт; тяговий електричний двигун; діагностування; експлуатаційна надійність; інтенсивність відмов

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МЕТОДОЛОГИЯ ОПРЕДЕЛЕНИЯ ПАРАМЕТРОВ ОТКАЗОВ ТЯГОВЫХ ЭЛЕКТРИЧЕСКИХ ДВИГАТЕЛЕЙ ПРИ ЭКСПЛУАТАЦИИ ТРОЛЛЕЙБУСОВ

Цель. В работе необходимо провести исследование изменения параметров тяговых электродвигателей (ТЭД) троллейбусов в процессе эксплуатации и совершенствования системы управления техническим состоянием посредством использования современных методов диагностики. **Методика**. Решение научной задачи базируется на процедуре контроля технического состояния и изменения параметров тяговых электрических двигателей в процессе эксплуатации. Для анализа эксплуатационных факторов применен метод математической статистики и теории вероятности. Математическое моделирование и планирование эксперимента, многофакторный регрессионный анализ дает оценку надежности элементов тяговых электрических двигателей. Физико-статистические методы предусматривают исследования и выявления закономерностей влияния факторов, которые ускоряют износ деталей. Это позволяет сформировать модели надежности системы, учитывающие влияние эксплуатационных факторов на надежность. **Результаты.** Авторами в резуль-

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тате проведенных исследований получены количественные характеристики надежности коллекторно-щеточного узла и установлено, что отказы тяговых двигателей составляют 20 % от всех отказов электрооборудования. Проанализированы условия эксплуатации тяговых электрических двигателей и определен закон распределения отказов N $\{m_x,\sigma_x\}$, что позволяет оценить наработки между постепенными отказами. Получена математическая модель, которая характеризует работу объекта во время эксплуатации. Найдено обобщенное уравнение интенсивности отказов элементов тяговых электродвигателей. Усовершенствованы методы оценки надежности элементной базы тяговых электродвигателей, которая позволяет определить ресурс ТЭД с учетом особенностей каждого троллейбуса. Установлена интенсивность износа коллекторов с использованием физико-статистических методов. **Научная новизна.** Впервые обоснован выбор физико-статистических методов моделирования и расчета надежности. Установлены закономерности изменения параметров элементов тяговых электродвигателей троллейбусов, что дает возможность контролировать процессы их износа в условиях эксплуатации. Создана математическая модель оценки надежности тягового электрического двигателя, которая базируется на системном анализе вероятностей отказов подсистем, подлежащих диагностированию. **Практическая значимость.** На основе полученных результатов исследования разработаны практические рекомендации по рациональному выбору диагностических параметров тяговых двигателей. Их реализация на предприятиях электротранспорта позволит повысить надежность электрических двигателей в целом до 10 %. Предложено использовать результаты работы в учебном процессе и в научно-исследовательской работе студентов на кафедре электрического транспорта Харьковской национальной академии городского хозяйства имени А. Н. Бекетова. Разработанная методология определения параметров тяговых электрических двигателей при эксплуатации троллейбусов позволяет проводить оценку надежности любого типа тягового двигателя троллейбуса.

Ключевые слова: электрический транспорт; тяговый электрический двигатель; диагностирование; эксплуатационная надежность; интенсивность отказов

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