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FORMALIZATION OF RELIABILITY INDICATORS OF INDUCTION MOTORS FOR ELECTRIC DRIVES OF RAILWAY ROLLING STOCK

FORMALIZÁCIA UKAZOVATEĽOV SPOĽAHLIVOSTI INDUKČNÝCH MOTOROV PRE ELEKTRICKÉ POHONY ŽELEZNIČNÝCH KOĽAJOVÝCH VOZIDIEL

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1 INTRODUCTION

The issue of increasing the efficiency of transportations is an important problem of the railway transport rolling stock. The efficiency of transportation implies, first of all, the ways of reducing the expenditures on the maintenance and operation of transport means, providing timely performance of logistic tasks at the high level of reliability and safety of the services provided.

Reliability and rhythm of transport infrastructure performance depends on trouble-free operation of, first of all, electric drives, the main part of them belongs to asynchronous electric motors with a squirrel-cage rotor. The topical issue for providing a necessary level of operation efficiency of transport electric equipment electric motors and planning technical and preventive maintenance aimed at preventing emergency nature rejections is formalizing the models and the main reliability indexes considering the purpose and the conditions of operation.

The assessment of industrial equipment reliability and planning the timely preventive technical maintenance is conducted with the application of theoretical models of rejections distribution in the exploitation period. The most efficient anticipation results are reached via the application of mathematical models for the specific equipment types and their operation conditions.

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Application of reliability indexes is widely used in many spheres of electric and mechanical equipment [1, 2]. However, according to experimental data, calculations and assessment of technical elements reliability or systems vary substantially with the actual ones depending on the accuracy of the accepted theoretical model. Therefore, a great number of theoretical models is explained by the approaches to reliability indexes considering the conditions of specific equipment types application and various tasks that are being solved. Thus, basing on the reliability indexes, in the work [3] the analysis and defining the strategy of technical maintenance of the common industrial equipment being operated. In the works [4, 5], it is offered the scheme of probability analysis of civil structure technical equipment life cycle basing on the indexes of efficiency, in particular, reliability and expenditures on the technical maintenance [6]. It is defined the policy of maintenance In the works [7, 8] basing on the current state of the technical equipment grounded on the mathematical modelling the order of conducting maintenance and element replacement. The development of the probabilistic method of technical system assessment that is constantly worsening with the consideration of planning technical maintenance was presented in [9]. Modelling parameters of reliability and efficiency assessment of technical equipment application with the external influence and for the systems prone to numerous dependable processes of separate elements of equipment degradation was considered in the works [10, 11].

Thus, to provide the necessary accuracy level of equipment condition assessment the theoretical model of rejections distribution should consider the individual conditions of the technical system exploitation, that is formalization of model and reliability indexes is necessary with the consideration of the external conditions influence of the industrial usage and degradation processes of the elements for the specific equipment elements.

It was offered In the work the approach to formalization calculation of the main reliability indexes of asynchronous engines of the transport equipment of the railway rolling stock with the consideration of exploitation factors.

2 DEFINING RELIABILITY INDEXES OF ASYNCHRONOUS ELECTRIC MOTOR

2.1 Structure scheme of motor reliability

Creating theoretical models of rejections distributions of the transport means asynchronous electric motors should take place on the basis of physical reasoning the structure s scheme elements with defining cause and effect relations of elements degradation and their rejection under the influence of accelerating external factors.

To build the structure scheme of the asynchronous electric motor with the short-circuited rotor it is necessary to use reliability indexes basing on its main elements considering statistic data and functional diagnostics specifics [12, 13, 14].

The average results of the quantitive analysis of asynchronous motors damage with short-circuited rotor according to the data of performance statistics [15,16] were inited into the groups considering the most frequent rejections and presented in ***fig. 1***.

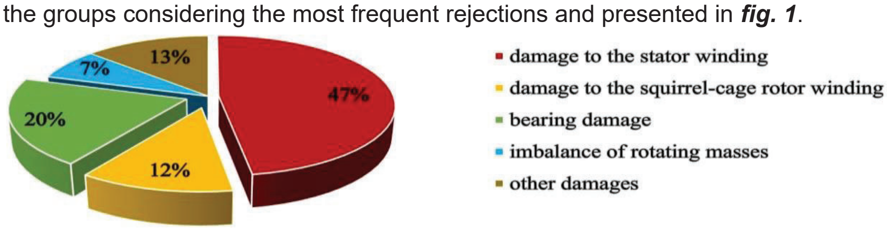

Fig. 1 *Asynchronous motor diagramme*

Obr. 1 *Schéma asynchrónneho motora*

Resulting ***fig.1***, the main elements of the asynchronous electric motor of the transport means influencing efficiency and reliability, are the stator, rotor and bearing unit [17]. Rejection of one of the stated elements of asynchronous electric motor construction leads to rejection of the whole motor, therefore at calculating overall reliability $P_{i.m.}$ the structure scheme is presented in the form of the sequential connection of the proper elements reliability: p_s, p_r та p_b, as presented in ***fig.2***.

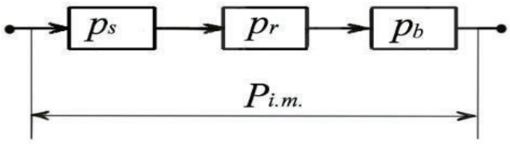

Fig. 2 *Structure scheme of electric motor reliability*

Obr. 2 *Schéma spoľahlivosti elektromotora*

Electric machines of different types are, practically, always presented in the form of sequential elements connection. The reliability of elements p_s, p_r and p_b do not depend on each other, therefore, motor reliability at known values of elements reliability, is defined by the ratio [18]:

$$P_{i.m.} = p_s \cdot p_r \cdot p_{b.} = \prod_{i=1}^{n} p_i. \quad (1)$$

From renewable systems like electric motor, to widely used quantitative reliability characteristics, the key reliability indexes are: probability of trouble-free operation for the certain performance time *P(t)*, rejections intensity λ(t) and the average time of its trouble-free operation T_{ave} [18].

2.2 Periods of motor exploitation

It is depicted in ***fig. 3*** generalised curve of rejections intensity alteration within the time at all the periods of technical objects exploitation that also corresponds to electric motors tife cyle duration.

The initial exploitation period - *running-in period* (*I*) of electric motor is accompanied ny the high level of rejjections intensity *λ*(*t*) that is gradually reducing (0 – t_1). These rejections are caused by technological, production and structural flaws and defects. To decrease rejections in the periods of *running-in* before the outlet, a separate setting of bearing units, insulation control, vibration control, examining rotating measses balance etc. takes place in electric motors catering for exploitation at the railway. Sometimes, the end of this period is bound with motor warranty service when removing rejections is conducted due to manufacturer's efforts.

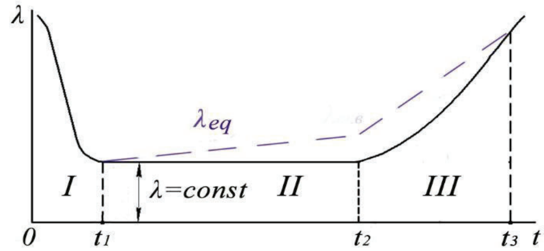

Fig. 3 *Rejections intensity curve within exploitation time*

Obr. 3 *Krivka intenzity odmietnutí v rámci doby využitia*

The next period – *the period of normal exploitation (II)* is the longest and the main performance period of electric motor (t_1 – t_2). This period is characterised with the minimum rejections intensity that as considered mostly have a gradual character from the apperance of concealed defects that were not detected in the period of running-in and suden rejections caused by the occasional factors, first of all, due to the violation of exploitation conditions, occasional loading alterations, non-favourable external factors etc. However, the processes of wearing off and ageing of the main motor joints in the period of normal exploitation are not taken into account. And these processes initially start from the beginning of the exploitation, and their failure takes place within the whole period. For railway electric rolling stock engines, it is special to increase the period of normal exploitation exclusively due to timely control, repairs and ongoing maintenance of the equipment.

Starting from the moment that conditionally responds to exploitation duration $t_2<t<t_3,$ the elements and details of the motor start, as considered in the classical case, age and wear off more intensively that corresponds to the finishing period *(III), the period of ageing and wearing off* (***fig. 3***) and followed by dramatic increase of rejections intensity $\lambda(t)$.

To define quatitative reliability indexes and to assess properly the efficiency of asynchronous electric motors of transport equipment it is reasobnable to consider only the period of normal operation corresponding to zone *II* of the period of rejections intensity curve (***fig. 3***).

2.3 Formalising motor reliability indexes in the normal performance period

The period of normal operation, in which failures are caused by random factors and have a constant intensity, for an electric motor is traditionally described by an exponential distribution with a constant value of the intensity of failures. The exponential distribution describes the build-up to failure of objects in which, as a result of control (passing) tests during initial control, there is no build-up period, and the assigned resource is established before the end of the period of normal operation, that is, until time t_2 (***fig. 3***).

The exponential distribution is one-parametric and has the characteristic property that the probability of trouble-free operation does not depend on how long the engine has worked in the time interval t1 - t2 (***fig. 3***). The probability distribution of failure-free operation over time, the average working time before failure, and the probability of failure are determined [18]:

$$P(t) = e^{(-\lambda t)}, \quad T_{ave} = \int_0^\infty e^{-\lambda t} dt = \frac{1}{\lambda}, \quad Q = 1 - P(t) = 1 - e^{(-\lambda t)}, \tag{2}$$

where λ – element rejection intensity;

For the object consisiting from n consequently connected elements, the rejection intensity comprises

$$\lambda(t) = \sum_{i=1}^{n} \lambda_i(t) , \tag{3}$$

where n – the number of consequntly connected main elements.

After replacing in the equation fault-free operation probability (2) λ to $\frac{1}{T_{ave}}$ it was obtained the following expression:

$$P(t) = \exp\left(-\frac{t}{T_{ave}}\right); \; t \geq 0; \; T_{ave} > 0 , \tag{4}$$

Thus, having the average time of fault-free operation T_{ave} or constatant rejections intensity $\lambda(t_0)$ for area $(t_1 - t_2)$, it is possible to find the probability of fault-free operation for the time interval from the moment of switching to the stated moment of time *t.*

It can be found the probability of fault-free operation for the time interval from the moment of switching to the stated moment of time *t.*

The conditional probability that the engine will work without failure in the time interval *t* following the interval t_0 after switching on, during which the device has already worked without failure, is traditionally considered:

$$P\left(\frac{1}{t_0}\right) = \frac{\exp\left\{-\lambda\left(t_0 + t\right)\right\}}{\exp\left\{-\lambda t_0\right\}} = \exp\left\{-\lambda t\right\}, \tag{5}$$

Resulting this, if the engine worked without failures until the moment of time t0, the further distribution of the time of failure-free operation will be the same as at the time of the previous operation, that is without any change in the technical condition of the product, that is the engine is not subject to wear and age within the period of normal operation . This does not correspond to the actual characteristics. Therefore, the use of uptime calculated according to the normal probability distribution law, even for an approximate assessment of the reliability of various electric motors operating in the operating conditions of the rolling stock of railways, will be incorrect and have significant deviations from the real ones.

The period of electric motors normal operation of railway rolling stock has a long duration in difficult operating conditions, where the engine is subject to a number of tangible influences, including changing environment, cyclic load changes, and wear and ageing processes that act, practically, from the beginning of electric motors operation and affect the time of trouble-free operation.

The biggest influence of rejections intensity and characteristic for electric motors of rolling stock is the cyclicity of motor performance [19]. To conduct quantitative analysis it is acceptable that the periods of motor operation cycles are equal within the normal period of operation and are equal to T, then for the exponetial time distribution between the rejections, rejections intensity can be noted in the following expression:

$$\lambda(x) = \begin{cases} \lambda_c(x),\ N \cdot T \le x \le N \cdot T + t_0 \\ \lambda_n(x),\ N \cdot T + t_0 \le x \end{cases}, \tag{6}$$

where $\lambda_c(x)$ – rejections intensity at the motor performance mode according to the cycles;

$\lambda_n(x)$ – rejections intensity at normal mode of motor performance;

t_0 – duration of transitional processes;

N – number of cycles.

The probability of the fault-free motor performance during *N* cycles is calculated according to the following expression:

$$P\left(t/N\right) = \exp\left\{-N\int_0^{t_0}\lambda_c(x)\,dx - N\int_{t_0}^{t}\lambda_n(x)\,dx\right\}. \tag{7}$$

Then the index of expression degree (12) under the condition is the following:

$$\int_0^{t_0} \lambda_c(x)dx = \int_0^{t_0+\sigma} \lambda_n(x)dx \quad (8)$$

It can be noted:

$$N \cdot \lambda_n(t_0+\sigma) + N \cdot \lambda_n(1-\sigma) = \lambda_n(t + N \cdot \sigma) = \lambda_n(1 + f \cdot \sigma), \quad (9)$$

where σ – fictitious (conditional) time equivalent to one "acceleration-braking" cycle of the motor; ;

$f = N/t$ – cycles frequency, 1/hour.

It follows from equation (9), that that in order to take into account the motor cyclic operation when calculating the probability of failure-free operation according to (2), it is necessary to consider the coefficient when calculating the intensity of failures λ:

$$k_\omega = (1 + f \cdot \sigma) \quad (10)$$

In addition, according to the statistics of repair companies, starting from the start of operation and before the ransition of motor to the final state, its elements start showing the effects of aging and wear, which affect the reliability indicators during the period of normal operation and are not taken into account in the exponential distribution of the probability of failure-free operation in the period normal operation. Considering aging and wearing off that begins immediately after the start of engine operation, distributions with an increasing function of failure intensity are used, for example, Weibull distribution with the shape parameter m>1 [18]. Weibull distribution is two-parameter and includes, in addition to the failure intensity λ, the parameter *m*, depending on which the characteristics of the distribution law change. At *m* =1, Weibull distribution becomes exponential (λ = const) (2), at *m* >1 the intensity of failures increases, at *m* <1 the intensity of failures falls according to a law close to the hyperbolic one. The probability distribution of trouble-free operation over time has the following expression:

$$P_w(t) = e^{-\lambda t^m} \quad (11)$$

In the type of calculation of trouble-free operation probability according to (11), Weibull law (at *m*>1) is used in the third period of operation, where wearing off and aging have a determining effect on the motor's performance [12]. Considering the effect of wearing off and ageing of motor elements during normal operation, when using the exponential law, it is proposed to use the coefficient k_w, which must be taken into account when calculating the intensity of failures. The coefficient that takes into account wearing off and ageing using Weibull's law has the following expression:

$$k_w = \frac{1}{P_w(t)} = \frac{1}{e^{-\lambda t^m}} = e^{\lambda t^m} \quad (12)$$

Operational data show that external factors (temperature, humidity, vibration) influence the intensity of trouble-free operation [12, 19]. To consider the degree of influence, it is necessary to use the appropriate factor k_z to correct the value of failures intensity obtained for operation under normal conditions. When using the k_z coefficient, it is possible to take into account one of the factors most influencing the intensity of failures during the operation of each of the engines, with a practically established quantitative value of the increase in the speed of the engine elements wear processes or use in forced modes of reliability tests [2, 19].

Thus, considering cyclicity (10), wearing off and ageing the elements (12) and external factors influence the equivalent intensity of motor rejections is defined in the following way:

$$\lambda_{eq} = \lambda_n \cdot k_\omega \cdot k_W \cdot k_z = \lambda_n \cdot (1 + f \cdot \sigma) \cdot e^{\lambda t^m} \cdot k_z \,. \quad (13)$$

Then the distribution of the trouble-free operation in the normal expolitation period considering operation conditions is:

$$P(t) = e^{(-\lambda_{eq} t)}, \quad (14)$$

Fig. 3 shows the presented variant of electric motor rejections intensity dependency considering refined calculation λ_{eq}.

Considering additional factors of influence on the index of the rejection intensity enables to approximate the value of the average working up to rejection T_{ave} more to the actual indexes of engines exploitation that is of great importance at assembling the models of reliability and planning the technical maintenance time.

3 CONCLUSIONS

On the basis of the conducted analysis of the main reliability indexes it was offered the formalization of the law of distributing the probability of trouble-free operation of the engine within the period of normal operation of asynchronous electric motors during operation in conditions of rolling stock of railways.

Refinement of the probability distribution law during the period of normal operation, taking into account operational factors, contributes to an increase in the level of reliability indicators, which is of significant practical importance when planning equipment maintenance modes.

Aiming this, when determining the probability of no-failure operation in the calculation of the engine failure rate, the following factors influence the operating conditions of electric motors of the rolling stock of railways are taken into account: engine operation mode (cyclicity), gradual degradation of the main elements of the engine from the beginning of the normal operation period and external factors by the corresponding coefficients. The obtained value of the equivalent intensity of failures T_{ave} allows to obtain a closer to the actual indexes value of working up to rejection time and the corrected law of probability of rolling stock electric engines while applying it further modeling the exploitation process of railways transport means.

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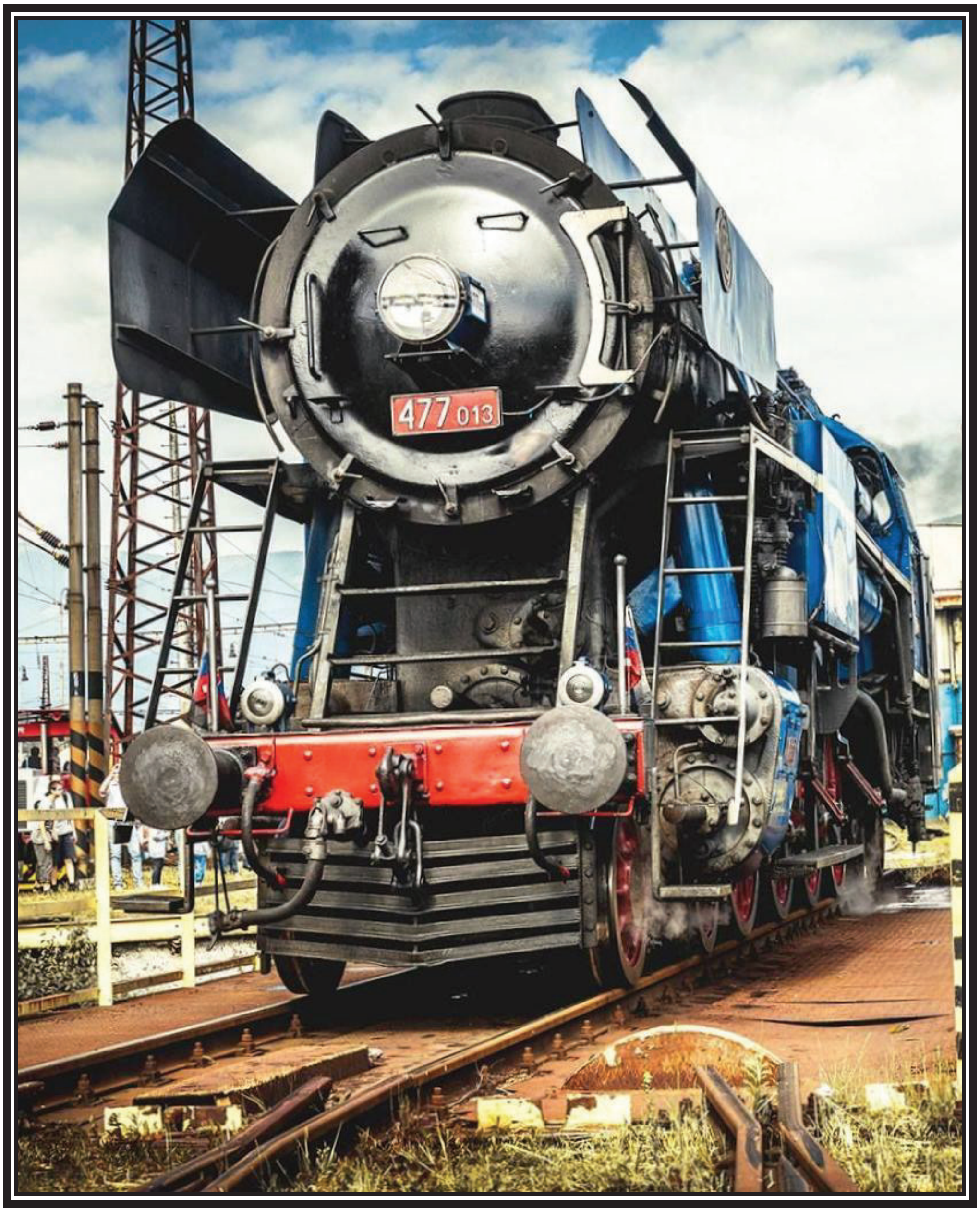
Summary

The article presents the results of formalization in the calculation of the main indicators of the reliability of induction motors for railway transport. To do this, when determining the engine failure rate, the equivalent failure rate is used, taking into account the influence of the engine operating mode, in particular, cyclicity, degradation of the main engine elements from the start of operation using the Weibull distribution and external factors by appropriate coefficients. The obtained equivalent value of the failure rate makes it possible to determine the time between failures, which is closer to the actual value, and to correct the law of *distribution of the probability of failure-free operation of electric motors in railway conditions, which contributes to the improvement of theoretical models of the reliability of railway transport operation.*

Resumé

Článok prezentuje výsledky formalizácie pri výpočte hlavných ukazovateľov spoľahlivosti asynchrónnych motorov pre železničnú dopravu. Na to sa pri určovaní poruchovosti motora používa ekvivalentná poruchovosť, berúc do úvahy vplyv prevádzkového režimu motora, najmä cyklickosť, degradáciu hlavných prvkov motora od začiatku prevádzky pomocou Weibullovho rozdelenia a vonkajších faktorov príslušnými koeficientmi. Získaná ekvivalentná hodnota poruchovosti umožňuje určiť čas medzi poruchami, ktorý sa približuje skutočnej hodnote a korigovať zákon rozdelenia pravdepodobnosti bezporuchovej prevádzky elektromotorov v podmienkach železničnej dopravy, čo prispieva k zdokonaleniu teoretických modelov spoľahlivosti prevádzky železničnej dopravy.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