Increasing the Operational Reliability of the Catenary System by Predicting Failures of Its Constructive Elements

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INCREASING THE OPERATIONAL RELIABILITY OF THE CATENARY SYSTEM BY PREDICTING FAILURES OF ITS CONSTRUCTIVE ELEMENTS

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Abstract: the catenary system and accompanying high-voltage lines of the electrified railways are stochastic systems consisting of a large number of constituent structural elements, therefore, in the process of long-term operation; each element is subjected to various natural influences as well as dynamic influence caused by interaction with electric rolling stock and other equipment. All these factors lead to a decrease in the reliability of the traction power supply system of the electrified railways, and, as a consequence, are the cause of an emergency situation caused by the possible failure of any component of the system. The catenary system and associated lines are multi-wire systems and are subject to mutual electromagnetic influences. The solution for many scientific and engineering problems requires in the capacitive connections between wires in such systems. The paper provides a substantiation of an engineering methodology for calculating the probability of the structural elements` failure of a catenary system.

Keywords: catenary alternating current, operational reliability, failure probability, prediction.

1. Introduction

The catenary system of the electrified railways serves to transfer electricity from traction substations to electric rolling stock, and is an important part of the modern railways.

The life cycle of the contact-wire of catenary system, like any other complex technical system, directly depends on the reliability of its component parts. Premature failure of one element of the catenary system can lead to failure of the suspension as a whole. Therefore, the tracks catenary system must have high reliability indicators at all stages of the life cycle.

The reason for the occurrence of instant damage and failure of the catenary system contact is the power load exceedence of the critical values for a given material or element. Such loads are random phenomena, and the element failure occurs regardless of the exploitation period and operational work of the element. In the theory of reliability, such failures are classified as sudden ones [1].

Referring to the author [9] and using the method of contributions of the following researchers [3-10], we will consider the problem of obtaining a sufficient volume of the reliable statistical data characterizing the operation of individual elements and nodes of the catenary system. This problem significantly complicates the determination of the parameters of their reliability. In this regard, to study the reliability of the catenary system devices, an approach is needed that will allow, on the basis of a small number of failures (10 values), to collect the maximum information about the laws of distribution of operating time between failures of certain nodes.

2. Results and Discussion

Analysis of the catenary system failures shows that, as a rule, more than 80% of failures are sudden and only up to 20% are gradual, which is explained by frequent preventive repairs. During this period, worn-out elements were renewed without leading to failures, and, by the fact, the service life of many elements of the catenary system exceeds the duration of the studied period.

The currently existing methods for calculating reliability are based on the assumption of the structure of the system as a set of independent (in the sense of reliability) units which are elements of calculating reliability, i.e. exclude dependence of several elements` failures. However, the exclusion from consideration of the functional dependencies between the failures of individual elements simplifies the calculation, but it significantly reduces the reliability of the obtained results. To analyze the activity of the measures taken to improve reliability and substantiate their feasibility, as well as the quality of current repairs, it is of great importance to divide all failures into preventable and non-preventable. According to statistics, about 40% of all failures could be prevented by operational maintenance. The majority of gradual failures (70%) and only 30% of sudden failures belong to preventable ones [2].

3. Materials and Methods

The principal of the rectangular contributions` method is to use some additional information on the unknown true distribution and, when constructing an empirical distribution function, when the fluctuation nature of the experimentally realized values of a random variable by uniformly distributing the information contained in specific realizations of a random variable over regions of a certain width, adjacent to these implementations.

Additional a priori information about the possible distribution density $f(x)$ should characterize the boundaries of the distribution curve and the absence of a spur increase in the function $f(x)$ within these boundaries.

The fluctuation nature of the experimentally realized values of a random variable x is taken into account by constructing a continuous symmetric function in the form of a rectangular pulse with a base d and an exact center x_i of the base (Figure 1).

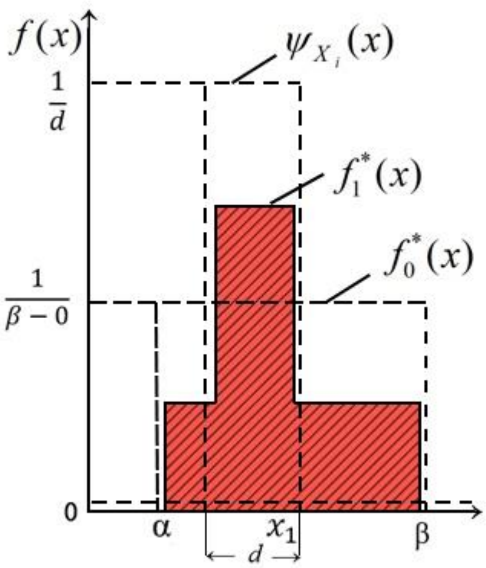

Figure 1. The graphical illustration of the function by the rectangular contributions` method with the number of observations n=1 .

The function should be normalized so that if a certain d , we have

$$\psi_{X_i}(x) = \begin{cases} \frac{1}{\alpha} npu\ x_i - \frac{d}{2} \le x \le x_i + \frac{d}{2} \\ 0\ npu\ x < x_i - \frac{d}{2}\ u\ x > x_i + \frac{d}{2} \end{cases}, \qquad (1)$$

However, this function (1) is not a density function $f_n^*(x)$. The latter is obtained by adding the function $f_0^*(x)$, which can be represented as

$$f_0^*(x) = \begin{cases} \frac{1}{\beta - \alpha} \; npu \; a \le x \le \beta \\ 0 \; npu \; x < a \; u \; x > \beta \end{cases}, \tag{2}$$

and $\psi_{x_i}(x)$, with pre-multiplied by weights ξ_i:

$$f_n^*(x) = \xi_0 \cdot f_0^*(x) + \xi_1 \cdot \psi_{X_1}(x) + \xi_2 \cdot \psi_{X_2}(x) + \dots \xi_n \cdot \psi(x)_{X_n} \; , \tag{3}$$

where $f_0^*(x)$ is the density function at n=0 i.e. in the absence of the specific realizations of the random quantities x in the interval $[\alpha, \beta]$.

Since the functions $f_0^*(x)$ and $\psi_{x_i}(x)$ are normalized, in order for the function $f_n^*(x)$ to be normalized as well, it is necessary that

$$\sum_{i=0}^{n} \xi_i = 1 \; , \tag{4}$$

Assigning the same weight to the preliminary knowledge of the properties of the function $f_0^*(x)$ as to the knowledge obtained from each realization of the random variable, we can assume that

$$\xi_0 = \xi_1 = \xi_2 = \dots \xi_n = \frac{1}{n+1} \; , \tag{5}$$

where n is the number of the random variable realizations.

Considering the previous equation, the function $f_n^*(x)$ can be written as follows:

$$f_n^*(x) = \frac{1}{n+1} \left[f_0^*(x) + \sum_{i+1}^{n} \psi_{x_i}(x) \right] , \tag{6}$$

When the distribution of the areas outside the interval $[\alpha, \beta]$, the previously given formula can be considered valid for constructing an empirical function $f_n^*(x)$.

When accepting boundaries α and β the principle of the practical certainty should be used, according to which the exit of a random variable x beyond the interval $[\alpha, \beta]$ is considered an impossible action.

One of the main questions that arise when using this method is the question of finding the optimal contribution length d_{onm} for different distribution laws and a wide change in the sampled object. The dependence of the optimal width d_{onm} of the rectangular contribution on the sample size n with an exponential distribution law is shown in Figure 2, where

$$\acute{\alpha} = \frac{d_{onm}}{\beta - \alpha} \; . \tag{7}$$

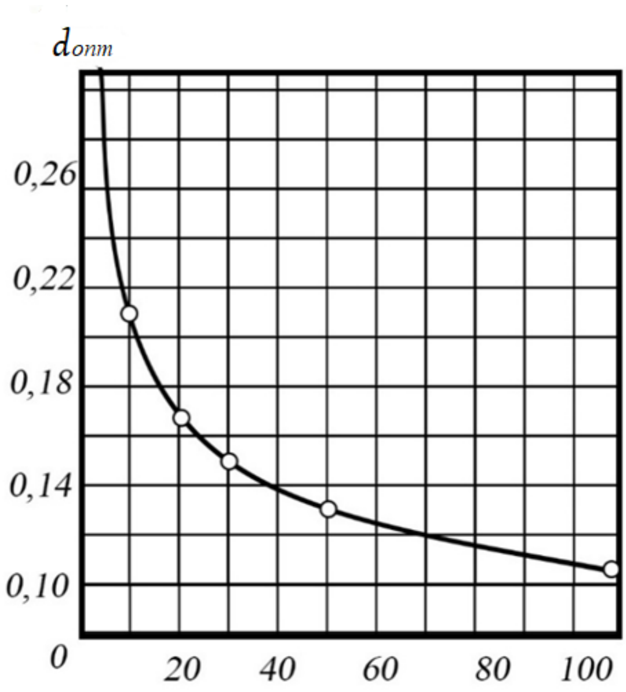

Figure 2. The dependence of the optimal width of the rectangular contribution on the sample size with an exponential distribution of a random variable

In figures 1 and 3, the empirical and theoretical functions are constructed with a sample size of 3 and 5 tests, respectively. As can be seen in these graphs, a good approximation to the theoretical distribution function is achieved using the methods of the rectangular contributions.

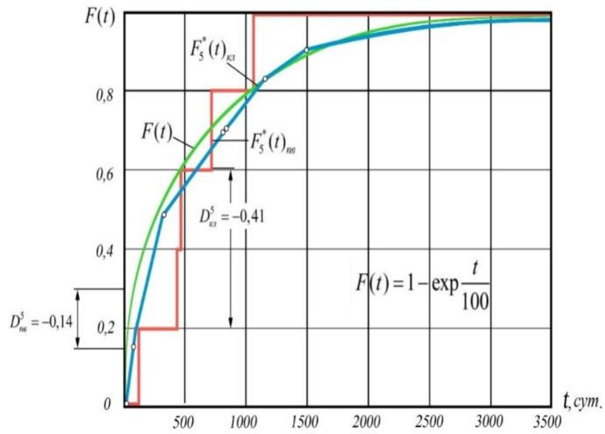

Figure 3. The Integral distribution functions of operating time between failures

It is therefore possible to study the reliability of the individual nodes and elements of the catenary system under rare failures` conditions, when the usual methods of the mathematical statistics do not provide sufficient convergence of the empirical and theoretical distribution laws or it is not possible to use them, the rectangular contributions` method turns out to be very effective.

It is not necessary to use a rectangle as a function of the contribution, especially since the rectangular shape of the contribution does not highlight the point x_i, which is fixed during a specific measurement of the value X. Although there is no need to ascribe an absolute value to the point x_i, it is logical to consider the density contribution at this point as maximum in comparison with others in the interval $[a,b]$ [14-20]. This condition is met by a contribution function in the form of an elementary Simpson`s distribution (a triangle with width d and height h, see Figure 4). Since the contribution is interpreted as a certain distribution density, the ratio of the parameters d and h is chosen so that it has a unit area, as

$$h = \frac{d}{2} \cdot \quad (8)$$

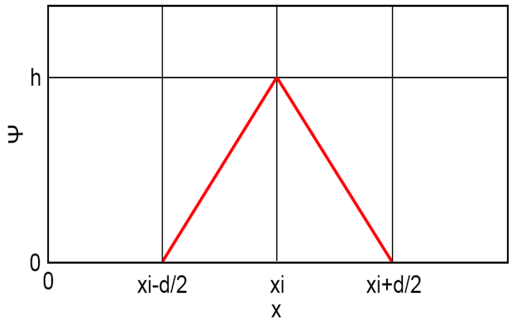

Figure 4. The triangular contribution $\varphi_i(x)$.

It is established that the normalization requirement is satisfied if the contribution function has the form

$$\varphi_i(x) = \frac{d}{2} - \frac{4 \cdot |x - x_i|}{d^2} \quad npu \quad x \in [a,b] \cdot \quad (9)$$

The form of the a priori component is selected with based on the available a priori data. If it is known that the desired distribution is symmetric and falls to the boundaries $[a,b]$, it makes sense to choose the a priori component of the form:

$$f_0(x) = \begin{cases} 0 \quad npu \quad x \le a \\ \dfrac{x - 0.5(3a-b)}{(a-b)^2} \quad npu \quad a < x \le c \\ \dfrac{0.5(3a-b) - x}{(a-b)^2} \quad npu \quad a < x \le b \\ 0 \quad npu \quad x > b \end{cases}, \quad (10)$$

where $c = \dfrac{b+a}{2}$.

The linear addition with the given weights of the prior density (9) and contributions (10) for all n elements of the sample leads to the desired density estimate are carried out.

Figure 5 shows the graphs of the distribution function and probability density obtained by the triangular contributions\` method from samples of 10 values. The width of the triangular contribution was chosen equal to $0{,}3d$, and in this case the density function turns out to be smoother. This fact makes it possible to identify the law of the probability distribution operating with small data samples.

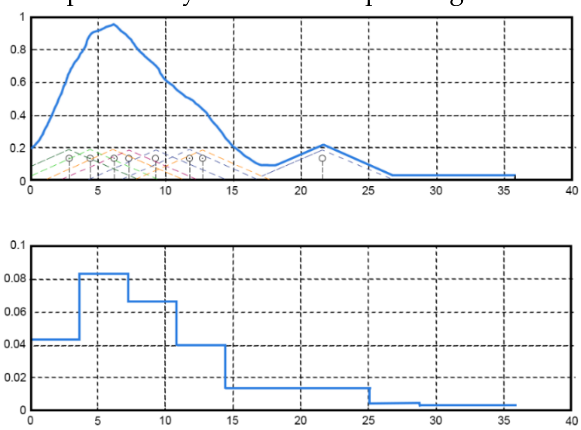

Figure 5. Plotting the empirical probability distribution using the triangular contribution method $n = 10$

To ensure a sufficient level of reliability of the catenary system and identify unacceptable risks of failures, various statistical methods can be used be implemented using various IT technologies.

This development belongs to the class of the specialized method-oriented applied software tools. The functional purpose of the applied software is to automate statistical methods for solving problems of primary data processing and calculating elementary statistics in the process of risk management, as well as loading and maintaining a database that is subsequently oriented to the principles of the machine learning. The presented functionality implements: assessment of the frequencies of certain events` occurrence in the past based on statistical data (data accumulated over a certain period of the elements operation of the catenary system) and predicting the frequencies with which these events will occur in the future. This approach implements a new mathematical method. The system software is implemented in the Microsoft Visual FoxPro version 9.0 development environment using the technology of a file-server relational database management system. The main computationally intensive operations use the structured query language SQL. The database in the package is a table space which attributes correspond to the variables to be processed (elements of the catenary system), and the sequences correspond to the observations of the values of the variables. The software component is implemented as an EXE executable file and VFP dynamic link libraries. The main calculation procedure for all elements of the representative sample, the value of the intermediate indicator is calculated, which characterizes the event, the value of the element under study, which occurred in time immediately after and before the calculated indicator. The resulting arrays of events are aggregated in order to determine the maximum values of the frequencies of the subsequent events for each element of the sample. The consolidated data is the source for predicting events occurring with the elements of the general sample. As a result of the trial operation program, a prediction accuracy of up to 75% was obtained.

The frequency prediction formula is written as

$$P(x) = \left[\max(\sum_{i=1}^{j} n_{i+1})\right] = (x_{j+1})\,. \tag{11}$$

The input information of the program is any files containing statistical samples of both one-dimension and two-dimension. In terms of one executable cycle, analysis is possible when different sample sizes account. The output information is a set of the generated analytical reports MS EXCEL.

The prediction accuracy = Maximum of (1 - Error, 0)

where Error –

$$Ошибка\ (WAPE) = \frac{\sum \left| Факт - Прогноз \right|}{\sum Факт} \cdot 100\%\,. \tag{12}$$

We will use the Weighted Absolute Percent Error (WAPE) as the main error for calculating the prediction accuracy, which is calculated by formula (12).

4. Conclusion

With the help of the methods given in the research article, it becomes possible to improve the operation and determine the failure with better accuracy.

The statistical and mathematical methods, as well as modern diagnostic tools in well-functioning work with software will improve the existing control system for the safe operating cycle of the catenary system.

Author Contributions: P.A. Bodrov carried out the theoretical research of the mathematical prediction; A.L. Bykadorov and N.A. Popova worked out the analysis of the operation of the catenary devices, Y/G/ Semenov developed the creation of a prediction algorithm. All authors have read and agreed to the published version of the manuscript.

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