

Reliability of Electro-Power Equipment Determined by Data in Its Operation and Storage [†]

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Abstract

The reliability of the electro-power equipment of electrical power transmission systems is essential in ensuring an uninterrupted power supply with the necessary voltage and frequency stability. This is especially important when performing lengthy procedures requiring the serviceability of the electrical equipment used, such as those related to foundries and metallurgical processes, or with the processes of testing complex means for the remote control of electromagnetic radiation within the implementation of the Sustainable development of the Competence Center “Quantum Communication, Intelligent Security Systems and Risk Management” (QUASAR) Project, funded with the participation of the EU under the “Research, Innovation and Digitalization for Smart Transformation” Program 2021.2027 according to procedure BG16RFPR002-1.014. One of the main issues in this case is related to the availability of information regarding the technical condition of the deployed or reserve energy resources. In this connection, this study proposes methods for determining the quantity of operational equipment that is either in use or in storage, based on the reliability testing of a representative sample of it.

Keywords: electro-power equipment; technical reliability; sample; probability of failure-free operation; probability of failure occurrence; reliability test



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1. Introduction

Ensuring an uninterrupted electro-power supply with the necessary voltage and frequency stability in conditions of the increasing requirements of industry and the mass cybernetization of society, including those related to the automation of processes in the areas of production of various products, the control of multiple processes, etc., defines the need for the continuous monitoring of the electric power equipment (hereinafter referred to as products/devices) of electrical systems and the prediction of their technical reliability [1–5] as well as in the execution of long-term, energy-intensive manufacturing or research processes, such as those in metallurgy [6–11]. This study proposes an approach for determining and predicting the technical reliability of electric power equipment of a specific type, in operating and/or storage conditions.

2. Description

For the purposes of this study, it is assumed that the object of determining and forecasting technical reliability is electrical power equipment of a specific type, located in conditions of operation and/or storage. Based on the verification of the technical parameters of individual units from a representative sample, the current condition of each technical means is determined. Those that have failed and those with parameters indicating an imminent failure are grouped together into a failure group. The probability of failure-free operation of the stored or operational products according to the technical documentation is known and equals p . It is necessary to determine the average quantity of functional electrical power equipment of the specific type that is either in operation or in storage.

We determine the sample volume with a given accuracy and an assumed probability of failure-free operation. Let us assume that as a result of checking the technical condition of n products, the number of failures is m , which includes both those that are inoperable and those on the verge of failure. The number of functional units among them is $k = n - m$. We assume that n is sufficiently large ($n \geq 20 \div 30$), while p has a considerable value, i.e., there is a presence of $np \geq 10$.

Let $P\left(\left|\frac{k}{n} - p\right| \leq \varepsilon\right)$ be the probability that the difference between the relative frequency $p^* = \frac{k}{n}$ and the probability p does not exceed in absolute value the predetermined value of the accuracy $\varepsilon > 0$. It is evident from [7,8] that

$$P\left(\left|\frac{k}{n} - p\right| \leq \varepsilon\right) = P(-n\varepsilon \leq k - np \leq n\varepsilon) = P(np - n\varepsilon \leq k \leq np + n\varepsilon).$$

Using the Laplace function [7,8], we get

$$P\left(\left|\frac{k}{n} - p\right| \leq \varepsilon\right) \approx \Phi\left(\frac{np + n\varepsilon - np}{\sqrt{npq}}\right) - \Phi\left(\frac{np - n\varepsilon - np}{\sqrt{npq}}\right) = \Phi\left(\frac{\varepsilon\sqrt{n}}{\sqrt{pq}}\right).$$

This finally results in

$$P\left(\left|\frac{k}{n} - p\right| \leq \varepsilon\right) \approx \Phi\left(\frac{\varepsilon\sqrt{n}}{\sqrt{pq}}\right).$$

Since the probability of failure-free operation of the stored or operational products is p , then $q = 1 - p$ is the probability of failure occurrence. We determine the reliability of the stored and/or operational products, represented by the frequency $p^* = \frac{k}{n}$, considering the specified accuracy ε .

Considering the symmetry of the normal distribution, the probability $P(|p^* - p| \leq \varepsilon)$ of not exceeding ε by a defined probability α is [7,8]

$$P(|p^* - p| \leq \varepsilon) = P\left(\left|\frac{k}{n} - p\right| \leq \varepsilon\right) = \Phi(u) = \alpha, \quad (1)$$

where $\Phi(u) = \frac{2}{\sqrt{2\pi}} \int_0^u e^{-\frac{t^2}{2}} dt$ is an integral Laplace function.

Considering the initial conditions, (1) takes the form of

$$P(|p^* - p| < \varepsilon) = \Phi\left(\frac{\varepsilon}{\sigma_p}\right) = \Phi\left(\frac{\varepsilon\sqrt{n}}{\sqrt{pq}}\right) = \alpha \quad (2)$$

From (2), the absolute error ε is determined by the following equation:

$$\varepsilon = u_{\alpha}\sigma_p = u_{\alpha}\sqrt{\frac{pq}{n}}. \quad (3)$$

Based on the defined error ε from the table with the values of the Laplace function, with α , we determine u_{α} [7,8]. Then, for the sample volume n , we have

$$n = \frac{u_{\alpha}^2}{\varepsilon^2} pq \quad (4)$$

For cases of testing high-reliability devices, it is recommended that as an acceptance criterion, it is assumed that the number of failures that occurred is equal to zero ($m = 0$) [9–11]. In this case, we have

$$P[m(t) \leq m_0(t)] = \sum_{i=0}^{m(t)} C_n^i q^i (1-q)^{n-i} = (1-q)^n = \gamma, \quad (5)$$

where γ is the confidence probability.

From (5), for the sample volume n , the following is obtained:

$$n = \log_{(1-q)} \gamma \quad (6)$$

In Table 1, the values of the sample size n are presented at a given confidence probability $\gamma = 0.90$ and different values of the probability of failure-free operation $p = 1 - q$.

Table 1. Sample size n at a given confidence probability and different number of failures.

p		0.90				0.99				0.999			
m		0	1	2	3	0	1	2	3	0	1	2	3
n		22	37	52	65	229	388	532	668	2301	3888	5320	6679

Let us determine the average quantity of functional units in operation or in storage. We assume that there are N units of a given product in operation or in storage. It is necessary to determine, with an accuracy of ε and a probability of α , based on a sample with a size of n , the quantity of functional units, given that according to the technical documentation, the probability of failure-free operation of one unit is p .

Under Equation (4), the volume of the sample to be tested for reliability has a volume of

$$n = \frac{u_{\alpha}^2}{\varepsilon^2} pq = \frac{u_{\alpha}^2}{\varepsilon^2} p(1-p)$$

where u_{α} is determined by the table with the values of the Laplace function by the given probability α [7,8].

After the conversion of

$$|p^* - p| = u_{\alpha}\sqrt{\frac{pq}{n}}$$

in the form

$$(p^* - p)^2 = \frac{u_{\alpha}^2}{n} p(1-p)$$

and as a result of solving the resulting quadratic equation, the following limit values p_1 and p_2 are obtained for the probability of failure-free operation p :

$$p_1 = \frac{p^* + \frac{u_\alpha^2}{2n} - u_\alpha \sqrt{\frac{u_\alpha^2}{4n^2} + \frac{p^*(1-p^*)}{n}}}{1 + \frac{u_\alpha^2}{n}} \quad (7)$$

$$p_2 = \frac{p^* + \frac{u_\alpha^2}{2n} + u_\alpha \sqrt{\frac{u_\alpha^2}{4n^2} + \frac{p^*(1-p^*)}{n}}}{1 + \frac{u_\alpha^2}{n}} \quad (8)$$

where $p^* = \frac{n-m}{n}$ and m is the number of failed devices in the control of the reliability of the sample with volume n .

Then, the number X_N of functional devices is

$$Np_1 \leq X_N \leq Np_2 \quad (9)$$

Considering (7) and (8), expression (9) is represented by the inequalities

$$X_N \geq N \frac{p^* + \frac{u_\alpha^2}{2n} - u_\alpha \sqrt{\frac{u_\alpha^2}{4n^2} + \frac{p^*(1-p^*)}{n}}}{1 + \frac{u_\alpha^2}{n}} \quad (10)$$

$$X_N \leq N \frac{p^* + \frac{u_\alpha^2}{2n} + u_\alpha \sqrt{\frac{u_\alpha^2}{4n^2} + \frac{p^*(1-p^*)}{n}}}{1 + \frac{u_\alpha^2}{n}} \quad (11)$$

In the case of highly reliable products, the determination of the quantity of functional units in storage or in operation can also be approached as follows [9–11]:

Let there be N units of a given product in storage or in operation, which is characterized by high reliability. Then, the probability of failure-free operation can be represented as [7,8]

$$p(t) = e^{-\lambda t}, \quad (12)$$

where $\lambda = \text{const}$ is the intensity occurrence of failure of a device in the process of operation or storage, and t is the duration of storage or operation.

In expression (13), after factorizing it and limiting ourselves to its first two terms, we get

$$p(t) = 1 - \lambda t \quad (13)$$

from where

$$\lambda = \frac{1 - p(t)}{t} \quad (14)$$

Expressions (13) and (14) can be considered fair with a sufficiently high degree of precision at $p(t) \geq 0.9$ and $\lambda t \leq 0.1$.

After placing in (14) the statistical estimate $p^*(t)$ defined as

$$p^*(t) = \frac{n - m(t)}{n} = 1 - \frac{m(t)}{n}$$

we obtain

$$\lambda^* = \frac{m}{nt}.$$

The denominator nt is the total operating time t_Σ ; therefore,

$$\lambda^* = \frac{m}{t_\Sigma}$$

where

$$t_{\Sigma} = mt_c + (n - m)t_c$$

as t_c is the time of storage or operation until the inspection is carried out.

The sample volume n is determined according to the approaches discussed above.

The probability of uptime for storage or operation t_c is [7,8]

$$p(t_c) = \exp(-\lambda^* t_c)$$

The mathematical expectation X_N of the quantity of functional units in operation or in storage for a given time t_c is determined as [7,8]

$$X_N = Np(t_c) = N \cdot \exp(-\lambda^* t_c). \quad (15)$$

The method described above is applicable when a sufficiently large volume of information is collected for a multitude of identical means over an extended period. This can be ensured by introducing logs for recording the failures of specific units provided for use or storage by different users.

3. Conclusions

This paper proposes an approach for calculating the mathematical expectation of the quantity of functional units in operation or in storage over a specified period. The basic information for this is the failure occurrence intensity of a single unit during operation or storage, and the proposed approach is effective for reliability characteristics of the utilized means, collected for many identical units over an extended period.

The results of this study will be used in the design and implementation of information and control systems in the process of implementation of the Sustainable development of the Competence Center “Quantum Communication, Intelligent Security Systems and Risk Management” (QUASAR) Project, funded with the participation of the EU under the “Research, Innovation and Digitalization for Smart Transformation” Program 2021.2027 according to procedure BG16RFPR002-1.014.

These results are also relevant in the planning and conduct of experiments and process studies in the field of foundry and metal science, as well as in other areas of research and production activities.

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