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MATHEMATICAL MODEL OF ELECTRICAL EQUIPMENT RELIABILITY

Ochilov Dilshod Muborakbekovich
T.f.f.d. (PhD), dotsent e-mail: ochilovdilshod131@gmail.com ORCID ID 0009-0001-8215-4657 Military Aviation Institute of the Military Security and Defense University of the Republic of Uzbekistan

Annotatsiya: *Ushbu maqolada elektr uskunalarining ishonchliligini baholash va prognozlashning matematik modellari tahlil qilinadi. Elektr energetika tizimlarida qoʻllaniladigan uskunalarning uzluksiz va xavfsiz ishlashi ularning ishonchlilik darajasiga bevosita bogʻliq boʻlib, bu koʻrsatkichlarni aniq baholash muhim ilmiy va amaliy ahamiyatga ega. Tadqiqotda ishonchlilik nazariyasining asosiy koʻrsatkichlari, jumladan, nosozlik ehtimoli, ishonchli ishlash ehtimoli, nosozliklar intensivligi hamda oʻrtacha xizmat muddati matematik jihatdan ifodalanadi. Elektr uskunalarining ishlash jarayonida yuzaga keladigan tasodifiy nosozliklar ehtimollar nazariyasi va statistik usullar asosida modellashtiriladi. Shuningdek, eksponensial va Veybull taqsimotlari yordamida uskunalarning ishonchlilik parametrlari aniqlanib, ularning amaliy qoʻllanish imkoniyatlari koʻrib chiqiladi. Tadqiqot natijalari elektr uskunalarining texnik holatini baholash, profilaktik xizmat koʻrsatish muddatlarini optimallashtirish hamda ekspluatatsiya xarajatlarini kamaytirishga xizmat qiladi. Taklif etilgan matematik model elektr energetika obyektlarida uskunalarning ishonchli ishlashini ta’minlaydi.*

Kalit soʻzlar: *elektr uskunalar, ishonchlilik, matematik model, nosozlik ehtimoli, ishonchli ishlash ehtimoli, Veybull taqsimoti, eksponensial taqsimot, nosozlik intensivligi, texnik diagnostika, elektr energetika tizimi.*

Аннотация: *В данной статье анализируются математические модели для оценки и прогнозирования надежности электрооборудования. Непрерывная и безопасная эксплуатация оборудования, используемого в энергосистемах, напрямую связана с его надежностью, а точная оценка этих показателей имеет большое научное и практическое значение. В исследовании математически выражены основные показатели теории надежности, включая вероятность отказа, вероятность надежной работы, интенсивность отказов и средний срок службы. Случайные отказы, возникающие в процессе эксплуатации электрооборудования, моделируются на основе теории вероятностей и статистических методов. Также с использованием экспоненциального и распределения Вейбулла определены параметры надежности оборудования и рассмотрено их практическое применение. Результаты исследования служат для оценки технического состояния электрооборудования, оптимизации периодов профилактического обслуживания и снижения эксплуатационных расходов. Предложенная математическая модель обеспечивает надежную работу оборудования на энергообъектах.*

Ключевые слова: *Электрооборудование, надежность, математическая модель, вероятность отказа, вероятность надежной работы, распределение Вейбулла, экспоненциальное распределение, интенсивность отказов, техническая диагностика, электроэнергетическая система.*

Abstract: *This article analyzes mathematical models for assessing and forecasting the reliability of electrical equipment. The continuous and safe operation of equipment used in power systems is directly related to their reliability, and accurate assessment of these indicators is of great scientific and practical importance. The study mathematically expresses the main indicators of reliability theory, including the probability of failure, the probability of reliable operation, the intensity of failures, and the average service life. Random failures that occur during the operation of electrical equipment are modeled based on probability theory and statistical methods. Also, using exponential and Weibull distributions, the reliability parameters of equipment are determined and their practical application is considered. The results of the study serve to assess the technical condition of electrical equipment, optimize preventive maintenance periods, and reduce operating costs. The proposed mathematical model ensures reliable operation of equipment at power facilities.*

Keywords: *electrical equipment, reliability, mathematical model, failure probability, probability of reliable operation, Weibull distribution, exponential distribution, failure intensity, technical diagnostics, electric power system.*

Determining the reliability of electrical equipment is a complex process, and in order to determine it at a high level, it is necessary to conduct research on one or more electrical equipment elements for a certain period of time. Determining reliability can cause certain difficulties in the conditions of water management enterprises.

Therefore, in order to speed up this process and increase the level of accuracy, reliability improvement studies are conducted using mathematical modeling. Using mathematical models, the quantitative relationship between the reliability criteria being studied (objective functions) and other important factors (independent variables) describes the real process with a high level of accuracy.

When building a model, the problem is solved through a certain idealization. Of the total reliability parameters of electrical equipment, only the necessary one was selected for the study. Thus, the model is a simplified representation of a specific object or process, reflecting its most important characteristics [1].

Two types of models are used to calculate reliability indicators: reliability and failure model. The simplest failure model is a failure model, which is a mathematical description of the reliability determination process. In most cases, a failed device is repaired and it is possible to restore the operability of electrical equipment without the use of spare parts.

Bringing electrical equipment to a working state does not completely eliminate the possibility of its failure. However, it significantly reduces the probability of failure and increases reliability.

The general mathematical description of this process is called a reliability model. The most common in reliability theory are failure models based on the use of probability theory and the laws of mathematical statistics, with the help of which they establish relationships between the probability of a certain state of elements and the events and conditions of the system.

If the probability of any future state of the system for each second of time depends only on the current state of the system and does not depend on how the system arrived at this state, then such a process is called a Markov process (or a flow without consequences). Such processes are characteristic of elements with constant failures.

Recovery $\lambda_i = const,\quad \mu_i = const$ (i.e., with an exponential law of the time distribution between failures and recovery times). Failure model of non-repairable electrical equipment.

Some types of electrical equipment, parts and low-voltage power transmission devices in power supply systems can be considered as non-repairable elements, the cost of repairing which is comparable to the cost of a new element. Let us consider the simplest case in which a sudden failure of electrical equipment can occur.

This is the operating and non-operating state of electrical equipment. The transition from the operating state to the non-operating state is determined by the intensity of the failures λ and is not possible to return [3; 4].

The probability of failure-free operation and the probability of failure during the transition are expressed by the differential equations:

$$\frac{dP}{dt} = -\lambda P(t); \qquad \frac{dQ}{dt} = -\lambda P(t); \qquad (1)$$

in this $P(t)$ – probability of trouble-free operation, $Q(t)$ – possibility of breakdown. $P(0) = 1$ and $Q(0) = 0$ The solution to the differential equations under initial conditions will take the following form:

$$P(t) = \exp(-\lambda t); \qquad Q(t) = [1 - \exp(-\lambda t)]. \qquad (2)$$

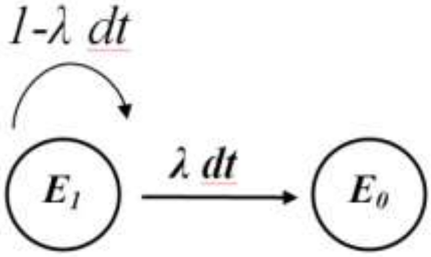

Figure 1. Reliability model for sudden failure of a non-recoverable element

If the intensity of the failures $\lambda = 0{,}0005$ 1/year if accepted, $m = 6$ for a year 0,4 kV To determine the probability of failure-free operation and the probability of breakdown of a high-voltage electromagnetic contactor, we use formula (2) above: $P(6)=\exp(-\lambda t)=\exp(-0{,}005\cdot 6)=0{,}997$; $Q(6)=1-\exp(-\lambda t)=1-\exp(-0{,}0005\cdot 6)=0{,}003$.

If gradual failures occur in an element, they $E_1, E_2,...E_N$ represented by a set of conditions in which the system gradually approaches a state of obsolescence, N At this stage, the element wears out completely and a malfunction occurs. [2; 5].

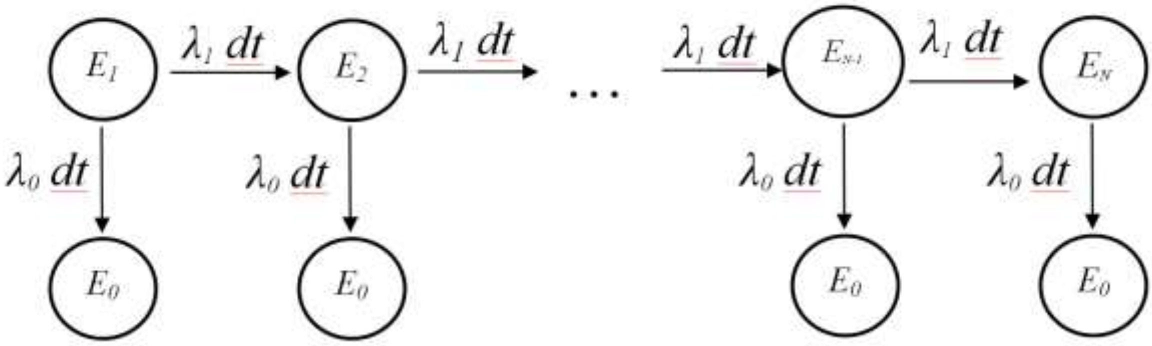

Figure 2. Reliability model of a system that is not subject to uniform wear and tear

When determining the instantaneous parameter of the flow of influences, the wear element $1/N$ part λ_1 is taken to be equal to:

$$\lambda_1=\lim_{\Delta t\to 0}\frac{P_1(t,t+\Delta t)}{\Delta t}, \qquad (3)$$

in this $P_1(t,t+\Delta t)$ – probability of passing once. In addition to the gradual wear and tear on the system, the intensity λ_0 Random failures can also be observed. As a result, each k - The differential transition equations for the case will have the following form:

$$\frac{dP_k}{dt}=-(\lambda_0+\lambda_1)P_k(t)+\lambda_1 P_{k-1}(t);$$
$$\frac{dP_N}{dt}=-(\lambda_0+\lambda_1)P_N(t); \qquad (4)$$

If the system performance $E_1, E_2,...E_N$ If we consider the sum of the states, then the probability of continuous operation is equal to:

$$P(t)=\sum_{k=1}^{N}P_k(t), \qquad (5)$$

$$\frac{dP}{dt}=\sum_{k=1}^{N}\frac{dP_k}{dt}=-\lambda_1 P_1(t)-\lambda_0\sum_{k=1}^{N}P_k(t)=-\lambda_1 P_1(t)-\lambda_0 P(t). \qquad (6)$$

$P(0)=1$ va $P_k(0)=0$ Under initial conditions, equation (6) has the following form:

$$P(t)=\exp(-\lambda_0 t)\left[1-\int\exp(-\lambda_1 t)\cdot\frac{(-\lambda_1 t)^{N-1}}{(N-1)!}dt\right]=1-\Phi\left(\frac{1-T_0}{T_0\sqrt{n}}\right); \qquad (7)$$

A general conclusion is made on the repair of a low-oil circuit breaker after 6 years of continuous operation or after 2000 switching cycles. After 4 years after the installation of the circuit breaker, if it has completed 200 switching cycles at the same time, the probability of its failure is determined. According to the data provided, the switching intensity of the circuit breaker (intensity of sudden failure) is:

$$\lambda_0 = \frac{200}{4 \cdot 2000} = 0{,}025 \ \ year^{-1}$$

Intensity of gradual deterioration:

$$\lambda_0 = \frac{1}{6} = 0{,}167 \ \ year^{-1}$$

According to the formula, the probability of working continuously for 4 years is equal to:

$$P(4) = \exp(-\lambda_0 t)\left[1 - \int_0^t \exp(-\lambda_1 t) \cdot \frac{(-\lambda_1 t)^{N-1}}{(N-1)!} dt\right] =$$

$$= \exp(-0{,}025 \cdot 4)\left[1 - \int_0^6 \exp(-0{,}167 \cdot 4) \cdot \frac{(-0{,}167 \cdot 4)^{6-1}}{(6-1)!} dt\right] = 0{,}864$$

Reliability model of renewable electrical equipment. Renewable elements of electrical equipment are considered as a complex case. The complexity lies in the fact that their reliability depends on the speed of creating a spare part stock and the speed of its restoration. Analysis of the simplest case shows that an element without a spare part can be in two states: E_1 – fit for work and E_0 – unusable. Fault current parameter of the recoverable system ω is equal to and the intensity of regeneration is $\mu (\mu = 1/\tau)$ If so, then the transition from one state to another can be represented graphically [6].

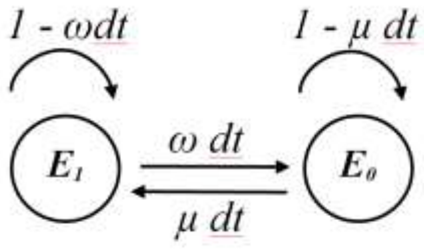

Figure 3. Reliability model of the simplest renewable system

Differential equations for transition probability:

$$\frac{dP_1}{dt} = -\omega P_1(t) + \mu P_0(t);$$
$$\frac{dP_0}{dt} = \omega P_1(t) - \mu P_0(t); \qquad (8)$$

in this $P_1(t)$ – of the equipment E_1 probability of occurrence, $P_0(t)$ – equipment E_0 probability of finding in the situation. $P_1(0) = 1$, $P_0(0) = 0$ in the initial conditions and E_1 va E_0 Considering the state, the state of the equipment represents complete groups of events, i.e. $P_0(t) + P_1(t) = 1$ (8) the differential equation will take the following form:

$$P_1(t) = \frac{\mu}{\omega + \mu}\left(1 + \frac{\omega}{\mu} \cdot \exp[-t(\omega + \mu)]\right); \qquad (9)$$

$$P_0(t) = \frac{\omega}{\omega + \mu}\left(1 - \exp[-t(\omega + \mu)]\right). \qquad (10)$$

Let us consider some special cases arising from expressions (9) and (10):

a) instantaneous automatic recovery $(\omega / \mu = 0)$ $P_1(t) = 1$, that is, at any arbitrary moment in time, the element is considered completely operational;

b) when recovery does not occur $(\omega / \mu = \infty)$: $P_1(t) = \exp(-\omega t) = \exp(-\lambda t)$, that is E_1 The probability of the state is equal to the probability of continuous (failure-free) operation;

v) big enough $t(t \to \infty)$ for $P_1(t)$ The probability does not depend on time (see Figure 4).

$$P_1(\infty) = \frac{\mu}{\omega + \mu} = \frac{t_P}{t_P + t_\Pi} = k_\Gamma. \qquad (11)$$

It is clear from expression (11) above that, $P_1(\infty)$ The value of is equal to the readiness coefficient. Therefore, the probability of failure-free operation of an electrical equipment element without a backup does not increase, and restoration only increases reliability from the point of view of readiness [8].

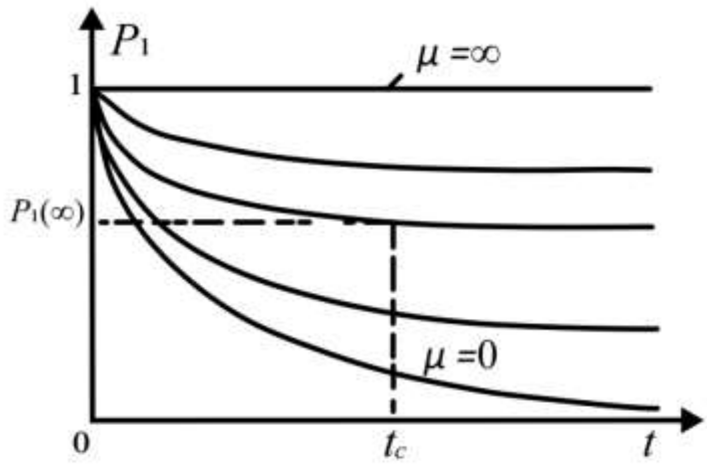

Figure 4. Graph of the relationship between the probability of a serviceable state and different recovery intensities over time

For two different options $t = 5$ during the year We determine the probability of a 10 kV cable network operating without failures: a) average recovery time $\tau = 24$ hour; b) the network is not restored. According to the fault flow parameter spravochnik $\omega = 0{,}20$ $year^{-1}$. We determine the recovery intensity over a given time period using the following formula:

$$\mu = \frac{1}{T_B} = \frac{8760}{24} = 365 \frac{1}{йил}$$

The probability of failure-free operation for the first option is determined by the formula (9):

$$P_a(5)=\frac{\mu}{\omega+\mu}\left(1+\frac{\omega}{\mu}\cdot\exp\left[-t(\omega+\mu)\right]\right) =$$

$$=\frac{365}{0,2+365}\left(1+\frac{0,2}{365}\cdot\exp\left[-5(0,2+365)\right]\right)=0,9995.$$

For the second option, we use a simpler formula: $P_б(5)=\exp(-\omega t)=\exp(-0,2\cdot 5)=0,368$.

Thus, the lack of restoration under given conditions reduces the reliability of electricity supply to consumers by 60%. Studies show that the mathematical model of electrical equipment reliability, the failure model of non-restored electrical equipment, and the reliability model of these regenerative electrical equipment paragraphs require a systematic approach to the problem of predicting the repair or replacement of spare parts. Ensuring the reliability of electrical equipment is closely related to the problem of predicting the repair or replacement of spare parts.

A systematic approach to predicting the repair or replacement of spare parts involves making decisions based on the condition and availability of spare parts to ensure the reliability and efficient operation of electrical equipment or systems.

The specific sequence of implementing such predictions may vary depending on factors such as the type of equipment, maintenance or repair practices, and objectives. A systematic approach to predicting the need for repair or replacement of spare parts is presented in the following sequence:

1. Data collection: Historical and real-time data about the electrical equipment is collected, including maintenance or repair and operation history. Data sources can include monitoring and control, maintenance logs, and inspection reports.

2. Condition assessment: The current condition of the equipment is assessed using the following methods: a) Visual inspection: Visible wear, damage, or deterioration is identified. b) Fault testing: Methods such as ultrasonic inspection, thermal imaging, and vibration analysis are used to identify hidden problems. c) Oil analysis: The condition of lubricants is checked to detect contamination or excessive wear. d) Electrical and electronic testing: Electrical parameters are measured to assess the integrity of components.

3. Failure Mode and Effect Analysis: The causes of potential failures and their consequences for the operation and safety of electrical equipment are analyzed. A criticality rating is assigned to each failure mode based on its impact.

4. Spare Parts Inventory Assessment: The availability of spare parts in the inventory is reviewed. Factors such as purchase dates, storage conditions, and part costs are determined.

5. Data Analysis: Data analysis and machine learning techniques are used to process and analyze electrical equipment condition, maintenance, and repair data. Conditions, trends, and anomalies that may lead to potential failures are identified.

6. Predictive Maintenance Models: Predictive maintenance models that take into account condition data and other factors are developed or implemented to predict

electrical equipment failure. These models include: a) Time-based maintenance: Scheduling repairs or replacing parts at predetermined intervals. b) Condition-based maintenance: Maintenance or replacement is performed based on a real-world situation. c) Predictive maintenance: Innovative analytics are used to predict when a failure will occur.

7. Decision-making: Based on predictive maintenance models, decisions are made to repair or replace parts. Factors such as the criticality of the electrical equipment, the severity of potential failures, and the cost-effectiveness of replacement are considered.

8. Scheduling: Based on the decision, the repair or replacement activities are planned. This includes purchasing parts and allocating resources.

9. Execution: Based on the decisions, the planned maintenance and repair or replacement are carried out. This is done by following established procedures and safety protocols.

10. Post-service inspection: After a part is repaired or replaced, the equipment is checked to ensure it is back in optimal working condition. Tests and inspections are performed to ensure proper operation.

11. Continuous monitoring: The condition of the equipment and the effectiveness of maintenance decisions are continuously monitored. Predictive maintenance models and parts management strategies are updated based on new data and insights.

12. Documentation and reporting: All maintenance and replacement activities, including the reasons for the decisions and results, are documented. They are retained for audit and future reference.

13. Continuous improvement: The process of repairing or replacing parts is regularly observed, monitored, and opportunities for improvement are sought.

14. Performance evaluation: The performance of predictive maintenance models is reviewed and reported by maintenance teams.

This sequence provides a systematic approach to making informed decisions about the repair or replacement of parts. The focus is on optimizing equipment reliability and reducing downtime. The specific steps and criteria may vary depending on the equipment, industry, and organizational requirements.

In conclusion, by dividing electrical equipment parts into conditionally repairable and non-repairable types, it was determined that the reliability of electrical equipment depends on various random factors, and it was possible to take into account all factors affecting reliability and track changes in reliability over time until the system is put into operation.

In order to make decisions about the repair or replacement of electrical equipment parts and ensure reliable and efficient operation of electrical equipment, a systematic approach to predicting the repair or replacement of parts was developed.

The probability of random failures over time, which takes into account the probability of failures of electrical equipment parts, was determined.

In order to prevent long-term downtime of electric motors in the event of a failure, a reliability model of single- and multiple-reserve backups was developed.

A method and algorithm for creating a reliable spare parts reserve were created in order to implement a systematic approach to ensuring the availability of spare parts necessary for maintenance and repair or to eliminate unexpected equipment failures.

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