ON THE ISSUE OF PREDICTING THE REMAINING SERVICE LIFE OF NUCLEAR POWER PLANT ELECTRICAL EQUIPMENT

Summary. This article addresses the issues related to the assessment and prediction of residual life of power plant equipment, taking into account the wear rate of its main components. Theoretical aspects arising during probabilistic calculations for predicting the residual life of three-phase induction motors are investigated. The study assumes that the prediction of residual life is based on determining its minimum estimate through calculation. A comparison is made between the minimum estimate result and the normative permissible level of wear of the investigated objects. The authors propose using a probabilistic-physical approach to objectively assess the technical condition and predict the residual life of this technical equipment. Within this approach, a probabilistic model based on the application of the diffusion-monotonic distribution for failures is considered for assessing longevity. The parameters of the model used have a physical interpretation. The key parameters taken into account are the average rate of change of the determining parameter, namely the insulation absorption coefficient and its resistance, as well as the coefficients of variation of selected degradation processes, assuming the possibility of their measurement or the use of prior estimation for the variation coefficient of processes. The article presents criteria for assessing the residual life of the investigated objects, which allows reducing operational costs by increasing the maintenance intervals and establishing the actual service life of the motors.

Keywords: probabilistic-physical approach, residual life, probabilistic-physical model of reliability.

DO ПИТАННЯ ПРО ПРОГНОЗУВАННЯ ЗАЛИШКОВОГО РЕСУРСУ ЕЛЕКТРООБЛАДНАННЯ АЕС

Анотація. Стаття присвячена вирішенню питань, пов’язаних із проведенням оцінки та прогнозування залишкового ресурсу електроустаткування атомних електростанцій з урахуванням швидкості зношування його основних деталей. У статті досліджено теоретичні питання, що виникають під час проведення ймовірнісних розрахунків при прогнозуванні залишкового ресурсу асинхронних трьохфазних двигунів змінного струму. В роботі приймається допущення, що прогнозування залишкового ресурсу базується на визначенні розрахунковим шляхом його мінімальної оцінки. Проводиться порівняння результату мінімальної оцінки з нормативним допустимим рівнем зносу досліджуваних об’єктів. В статті авторами запропоновано для виконання оцінки об’єктивного технічного стану та виконання прогнозування залишкового ресурсу цього технічного обладнання, використовувати ймовірнісно-фізичний підхід.

Ключові слова: ймовірнісно-фізичний підхід, залишковий ресурс, ймовірнісно-фізична модель надійності, процеси деградації.

F Formulation of the problem. The reliability of electrical equipment is one of the most important aspects of safety in nuclear power plants (NPPs). Electrical systems are used in various executive and control systems in NPPs, such as ensuring reactor safety and emergency cooling. In this regard, the reliability of electrical systems and equipment is of paramount importance in ensuring the safety of nuclear energy as a whole.

Another important aspect of the reliability of electrical equipment is its ability to withstand various types of external influences, such as interference, overloads, and short circuits. In this regard, the reliability and durability of electrical systems and equipment must meet safety requirements.

One of the main executive devices of electrical systems is electric motors, and this article focuses primarily on assessing their residual life. The widespread use of electric motors in nuclear power plants (NPPs) is due to their ability to operate under high temperatures and radiation exposure. However, similar to other equipment in NPPs, elec-
Analysis of recent research and publications. One of the key challenges in determining the residual life of nuclear power plant motors is the complexity of accounting for multiple factors that affect the durability and reliability of motors under extreme conditions of high temperature and radiation. These factors include mechanical loads, wear of components, corrosion of metallic surfaces, radiation effects, lubrication quality, and others. Considering that the residual life of motors can significantly differ even under identical operating conditions [1], depending on the manufacturer, design features, and materials used, reliable methods for analyzing durability are necessary, taking into account all factors that influence the operation of nuclear power plant motors.

The complexity of predicting the residual life of equipment that has already exceeded its designated project lifespan is primarily associated with the choice of a mathematical prediction model. The selected model should be supported by a rationale based on the knowledge of the physical properties and degradation processes of the equipment over time, while also considering the stochastic nature of these processes. In many studies and references in particular authors Thomson W.T., Bardik E.I. [2; 3], exponential distribution is often recommended, but it does not accurately describe the random nature of failure distributions, leading to distorted results.

In recent times, with the development of computational software tools, methods based on neural networks are finding increasing applications. This approach is highly demanding because training models requires large annotated datasets. Consequently, the resulting diagnostic models have a narrow focus.

Purpose of the article. To solve the stated problem, a probabilistic-physical approach is proposed for assessing resource, based on the use of a specially developed model of diffusion-monotonic distribution of random variables (DM-distributions) for electromechanical objects [4]. The parameters of this model have a physical interpretation, representing the average rate of change of the determining parameter (stochastic criterion) and the coefficient of variation of the generalized degradation process. The model assumes that the degradation processes occurring are independent, irreversible, and monotonic, with a constant average rate. Furthermore, it is assumed that the influence of multiple degradation processes is taken into account, which significantly affects the accuracy of the estimation [5].

Probabilistic-physical method. Within the framework of the probabilistic-physical method for predicting the residual life of objects [4], it is assumed that there is a possibility for periodic measurement of the resource-defining parameter $\phi(t)$, at the same time, its limit value is set $\phi(t) = \Pi_{lim}$.

During the operation of the facility, measurements of the determining parameter are carried out after a certain period of time $\Delta t$, resulting in a series of resource values $\phi(t)$ for certain operating times:

\[ \phi(t) = \phi(t_{n-1} + \Delta t); \]

\[ \phi(t_{n}) = \phi(t_{1} + \Delta t). \]

Note 1 In the following discussion, it is assumed that the values of the determining parameter increase in the course of operation through the same $\Delta t$, although it is not difficult to convert the calculations to (1) and in the case of its decrease and through different $\Delta t$.

In the general case, according to the measurement data, the average rate of change of the determining parameter is calculated by one of the known methods, for example, by the formula:

\[ a = \frac{1}{\Delta t \cdot n} \sum_{i=1}^{n} (\phi(t_{i+1}) - \phi(t_{i})) = \frac{1}{\Delta t \cdot n} \sum_{i} \Delta \phi_{i}. \]

(1)

Note 2 Roughly, the rate of change of the determining parameter can also be determined from two measurement points from the beginning of operation at $t_{0} = 0$ and at the time of the first measurement of the defining parameter at $t_{1}$, in this case $\Delta t_{1} = t_{1} - t_{0}$, $\Delta \phi_{1} = \phi(t_{1}) - \phi(t_{0})$ and $n = 1$.

As mentioned above, we adopt the DM-distribution as a theoretical reliability model, since failures are irreversible and degradation processes are monotonic.

We will use the parametric form of the DM-distribution, as presented in [4; 6]:

\[ F(t) = DM(t; a, v) = \Phi \left( \frac{at + \Pi_{0} - \Pi_{1}}{\sqrt{av} \Pi_{0} - \Pi_{1}} \right) \]

(2)

where $a$ – average rate of change of the determining parameter;

$\Pi_{0}$ – initial measured value of the determining parameter;

$\Pi_{1}$ – maximum measured value of the determining parameter;

$v$ – coefficient of variation of the degradation process.

If the defining parameter of the product changes monotonously, then the average residual life is calculated by the formula:

\[ \bar{\Pi} = \frac{\Pi_{lim} - \Pi_{i}}{\alpha} \left( 1 + \frac{v^2}{2} \right), \]

(3)

where $\Pi_{lim}$ – limit value of the determining parameter (validity criterion.)

$\Pi_{i}$ – the current value of the defining parameter.

If, as a result of research, several types of degradation processes are established (for example, two), then it is necessary to calculate the residual resources $\bar{\Pi}_{1}, \bar{\Pi}_{2}$ for each of the considered degradation processes. In this case, the resulting estimate of the residual resource is as follows:

\[ \bar{\Pi} = \frac{1}{\sqrt{\bar{\Pi}_{1}} + \sqrt{\bar{\Pi}_{2}}}, \]

(4)

Estimation of the residual life of an induction motor. As an example, let’s calculate the remaining resource of the engine 6 kW of pump unit in power unit No. 1 of Zaporizhzhia Nuclear Power Plant [7]. The absorption coefficient of the winding insulation is taken as the main degradation processes $R_{i0}$ (Dielectric Absorption Ratio) and winding insulation resistance value ($R_{i0}$), for which statistics of measurement results are available for the period of operation from 1983 to 2008 years.
Absorption coefficient values \((K_{\text{dar}})\) for windings C1-C4, C2-C5, C3-C6  

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Winding insulation resistance values \((R_{\text{res}})\) for the period of operation for windings C1, C2, C3 (MOhm)  

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Limit state criterion (limiting normative value \(\Pi_{\text{lim}}\)) [8]:  
- for absorption coefficient \(K_{\text{dar}} = 0.8\);  
- for winding insulation resistance \(R_{\text{res}} = 30\) MOhm.

Let us calculate the average rate of change of the determining parameter for the minimum measurement values \((\min)\) for different durations of observation periods:

\[
a = \frac{1}{n} \sum_{i=1}^{n} \frac{\Delta \phi_i}{\Delta t_i},
\]

where \(n\) – number of registration periods of the defining parameter \((n = 6)\);
\(\Delta t_i\) – duration of the observation period.

The total duration of observation is \(\Delta t = 25\) years.

\[
\Delta \phi_1 = 3.57 - 3.07 = 0.5; \\
\Delta \phi_2 = 3.07 - 2.8 = 0.9; \\
\Delta \phi_3 = 2.8 - 2.6 = 0.2; \\
\Delta \phi_4 = 2.6 - 2.5 = 0.1; \\
\Delta \phi_5 = 2.5 - 2.3 = 0.2; \\
\Delta \phi_6 = 2.3 - 2.3 = 0; \\
\sum_{i=1}^{6} \frac{\Delta \phi_i}{\Delta t_i} = 0.43; \\
\Delta t_i = \frac{1}{6} \times 0.43 = 0.0716 \text{ (years)}.
\]

According to the recommendations [6], we choose a priori values of the coefficients of variation for degradation processes (electrical wear):

\(v_{\text{dar}} = 1.1\); \(v_{\text{ac}} = 1.1\).

Let us calculate the value of the resulting residual resource after the entire measurement cycle of 25 years has elapsed:

\[
\bar{\pi} = \frac{\Pi_{\text{lim}} - \Pi_{\text{lim}}}{\alpha} \left(1 + \frac{v^2}{2}\right).
\]

Since degradation processes have determining parameters decreasing in time, therefore, the limiting value will always be less than the current one. In this case, the formula for calculating the residual resource will take the form:

\[
\bar{\pi} = \frac{\Pi_{\text{lim}} - \Pi_{\text{lim}}}{\alpha} \left(1 + \frac{v^2}{2}\right).
\]

Based on the residual resources for different degradation processes, we determine the resulting residual resource of an induction motor by the formula (4) for \(\bar{\pi}_{\text{1}} = 22.54\) years; \(\bar{\pi}_{\text{2}} = 17.15\) years:

\[
\bar{\pi} = \frac{1}{\sqrt{\frac{1}{\bar{\pi}_{\text{1}}} + \frac{1}{\bar{\pi}_{\text{2}}}}} = \frac{1}{\sqrt{\frac{1}{22.54^2} + \frac{1}{17.15^2}}} = 13.8\text{years}.
\]

Thus, the full resource of the electric motor is:

\[
\bar{\pi} + \Delta t = 25 + 13.8 = 38.8\text{ years}.
\]

**Conclusions.** An example of an engineering method for calculating the value of the residual life for three-phase asynchronous AC motors is considered. For the first time, the proposed method makes it possible to take into account the influence of two degradation processes occurring simultaneously. Further development of the method will make it possible to take into account an unlimited number of degradation processes occurring simultaneously, taking into account the share participation of each of the processes in the generalized process of object degradation.

The results of calculations of the residual and total resources are commensurate with the allowable service life [8] for engines of this type, which fully confirms the validity of the above calculations.
References: