Application of statistical methods in the diagnosis of electric plastic insulating materials used in electric machines

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Abstract

As we know, the use of electricity is one of the most important issues today. The requirements set in this regard are related to the reliability, physical characteristics and cost of various types of electrical machines and devices. These listed requirements depend fundamentally on the materials used in their preparation and their technical resources. It is shown in the work that in the production of Electric machines (EM), mainly, the test-diagnostic method is used, and in their operation, both functional (in working mode) and test (after repair) diagnostic methods are used. "Destructive" methods are accepted as the most reliable and correct method during test-diagnostics.

The article examines the shortcomings of "destructive" methods. It was mainly shown that the majority of punctures in plastic insulation materials occurred during handover tests. This, in turn, is due to the excessively high selection of the test voltage.

The specified procedures of the isolation system allow to predict their reliability. In the article, as a result of testing a limited number of samples (selection tests), the issues of statistical control of the quality of the object were investigated and some mathematical models were given for stationary states of the controlled parameter.

Keywords: *electric machines (EM), plastic insulation, statistical control, turbogenerator, technical resources, test test-diagnostics.*

Introduction

An electrical insulating material is a material in which electric current does not flow freely. Electrical insulating materials are referred to as substances with high resistance to electric current, and in this regard, they are used to keep the current in a suitable path within the conductor[1,2]. The insulating material used in bulk to wrap electrical cables or other equipment is called insulation.

Reliability and safety of various types of constructions, machines and devices fundamentally depends on the quality and technical resources of the materials and structural elements used in their preparation. International standards (ISO 9000-ISO 9004, ISO 8402, etc.) emphasize the reliability, safety and resources of industrial and household machines and equipment [3,4], increasing the relevance of the problem of quality control and diagnostics of materials and structural elements.

In general, the following parameters and characteristics are recommended to be evaluated and noted in the standards: temperature, pressure and degree of compression, leakage of the working medium; current intensity and voltage; resistance, input and output power; torque and speed; noise and vibration; oil pressure and consumption; tirbological properties of oil; useful work factor. These parameters and characteristics characterize the operational reliability and safety of a specific facility, along with the quality and efficiency indicators. So, in many cases, operating costs can reach a level that can be compared with the income obtained from the application of the facility. For example, operating costs in energy and petrochemical industries, in transport can make up (15-18)% of the cost [3]. Therefore, technical diagnostics and quality forecasting of industrial machinery and equipment have traditionally always attracted attention [4]. In the market economy, this problem manifests itself more prominently [5].

The above-mentioned problems are more urgent and complex in the electrical engineering industry, whose products and products are in massive demand by most sectors of the economy, as well as by households, one of the priority areas of modern industry [6-7].

It is known that electrotechnical industrial production is material intensive (electrotechnical steel, copper, aluminum, cast iron, insulating materials, absorbents, etc.) and labor intensive [7]. The quality and efficiency indicators of manufactured goods and products depend on the physical properties of these materials, their reliability, and their ability to maintain working resources under extreme conditions (high voltages, currents, electromagnetic fields, etc.).

In the production of electric machines (EM), mainly, the test test-diagnostic method is used, and in their operation, both functional (in working mode) and test (after repair) diagnostic methods are used.

"Destructive" methods are accepted as the most reliable and correct method during test-diagnostics. However, these methods have the following disadvantages [8,9]:

- additional technical and economic costs for the repair (restoration) of the destroyed junction;
- unique or small series of complex equipment (nuclear energy, rocket and space equipment, etc.).

As an example of the above, the information given in the article [10] attracts attention (see the table).

Table 1. Statistical information on the perforation of the insulation of the stator windings of turbogenerators

The reason for the puncture	Power, MVt/voltage, kV	To make a hole arrival conditions
Released during production technological errors	200/15,75	during operation
	320/20	during testing
	60/10,5	during testing
	500/20	during testing
	800/24	during testing
	12/10,5	during testing
	50/10,5	during testing
	12/10,5	during operation
	60/10,5	during testing
	100/10,5	during testing
As a result of poor repair	320/20	during testing
	30/10,5	during operation
	30/10,5	during operation
	120/10,5	during testing

As a result of the analysis of the relevant statistical data, the following basic requirements are imposed on it in order to increase the strength of the insulation of the stator windings of turbogenerators [10]:

- reducing the thickness of insulation in order to improve monolithicity and thermal conductivity;
- increasing mechanical and static strength during bending and twisting;

- increasing the electrical strength in order to reach the limit of the static test voltage of the loop to 2, 5 U_{nom}.

The technical condition of the stator core in turbogenerators (weakness in pressing) also leads to an irreversible loss of their working capacity [11].

As can be seen from the table, most of the punctures, both after production and after repair, occurred during the handover tests. This, in turn, is due to the excessively high selection of the test voltage. For example, IEEE standards require that the test voltage be selected R = 3,76 times greater than the operating voltage [12].

In terms of evaluating both efficiency and quality indicators, as well as technical conditions of alternating current EM, their following nodes are of great importance [13]:

- winding of the stator;
- iron of the stator;
- rotor winding
- cushion joints

The reliability of the EM depends significantly on the reliability of the windings (stator and rotor). The reliability of the windings is determined by the technical condition of the windings themselves and their insulation.Belə ki, əksər (85-95)% hallarda gücü 5 kVt həddini aşan asinxron mühərriklərin işdən çıxması dolaqlar arasında qısa qapanmalar (93 %), fazlararası izolyasiyanın (5 %) və paz izolyasiyasının (2 %) deşilmələri səbəbindən baş verir. Thus, in most (85-95)% of cases, failure of asynchronous motors with a power exceeding 5 kVt occurs due to short circuits between windings (93%), interphase insulation (5%) and wedge insulation (2%) punctures. The most "elegant" node of synchronous motors is the stator. Failures due to stator winding insulation puncture (mainly the wedge part of the winding) account for 50% [14]. For high-power EM, the strength (endurance) of the body insulation is also important.

In order to reduce costs caused by destructive tests, it is necessary to switch from handover tests of each manufactured product to selection tests of a limited number of samples. However, at this time, ensuring the validity of test-diagnostic decisions should be prioritized. For this purpose, the statistical processing of the information obtained during the test-diagnosis is considered the most effective method.

One of the modern approaches to solving the above-mentioned problem is the creation of an automated design and management system of test-diagnostic processes. The creation of such a system should, first of all, be aimed at ensuring high accuracy of test-diagnostic results. For this purpose, the following functions should be automated within the system [15]:

- test-diagnostic procedures;
- processing of test-diagnostic results;
- dynamic registration and analysis of the processes occurring in the facility during testing and diagnostics;
- placement and use of similar test-diagnostic protocols and materials in a constantly updated database in other enterprises (even in foreign countries) through the information exchange network;
- giving the necessary recommendations to design institutions.

Based on a statistical approach to the electrical aging of the insulation of the dtator in high-voltage EM, it was estimated that the minimum period of maintenance of the predicted working capacity of the insulation meeting the test conditions defined in the IEEE standards exceeds the actual service life of the machine by at least one order. This effect is explained by the fact that the ratio of test and working (phase) voltages in IEEE standards is R = 3.76. But to ensure a "reasonable" minimum service life (30 years until the first puncture), it is enough to take R = 3 [16,20].

In the article [17], the issue of classification of the degree of wear of the insulation of EM coils according to the results of DC tests was considered. For this purpose, the following diagnostic operations are recommended:

- Extraction of the $R_{60}=f(U)$ characteristic under the condition of changing the voltage in the range (0 ÷ 2)U_N (where R_{60} is the insulation resistance 60 seconds after applying the voltage; U_N is the nominal voltage);
- recording the change process of the leakage current $i_s(t)$ (after the sudden application of the voltage $U_0 \geq U_N$);
- recording $U_b(t)$ of the voltage recovery process of the isolation system (voltage $U_0 \geq U_N$ is applied to the isolated current-carrying parts, the power source is opened at the moment of current settlement, those parts are short-circuited, and then disconnected).

It should be noted that the first two tests provide guidelines for periodic testing of EM insulation.

According to the measurement results, the following parameters and characteristics of the insulation system are evaluated:

- Resistance R_{60} corresponding to U_N voltage ($R_{60} = f(U)$based on dependence);
- breakdown voltage U_d (by extrapolation of $R_{60} = f(U)$ dependence);
- recovery time t_b and the minimum value of recovery voltage U_{bmin} (based on the diagram of the U(t) process);
- absorption coefficient (i_s/i_{s60}).
- Leakage current pulses ($\dot{I}_{s60max}$, $\dot{I}_{s60min}$);

Thus, the proposed methodology is based on the use of statistical procedures (estimation of U_d voltage by extrapolation, leakage current pulses, etc.) in the considered subject area. During the conducted tests, the maximum limit of the constant voltage applied to the insulation system is limited by the double value of the nominal voltage U_N.

The above-mentioned procedures of the isolation system allow to predict their reliability ratios.

The article [8] examines the issues of statistical control of the object's quality as a result of testing a limited number of samples (selection tests) and recommends and justifies the use of the Bayesian approach for this purpose.

It is known that the use of Bayes' theorem is conditioned by the presence of a priori information about the distribution law of the controlled parameters vector of the object. Ona görə də bir tərəfdən keyfiyyət və etibarlılıq parametrləri barədə aprior informasiya səmərəli istifadə olunmalı, digər tərəfdən isə obyektin sınaqları zamanı fasiləsiz müşaidə nəzarəti aparılmalıdır. Therefore, on the one hand, a priori information about quality and reliability parameters should be effectively used, and on the other hand, continuous supervision should be carried out during the testing of the object. The last condition requires compression (tightening) of the allowance interval. So, only in this case, the conclusion that deviations of the controlled parameter from the permissible level (jumps or jumps) are in accordance with Poisson's law can be considered reasonable.

Thus, increasing the accuracy of decisions about quality and reliability during selection tests requires increasing the efficiency of both the planning of the control process and the use of information (a priori and a posteriori) about the controlled parameters.

If there is a priori information $\sigma_y^2 = r(0)$ about the normalized correlation function *r(τ)* for the stationary Haus model of the controlled parameter y(t), then $y(t) \leq y_0$ during the period t ∈ [0, t_0] in the normal mode of the object The guaranteed probability of meeting the condition is estimated as follows [18]:

$$p(t_0) \geq 1 - n_0 t_0 exp\left[-\left(y_0 - m_{y0}\right)^2 / (2\sigma_{y0}^2)\right], \quad (1)$$

where $n_0 = \sqrt{-r_0^{II}}/2\pi$ - is the number of times the parameter exceeds the level of mathematical expectation m_{y0} during the unit time $r_0^{II} = \frac{d^2 r(\tau)}{d\tau^2}/\tau = 0$.

If the a priori information about the controlled parameter includes the regular distribution of its mathematical expectation m_{y0} in the known interval [ɑ 1, ɑ 2] in the nominal mode (Jefferson's rule), then the lower bayes γ - acceptable limit of the probability of satisfying the condition $y(t) \leq y_0$ is estimated as follows [8] :

$$R\gamma(t_0) = 1 - n_0 t_0 exp\left[-\left(y_0 - m_y\right)^2 / (2\sigma_{y0}^2)\right], \quad (2)$$

The non-stationarity of the controlled parameter in the case of $y(t) = m(t) + x(t)$ in expressions (1) and (2) the constant y_0 tolerance limit is replaced by the variable $y_o(t) = y_o - m(t)$ tolerance limit.

Thus, the assessment of the probability of the object maintaining its working capacity is based on the condition of non-stationarity

$$Y(t) = m(t) + x(t) \geq y_0 , t \in [0, t_0] \quad (3)$$

to the condition of stationarity

$$x(t) \geq y_0 - m(t), t \in [0, t_0] \quad (4)$$

is brought. In these expressions, m(t) is any deterministic function, and x(t) is a stationary random process.

For dynamic models, it is also possible to solve the problem of prediction using bayesian estimation. For this purpose, it is sufficient to write $t_p > t_s$ instead of to on the right side of the expression (2) (where t_s -is the test period; t_p -is the predicted amount).

Approaches (1) and (2) to the evaluation of the quality and reliability indicators of the object use the number n_o of times the random process (parameter) *y(t)* exceeds its mathematical expectation in the observation interval. Elektrotexniki materialların (xüsusən də, izolyasiya sisteminin) texniki vəziyyətinin test sınaqlarının nəticələrinə görə diaqnostikası və proqnozlaşdırılması məsələlərinin həllində n_o-dan əlavə *y(t)* prosesinin aşağıdakı statistik xarakteristikaları da vacibdir: In addition to n_0, the following statistical characteristics of the *y(t)* process are also important in solving the problems of diagnosis and prediction of the technical condition of electrotechnical materials (in particular, the insulation system) according to the results of tests:

- the initial arrival time of process (parameter) deviations to a given limit (norm) (for example, if the breakdown voltage of the insulation is accepted as the norm, then this approximation allows to estimate or predict the service life of the insulation);
- the period between two successive discharges of the process (parameter) (estimation of intensity characteristics of technological errors);
- the duration of the process (parameter) exceeding the norm (reliability assessment).

The solution of these issues is possible based on the involvement of the theory of trajectories of random processes [19,20] in the study.

Summary:

The broad application of statistical methods in the considered subject area is theoretically and practically important. On the basis of such convergence, it is possible to achieve a more accurate solution of a number of important issues. The questions of statistical methods application are analyzed and recommendations for increase of decision atheneite through effective using of a priory and aposteriory

information at limited quality of selection examples during electrotechnical materials testing at electrical machines' mass production.

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