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METHOD FOR DETERMINING A TECHNICAL RESOURCE OF THE POWER TRANSFORMER OF TRACTION SUBSTATIONS UNDER OPERATING CONDITIONS

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Встановлено, що і після нормативного терміну служби значна частина силових трансформаторів тягових підстанцій залізниць зберігає працездатність за умов дотримання допустимих навантажувальних режимів, своєчасного проведення випробувань, діагностування та обслуговування. Удосконалено метод прогнозування ресурсу трансформатора, який дозволяє більш точно визначати ресурс, що залишився при впливі різних факторів і умов експлуатації для забезпечення повного його використання, продовження терміну служби трансформатора і зниження витрат на експлуатацію

Ключові слова: трансформатор, технічне обслуговування, життєвий цикл, швидкість відносного зносу ізоляції

Установлено, что и после нормативного срока службы значительная часть силовых трансформаторов тяговых подстанций железных дорог сохраняет работоспособность при соблюдении допустимых нагрузочных режимов, своевременного проведения испытаний, диагностирования и обслуживания. Усовершенствован метод прогнозирования ресурса трансформатора, который позволяет более точно определять оставшийся ресурс при воздействии разных факторов и условий эксплуатации для обеспечения полного его использования, продления срока службы трансформатора и снижения расходов на эксплуатацию

Ключевые слова: трансформатор, техническое обслуживание, жизненный цикл, скорость относительного износа изоляции

1. Introduction

Maintaining the means of railroad transport at high operational level, which ensures safety of the motion of trains and high efficiency of the transportation process, is impossible without reliable information about technical state of equipment. Railroad facilities have a large number of devices. Continued exploitation of these devices can lead to their failure and considerable material losses. A gradual ageing of the fleet of equipment, reduction in the reserves of strength in the equipment of recent generations necessitated assessment of its condition and the degree of risk during operation beyond standardized service life.

Over the past 20 years, many countries privatized a large number of electrical engineering companies that produce, transmit and distribute electricity. Development of a free market of electricity and increased financial costs became additional factors of maximally possible extension of terms of service. Intention of the owners of companies to maximize the use of resource of existing equipment, which allows them to minimize or postpone investments for purchasing the new, under condition of ensuring its reliable operation and minimizing the number of accidents, is predetermined by the fact that the electrical railroads and electrical engineering companies supply, convert, transmit and distribute electricity in the independent market of electrical energy. Solving this task is impossible without the creation of a modern system of maintenance and repair.

An analysis of international experience reveals that through the use of more advanced technologies in the countries of the EU and the USA, effective operation, for example, of worn transformers is possible based on the developed systems of monitoring and diagnosis of technical condition, executed using modern computer and information technologies. In this regard, the new conditions of functioning of the energy sector in Germany, the USA, Brazil and other countries forced to pay close attention to the operation of electrical equipment, which used up standard resource. The main task in the maintenance of means of railroad transport at high operational level of reliability is the creation of a modern system of maintenance and repair based on intelligent networks Smart Grid [1].

The main task of modern intelligent system of maintenance and repair of technical means of railroad transport is determining (prediction) residual resource with the purpose of subsequent maintenance of substantiated periodicity and scope of recovery of efficiency throughout the entire life cycle. As well as the maximum possible extension of equipment operational period and reduction in the cost of operation.

2. Literature review and problem statement

One of the main tasks of power supply to electrified railroads that require urgent solution is the problem of the use of power electrotechnical equipment (PEE) of traction substations (TP) whose term of operation exceeds the norm. At present, at a number of power supply distances, the quantity of aging power equipment of TP exceeds 50 % [2, 3]. A relevance of the problem is predetermined by a real ratio between the rate of increase in the volumes of aging equipment and the possibilities of its renewal. A consequence of the growth in the rate of volumes of aging equipment is additional material-technical and financial losses. Currently, according to the requirements of normative-technical documentation, a system of planned and preventive repairs (PPR) is applied, where the main techno-economic criterion is minimum downtime of equipment based on tight regulation of repair cycles. However, the PPR system, under conditions of the development of market relations in the field of repair, does not in many cases provide making optimal decisions because of insufficient funding. Under these conditions, the main direction to support serviceability of power electrical equipment of TP is the development of modern methods based on individual monitoring over actual changes in the technical condition of equipment during operation.

A study that was conducted into technical condition of equipment of TP, which needs special attention during monitoring, diagnosis and maintenance and repair, indicates that main violations in the normal operation of electrical supply system occur due to failure of power transformers [4]. Power transformers are the basic elements of electric networks and systems that define reliability and economy of operation. At present, the railroads of Ukraine have 422 traction transformers in operation, including 337 transformers with a period of operation exceeding 25 years. An experience of operation of power transformers reveals that even after a standard life cycle, a large part of the transformers retain working ability under conditions of compliance with permissible load regimes, timely testing and diagnosing [5]. On the other hand, operation life of a transformer depends on its residual resource [6]. Accurate information about the life cycle of a power transformer allows employing the most effective strategy for maintenance and diagnosis for the purpose of complete use of its resource and thereby extending the life cycle of its operation.

Proof of this is the results of survey of over two hundred transformers with capacity from 6.3 to 1000 MW, manufactured in Ukraine, Russia, Sweden and Belgium, installed under different climatic zones. Almost 70 % of the surveyed transformers had worked longer than 25 years. About half of them are large (larger than 100 MW). Results of the survey show that 30 % of the examined transformers can continue to operate without any restrictions, and only 2 % have to be replaced. Other transformers require overhaul (15 %), or relatively small and low-cost recovery repairs (23 %) or simply a better control (30 %) [7].

Therefore, along with the planned replacement of outdated equipment, the most important task is to use the full resource of transformers through integrated application of modern methods of diagnosis and repair technologies based on the actual technical condition of equipment. A complexity of the solution to this problem is in the fact that the methods of evaluation of residual term of operation for power transformers are insufficiently studied currently.

In addition, it is necessary to consider that deviation inn any parameter contributes to a transition of the transformer to the new mode of operation, which requires new speed of the use of resource by the *i*-th controlling parameter. A direction of considering this factor is the improvement of methods of tracking the mechanism of dynamics of aging of insulation of oil power transformers over the entire period of operation.

3. The aim and objectives of the study

The goal of present study is to improve a method for determining a residual technical resource and the expected operation life of power transformer of traction substations under operating conditions and effect of different factors.

To accomplish the set goal, the following tasks had to be solved:

– we examined technical condition of the power electrical equipment of traction substations, which should be given top priority;

– to study experience in the operation of power transformers after expiry of normative operation time;

– improvement of the method for determining residual resource of a power transformer.

4. Materials and methods for examining evaluation of the period of operation of power electrical equipment of traction substations

4. 1. Examined materials and equipment used in the experiment

Today, the main problem in the operation of transformer fleet of TP is the operation of transformers that have already used their normative service life. At present, the aging process of TP fleet and electrical power equipment is practically not slowing down. Under these conditions, improving a system of servicing the aging electrical equipment of TP has become the main task for maintaining its working ability.

The key issues in this situation are the following:

– which is the actual or residual resource of TP working ability and of particular group or unit of electrical equipment?

– which are the actual characteristics of reliability of a particular group or a unit of electrical equipment of TP whose service life substantially exceeds that, which is specified in technical documentation?

However, at present, absolutely accurate and unambiguous answers to these questions are practically missing. This is due, above all, to the lack of reliable source data and the complexity of their obtaining under real conditions. Experience of operation of power transformers shows that even after a standard life cycle, a large part of transformers retains their efficiency while complying with permissible loading modes and timely and quality maintenance. Service life of transformer depends on its residual resource. It is necessary to highlight two main components in the notion of resource of the transformer [8]:

– the first component is a renewable resource. This is primarily a resource of the insulation system. The renewable resource may also include repair or replacement of individual components of the transformer, such as bushings, switching devices, pumps and fans of cooling system, etc.;

– the second component of resource is the resource of cellulose insulation, which cannot be renewed, which ultimately determines the residual resource of the transformer as whole.

The study was conducted using the transformer TDTN-25000/150-70 U1.

4. 2. A procedure for the evaluation of wear of isolation of power transformers at traction substations of electrified railroads

The studies, carried out in recent years to examine power transformers [9, 10] that had been in operation for more than 20 years, allowed us to identify major defects, given in Table 1. Size of the sample is 216 units.

Table 1

Main defects of power transformers
(35 kV, 110 kV, 150 kV, 220 kV)

Equipment and type of defect	Number of cases	Share, %
Cooling system	146	23.1
High-voltage inputs	92	14.5
Release of gases into oil	58	9.2
Oil aging	48	7.6
Defects in device RUL (regulation under load)	46	7.3
Leak through sealings in the equipment of transformer	44	7
Pressing out the windings	42	6.6
Contamination of solid insulation	34	5.4
Wetting of solid insulation	26	4.1
Pressing out the magnetic core	26	4.1
Contamination of oil	14	2.2
Deformation of windings	10	1.6
Damage to the unit of automated control over cooling of transformers	8	1.3
Elevated vibration	8	1.3
Damange to outputs	7	1.1
Damage to magnetic shunts	6	0.9
Damage to devices SWE (switching without excitation)	6	0.9
Oxidation of oil	4	0.6
Overheating of connector	4	0.6
Leakage	4	0.6

Table 1 shows that the main defects of power transformers are damage to the cooling system, release of gases into oil, leaking oil along the sealing, oil contamination. The result of these processes is the wear of the insulation. Evaluation of the wear of isolation of power transformers at traction substations of electrified railroads can be performed by the following main factors: elevated temperature, wetting of insulation, oxidation of oil and increasing concentration of oxygen dissolved in the oil tank of the transformer, etc.

Until now, there has not existed a single simple criterion when service life expires, which could be used for quantitative estimation of useful life cycle of the isolation of a transformer, but it is possible to make a comparison, based on the rate of wear of insulation. The easiest way to describe the dynamics of wear of insulation is to use the Montzinger's formula [9, 11]. For the range of temperatures considered in the present study, applying the Montzinger's ration can be regarded as sufficient and such that gives an assessment of thermal wear with a margin of safety.

Montzinger's formula for calculating relative wear of insulation, for time interval $(t_0, t_0 + T)$, takes the form:

$$L(t_0, t_0 + T) = \int_{t_0}^{t_0+T} V(\theta_h, K_w, K_a, K_{O2}), \qquad (1)$$

where V is the speed of relative wear of insulation, rel.units; θ_h is the temperature of the most heated point in a winding, °C; K_w, K_a, K_{O2} are the coefficients of effect of moisture, dissolved acids and oxygen, respectively, rel.units.

In this case, the rate of relative wear of insulation with regard to the impact of the examined operational factors will take the following form [11]:

$$V = \left(\frac{C_w}{C_{w.b}}\right)^{\alpha} \cdot \left(\frac{C_a}{C_{a.b}}\right)^{\beta} \cdot \left(\frac{C_{O2}}{C_{O2.b}}\right)^{\gamma} \cdot 2^{\frac{\theta_h - 98}{6}}, \qquad (2)$$

where C_w, C_a, C_{O2} is the content of moisture in solid insulation, the content of acids and oxygen in the oil, respectively, g/t; $C_{w.b}$, $C_{a.b}$, $C_{O2.b}$ are the basic values of the contents of moisture in solid insulation, the content of acids and oxygen in the oil, respectively, g/t; α, β, γ are the indicators defined in [12]; θ_h is the temperature of the most heated point in the winding of a transformer, °C.

Calculation that we performed for different indicators of the components of expression (2) using the MathCAD software shows that considering a moisture content of solid insulation, the content of acids and oxygen in the oil increases the accuracy of determining a rate indicator of relative wear of insulation; results of the calculation are shown in Fig. 1.

Fig. 1 shows that determining the rate of relative wear of the insulation of a transformer without regard to the content of moisture in solid insulation, the content of acids and oxygen in the oil yields an error (with an increase in MHP, the error grows), and an increase in the moisture content of solid insulation, in the content of acids and oxygen in the oil leads to an increase in the rate of relative wear of the insulation of a transformer.

In addition, another basic operational factor that affects the service life of transformers is temperature (GOST 14209-85 Power oil transformers). It is believed that an increase in the temperature of the most heated point (MHP) by each $\Delta = 6$ °C reduces the service life of a transformer by almost 2 times (GOST 14209-85). This magnitude is an absolute deviation of temperature factor $\Delta\theta$ for the base of degree 2. Recalculate $\Delta\theta$ for the base of degree e and we shall receive $\Delta\theta = 8.154$ °C. In addition, according to GOST 14209-85, temperature of the most heated point (MHP) of the winding of a transformer at which the rate of estimated wear of insulation matches the operation life cycle of a transformer is the magnitude of 98 °C. Given this concept of resource, we shall accept as an equivalent notion the life cycle of a transformer. Let us calculate relative deviation from MHP 98 °C, $\Delta\theta^{*}=0.083$ rel.units. Standard life cycle of transformer is accepted as $T_0=25$ years. It is obvious that a temperature factor is not the only one, but the strength of influence from other factors is negligible in comparison with it, as it can be seen in Fig. 1 on the comparison chart of the rate of relative wear of the insulation of a transformer at different temperatures of the most heated point of the transformer.

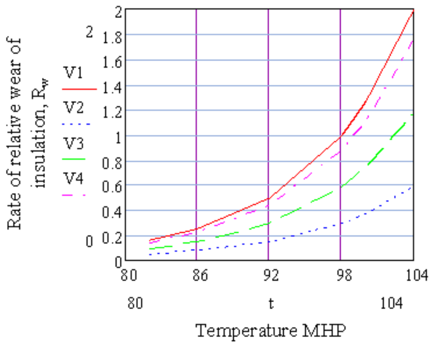

Fig. 1. Dependence of the rate of relative wear of insulation on the content of moisture in solid insulation, the content of acids and oxygen in the oil: V1 is the rate of relative wear of insulation isolation (relative units, rel.units) excluding the content of moisture in solid insulation, the content of acids and oxygen in the oil; V2, V3, V4 is the rate of relative wear of insulation with regard to the content of moisture in solid insulation, the content of acids and oxygen in the oil (e. g., for the values of generalized coefficient $K_{w,a,O2}=0.005$; 0.01; 0.015, respectively), MHP is the temperature of the most heated point of a transformer

Taking into account determining of the actual used resource of power electrical equipment of TP according to the developed mathematical model in [13] and given the rate of change in the relative wear of insulation (2), we propose to calculate the actual used resource of a transformer using a modification of the mathematical model [13], expression (3):

$$R_f^{*}=1-\frac{T_1\left[e^{-v1\frac{(\theta_1^{*}-1)}{\Delta\theta^{*}}}-1\right]+T_2\left[e^{-v2\frac{(\theta_2^{*}-1)}{\Delta\theta^{*}}}-1\right]+T_3\left[e^{-v3\frac{(\theta_3^{*}-1)}{\Delta\theta^{*}}}-1\right]+T_4\left[e^{-v4\frac{(\theta_4^{*}-1)}{\Delta\theta^{*}}}-1\right]}{T_0}, \quad (3)$$

where T_1, T_2, T_3, T_4 is the period of work of the transformer under each temperature regime (years), which are characterized by temperatures of MHP θ_1, θ_2, θ_3, θ_4, taking into account the rate of relative wear of insulation θ^{*} (for respective MHP).

To verify the model, we shall consider several variants of temperature modes of transformer operation:

Variant 1: $T_1=17$, $T_2=3$, $T_3=4$, $T_4=1$; $\theta_1=98$ °C, $\theta_2=90$ °C, $\theta_3=82$ °C, $\theta_4=100$ °C.
Variant 2: $T_1=10$, $T_2=6$, $T_3=0$, $T_4=9$; $\theta_1=98$ °C, $\theta_2=90$ °C, $\theta_3=82$ °C, $\theta_4=100$ °C.
Variant 3: $T_1=1$, $T_2=3$, $T_3=4$, $T_4=17$; $\theta_1=98$ °C, $\theta_2=90$ °C, $\theta_3=82$ °C, $\theta_4=100$ °C.

Relative value of temperature factor θ^{*} relative to basic $\theta_1=98$ °C rel.units for all variants will be:

$$\theta_1^{*}=1,\quad \theta_2^{*}=0.918,\quad \theta_3^{*}=0.836,\quad \theta_4^{*}=1.020.$$

Calculation of the used resource of a transformer for the accepted input data on operation (variants 1, 2, 3) will be conducted according to expression (3) using the MathCAD software.

5. Results of examining relative wear of insulation and determining a life cycle of transformer

Calculation of the rate of relative wear of insulation was carried out using expression (2).

Variant 1: as a result of the calculation using expression (3), we receive $R_f^{*}=0.924$ rel.units. The obtained value R_f^{*} indicates that the operation of a transformer was carried out under a light mode and expected actual service life was increased by 8 % (25 yr·0.076 rel.units=2 years). Graphically, the use of resource of a transformer for input data on the operation (variant 1) was conducted according to expression (3) using the MathCAD software and it is shown in Fig. 2.

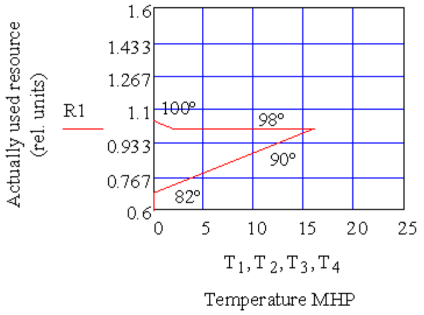

Fig. 2. Actual use of resource of transformer (variant 1)

Results of the calculation of actually used resource of a transformer for other variants of operation of transformer demonstrate:

Variant 2: $R_{f,}^{*}=1.231$ rel.units. The obtained value R_f^{*} indicates that operation of the transformer was not effective and the expected actual life cycle is reduced by 23.2 % (25 yr·0.231 rel.units= =5.8 years). Graphically, the use of resource of a transformer for input data on the operation (variant 2) was conducted according to expression (3) using the MathCAD software and it is shown in Fig. 3.

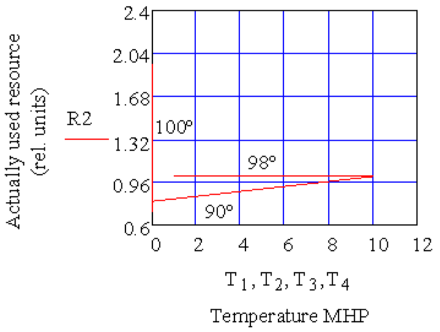

Fig. 3. Actual use of resource of transformer (variant 2)

Variant 3: $R_f^{*}=1.533$ rel.units. The obtained value R_f^{*} indicates that operation of the transformer was not effective and the expected actual life cycle is reduced by 53.3 % (25 yr·0.533 rel.units=13.325 years). Graphically, the use of resource of a transformer for input data on the operation (variant 3) was conducted according to expression (3) using the MathCAD software and it is shown in Fig. 4.

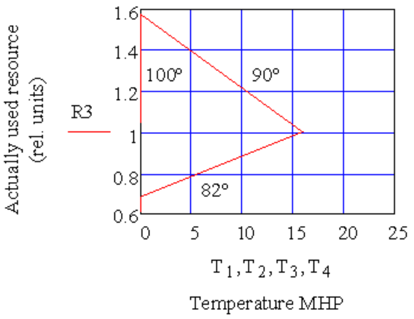

Fig. 4. Actual use of resource of transformer (variant 3)

Calculation of the use of resource of a transformer for temperature MHP 98 °C, over the period of operation made up 25 years (T) (Fig. 5).

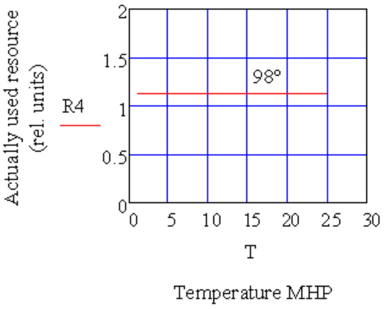

Fig. 5. Actual use of resource of transformer at MHP 98 °C

Fig. 6, 7 show the use of resource of a transformer for temperatures MHP 82 °C, 100 °C, taking into account the rate of relative wear of insulation (R5, R6) and excluding the rate of relative wear of insulation (R5a, R6a). Graphically, the use of resource of a transformer for input data on the operation was conducted according to expression (3) using the MathCAD software (Fig. 6, 7).

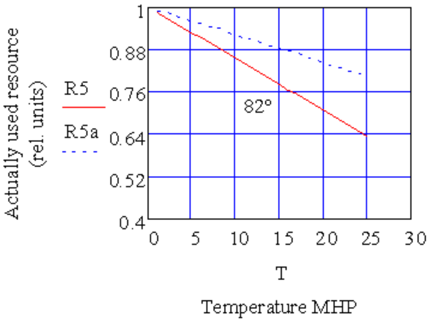

Fig. 6. Actual use of resource of transformer (MHP 82 °C)

Fig. 6, 7 demonstrate that accuracy of the calculation improves when considering the rate of relative wear of insulation.

Results of calculations using the MathCAD software (Fig. 2–7) and the proposed expression (3) indicate the adequacy of the given approach.

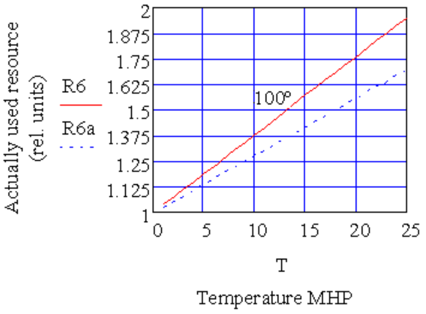

Fig. 7. Actual use of resource of transformer (MHP 100 °C)

6. Discussion of research results

We improved a method for determining technical resource of a power transformer of the traction substation using the developed expression (3), which makes it possible to more accurately (by 10...12 %) perform calculation of the residual resource of a transformer under the influence of various factors and conditions of operation.

Such solution to the problem allows us to determine and predict the actual life cycle of a transformer. For example, during operation of transformer at MHP 82 °C (Fig. 6), the value R_f^* indicates that the actual expected operation period of the transformer can be increased by 64 % (16 years). When operating a transformer at MHP 100 °C (Fig. 7), the value R_f^* indicates that the actual expected operation period of the transformer is reduced by 50 % (12.5 years).

Research results have been implemented by the department of power supply at the Southern railroad, the distance of power supply Nizhnedniprovsk-Vuzol (ECh-2) at the Prydniprovska railroad.

Determining a technical resource of power transformer makes it possible to establish its actual technical condition and to carry out effective planning of maintenance and repairs in the direction of increasing periods between maintenance (decrease in the number of service operations), reducing financial and labor costs. Thus, payload of workers at TP when servicing the transformer TDTN-25000/150-70 U1 at the traction substation Synelnykove ECh-2, Prydniprovska railroad, was reduced over one year by: C_{CR}=USD 50 – current repair; C_{IRT}=USD 18 – inter-repair testing; C_R=USD 17.4 – a reduction in wages to the employees for servicing the transformer over 1 year of operation totaled: $C=C_{CR}+C_{IRT}+C_R=$ =USD 85.4.

A reduction of costs for materials to carry out a planned repair of the transformer over 1 year amounted to: $C_M=$ =USD 95.24.

The total reduction of costs for the maintenance of transformer TDTN-25000/150-70 U1 over 1 year of operation totaled: $C_C=C+C_M$=USD 180.64. Given that railroads of Ukraine operate more than 422 traction transformers, it is possible to gain considerable economic effect.

This method could be used to predict technical condition of other power equipment at traction substations.

Present study is continuation of the research work [13]. In the future, it is planned to investigate relative importance of the effect of moisture, dissolved acids and oxygen on the rate of wear of insulation of power equipment filled with oil.

7. Conclusions

1. It is established that at present a significant part of the infrastructure equipment of railroad transport of Ukraine has already exhausted its technical resource. Research into technical condition of equipment of TP that we conducted shows that the main breaches in the normal operation of power supply system occur because of the failure of transformers. Currently, the railroads of Ukraine operate 422 traction transformers, of which 337 transformers have been in operation for more than 25 years. In addition, this problem is complicated by the lack of financing for the implementation of PPR and by missing modern intelligent systems of diagnosis and maintenance.

2. Experience of operation of power transformers reveals that even after a standard life cycle a large part of the transformers retain working ability under conditions of compliance with permissible load regimes, timely testing and diagnosis. Results of inspections show that 30 % of the examined transformers can continue to operate without any restrictions. And only 2 % have to be replaced. Other transformers require overhaul (15 %), or relatively small and low-cost recovery repairs (23 %) or simply a better control (30 %).

3. We improved a method for determining residual technical resource of power transformer of a traction substation during evaluation of the dynamics of aging of equipment through the introduction of an indicator of the rate of wear in the resource of insulation under the influence of various factors. This allowed us to more accurately determine a residual resource of the transformer (accuracy of calculation increased by 10...12 %).

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