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V.M. Kyrylenko, K.V. Kyrylenko

Theoretical determination of individual values of insulation four-element equivalent circuits elements parameters at technical diagnostics of insulation by absorption methods

*The **aim** of this article is to present a methodology of determining of the individual values of the parameters of four-element equivalent circuits for insulation with through conductivity. **Methodology**. The proposed method consists in the fact that at a time interval of more than 10 s, when the charge indicator no longer contributes to the leakage current, three points t_1, t_2 and t_3 are selected, such that $t_2 - t_1 = t_3 - t_2$. To be able to determine the absorption coefficient R_{60}/R_{15}, it is recommended to take t_1 = 15 s, t_2 = 37.5 s and t_3 = 60 s. At the same time, by subtracting $I(t_2) - I(t_1)$ and $I(t_3) - I(t_2)$, the constant component of the absorption curve is excluded and it becomes possible to determine the individual values of the parameters of the generalized equivalent circuit of insulation, additionally using its conductivity in operator form. **Results.** As calculations show, the correct determination of the parameters of insulation equivalent circuit according to the proposed method is possible only with a certain ratio of these parameters. The charge time of the geometric capacitance $C_g(R_0+R_d)$, where R_0 and R_d are the resistance that forms the charging exponent, and the resistance of the sensor, should be within 0.2 s $<C_g(R_0+R_d)<$1 s, the time constant C_aR_a, where C_a and R_a are the capacitance and resistance of the absorption chain, should be more than 3 s, the product of C_gR_l, where R_l is the leakage resistance, more 0.5 s, the leakage resistance R_l is less than the absorption resistance R_a. Checking the methodology on a model example gives the values of the parameters of the insulation equivalent circuit that match the specified ones with high accuracy. **Practical value.** The use of individual values of the parameters of insulation equivalent circuits when applying absorption diagnostic methods with considering the time values and dimensional factors, allow to calculate all currently used diagnostic parameters, to determine the conditions of certain insulation types, as well as in more detail, in comparison with the existing approach, to assess the technical condition of the insulation and the reasons of its changes.* References 20, figures 2.

Key words: **non-destructive methods of insulation diagnostics, absorption methods of diagnostics, parameters of elements of insulation equivalent circuits.**

Розглянута теоретична методика визначення індивідуальних значень параметрів елементів узагальненої схеми заміщення ізоляції по залежності абсорбційного струму від часу, а також інших чотирьохелементних схем заміщення ізоляції з наскрізною провідністю та їх взаємного перерахунку, що повністю розкриває інформативний потенціал абсорбційних методів діагностування електричної ізоляції. Знання цих значень теоретично дозволяє, враховуючи значення часу та розмірні фактори, сформувати будь-який абсорбційний діагностичний параметр, що використовується зараз, і прослідкувати його зміни в процесі експлуатації ізоляції. Наголошується, що для фізично обґрунтованої інтерпретації результатів діагностичного контролю абсорбційним методом за однією з схем заміщення ізоляції необхідно мати інформацію про склад і структуру ізоляції. Бібл. 20, рис. 2.

Ключові слова: **неруйнівні методи діагностики ізоляції, абсорбційні методи діагностики, параметри елементів схем заміщення ізоляції.**

Introduction. The electrotechnical and electric power equipment used at Ukrainian enterprises has worked out a significant part or all of the designated service life, taking into account that the most intensive commissioning of it took place until the 90s of the last century. This applies to power plant equipment such as generators, transformers, internal demand motors and high-voltage switchgear equipment, insulation of overhead networks and cable lines, as well as induction electric drive motors.

Currently, most of the power generating equipment of TPPs and CHPs has reached their limit service life (more than 200,000 hours), they are worn out and, according to the existing regulatory documentation, they need to be reconstructed or replaced. The distribution of specific damage of the main units of turbo- and hydrogenerators, which increases with increasing power, shows that the stator insulation is subject to control as the most «weak» unit [1].

If we take into account all the main equipment of power plants, it should be noted that great attention should be paid to monitoring the technical condition of power transformers [2-7], especially with extended service life.

Due to wear, in the vast majority of cases (85-95 %), failures of induction motors with a short-circuited rotor (the most widely used in the country's enterprises) with power of more than 5 kW occur due to damage to the stator and rotor windings and are distributed as follows: stator winding – up to 80 %, rotor winding – up to 10 % [1, 8-11]. This causes increased attention to control the reliability of their insulation.

Moral and physical wear of cable lines with voltage of 6-10 kV in power supply systems ranges from 40 to 90 %. Here, up to 70 % of all power supply violations occur when cable lines with voltage of 6-10 kV fail, and therefore control of their technical condition is also an urgent issue [12-15].

When using worn-out electrical equipment, it should be borne in mind that when we talk about the designated service life, according to the regulatory documentation, this is about the group resource, which is defined as the working time of a group of products, for which n percent of the most defective products are rejected. This time is taken as a group service life with a reliability of 1–*n*/100. This generally accepted approach does not take into account that life dissipation can be several hundreds of percent, and therefore the residual life of some products, especially if the life is distributed according to the log-normal law, may be several times greater than intended. Based on this fact, it can be considered justified to try to extend the life of the equipment by determining an extended life. However, we emphasize that the operation of electrical equipment, which has worked out and for which an extended life has been established, due to the uncertainty of the real life, requires continuous monitoring of its technical condition. Only under such conditions the unused service life of the equipment can be effectively used.

Control of the level of reliability of electrical insulating materials and structures in operation is carried out by measuring the influence of external and operational factors on the parameters of the insulation characteristics, which lead to a change in the technical condition of the insulation, including those that are not related to functioning. Most often, the technical condition of insulation and electrical insulating materials is determined using integral parameters, such as resistance, capacitance, dielectric loss angle tangent, leakage current, absorption coefficient, recovery voltage, etc. [16].

One of the methods of monitoring the technical condition of electrical equipment is absorption diagnostic methods, which are recommended as normative for diagnosing insulation of transformers, synchronous generators, compensators, collector exciters, and AC electric motors [16]. A brief description of absorption methods is given in [1].

Modern scientific studies of absorption methods and their use relate to diagnosing the state of insulation of power transformers [2, 3, 9-12, 15], rotating electric machines [8-11], low- and high-voltage cables [7, 12-14].

Insulation defects and methods of their diagnosis are generally described in [1, 8, 9]. In [1], the general issues of diagnosis of insulation and, in particular, the use of absorption methods are considered. Diagnostic parameters in the case of using absorption diagnostic methods include, firstly, parameters that use the characteristics of the rate of decline of the absorption current curve (increase in insulation resistance) depending on the time of application of constant voltage to the insulation in different sections of this curve, i.e. absorption coefficient, polarization coefficient, dielectric absorption ratio, polarization index and other similar characteristics and their derivatives. The second direction related to absorption methods is the recovery voltage method, which is implemented in two variants. In the first case, the ratio of the maximum value of the recovery voltage resulting from the charge from the absorption capacitance of the insulation disconnected from the voltage source after the discharge of its geometric capacitance to the charging capacitance (capacitive absorption coefficient) is determined. In the second variant, it is the same ratio determined at different time intervals for the discharge of the geometric capacitance, which leads to partial discharge and absorption capacitance. In addition, the initial rate of rise of the r recovery voltage, the time to reach the maximum value of the recovery voltage, nonlinearity coefficients of the recovery voltage, the self-discharge time constant, and other characteristics can be used as diagnostic parameters.

The generalized equivalent insulation replacement circuit (Fig. 1,*a*) is the basis of all absorption diagnostic methods. Its elements include the geometric capacitance C_g, which reflects the capacitance associated with fast processes of electronic and ionic polarization, the through resistance R_l, i.e. the steady value of insulation resistance to the flow of direct current, the absorption capacitance C_a, which is responsible for the slow processes of migration polarization caused by accumulation of free charges on the boundaries of the regions of the dielectric with different electrophysical properties or in the near-electrode regions, and the absorption resistance R_a, which is introduced to correctly reflect the inertial properties of the migration polarization [1].

The absorption coefficient (and other differential diagnostic parameters for the generalized circuit and other four-element substitution circuit), as a rule, can be written in the form:

$$k_a = \frac{R_1 + R_2 \exp\left(-t_2 \alpha_{1v}\right)}{R_1 + R_2 \exp\left(-t_1 \alpha_{1v}\right)},$$

where t_1 and t_2 are the time of measuring resistances R_1, R_2, in the general case R_i are resistive elements, α_{iv} is the function of resistive and capacitive elements of the substitution circuit. Specific expressions for R_i and α_{iv} used for the absorption coefficient will be given below for all four-element insulation replacement circuits.

In [8, 9], the main causes and defects of insulating structures, the processes that occur in the insulation under the action of an electric field and lead to the formation of its defects are considered. In [9], a generalized analysis of control methods and diagnostic parameters of insulation of DC traction motors is presented. Here, a generalized insulation substitution circuit was used, the parameters of the substitution circuit were determined through the parameters of the model containing parallel absorption circuits of series-connected capacitances and resistances.

In [2] it is noted that two fundamental processes take place in insulation: polarization and electrical conductivity, and that both processes should be sensitive to changes in composition and characteristics that occur in the insulation during operation, and a list of potentially possible diagnostic methods is given. In [10], the procedures of constant voltage tests for measuring the insulation resistance and polarization index of the insulated stator, as well as the rotor windings and methods of interpreting the results obtained during the diagnosis of rotating machines are outlined.

At the same time, it was established [11] that when diagnosing the windings of rotors and stators of generators and motors, the insulation resistance and the polarization index well detect moisture and partially conductive inclusions, but are not sensitive to many other defects: the weakening of the turns in the slot, which leads to abrasion of the insulation, delamination of insulation due to use at high temperatures, separation of copper from insulation due to cyclic loads, destruction of protective coatings and partial discharges between coils. The authors suggest using a comparison of charging and discharging current for each phase of the winding and individual coils with simultaneous measurement of resistance and polarization index.

In the works reviewed by us above, the authors use standard indicators, which are standard integral combinations of the parameters of the elements of the generalized equivalent circuit, as was shown for the absorption coefficient, and do not consider the issue of simultaneous determination of all individual parameters of the elements of the substitution circuit, as such, as well as their interdependence.

If we talk about the possibility of diagnosing electrical insulation with the help of recovery voltage, then the work [3] demonstrated a good correspondence between the model based on the generalized dielectric substitution circuit and real insulation for the coefficients of polarization, depolarization and recovery voltage.

The recovery voltage method is most widely used for power transformers. The conditions for monitoring the insulation of high-voltage transformers by the recovery voltage method are outlined in [4].

In [5], a new approach is considered to combine the results obtained using two methods, namely: reverse voltage measurement and polarization-depolarization current measurement for several power transformers, to find the relationship between the moisture content of oil and paper, relating to power transformers.

In the recovery voltage method [6], the recovery voltage is determined after charging the insulation with DC voltage. The so-called polarization spectrum can be created by repeatedly charging for different times and then obtaining the value of the recovery voltage. The recovery voltage range gives an indication of the condition in which the insulation of the transformer is. The results of measurements on two high-power transformers in operation, which determine the humidity of solid insulation, were analyzed.

With the help of equivalent circuits, in [7] the characteristics of the recovery voltage for paper-oil insulation were studied: the charge time, the shorting time, which was equal to half the charge time, the recovery voltage and the ratio of its maximum to the charging voltage was determined, and the time corresponding to the maximum was also fixed. The simulation was carried out for 14 cycles with different charge times from 0.1 to 819 s, and the moisture content and oil conductivity were evaluated. Analyzing the results, the authors note that traditional diagnostics used the value of a time constant during which the maximum of the recovery voltage is reached, although it can be masked by interphase polarization, which makes the use of this technique unacceptable in practice.

Taking into account that the aging of paper-oil insulation of power transformers occurs mainly due to moisture and oxygen, new methods of assessing the state of insulation based on dielectric response have been developed, but they use expensive tools. The work [7] shows the effectiveness of measuring recovery voltage using simple measuring devices. The relationship between the initial growth rate of the recovery voltage and the state of the insulation is established.

Conducted studies [12] show that the application of voltage response measurement is a very effective tool for determining the aging state of oil paper insulated cables. The initial slope of the charge voltage is directly proportional to the insulation conductivity and the initial slope of the recovery voltage is proportional to the intensity of the polarization processes. Therefore, the two main wear processes (wetting and thermal aging) of oil-paper insulation can be considered separately.

The work [13] considered the application of the voltage triggering method on laboratory-aged low-voltage polymer (PVC and PE) insulated cables and compared the results with the results of chemical and penetration tests. With the help of the method of voltage triggering, it is possible to detect the state of aging of the insulation, that is, the probable decrease in dielectric strength for cables of operational age in comparison with dielectric losses.

Recovery voltage, as a diagnostic factor, was also studied in [14, 15]. In [17], a method for determining the characteristics of phase and belt paper-oil insulation of medium voltage power cables is presented. The methodology is implemented using a three-core cable replacement circuit in a common metal shell and analysis of the results of aggregate measurements of absorption characteristics. The system of linear algebraic equations for determining the characteristics of phase and belt insulation is well conditioned. The article presents the results of determining the absorption characteristics of phase and belt insulation of a power cable at voltage of 6 kV, which are in good agreement with real values.

It should be noted that in the works where the recovery voltage, which depends on the charging voltage and combinations of the values of the elements of the generalized equivalent insulation replacement circuit, as well as related derivative diagnostic parameters, the analytical expressions for which are given below in the article, this is not about determining all the individual values of the parameters of the elements of the generalized equivalent insulation replacement circuit at the same time.

The third direction of diagnostic research is emerging almost now thanks to the works by G.V. Bezprozvannych [17-19], who was one of the first, if not the first, to understand that a statistical approach should be used to diagnose electrical insulation. But even in this case, the simultaneous determination of the individual values of the parameters of the elements of the generalized equivalent insulation replacement circuit remains outside the attention of the authors.

Authors of works on dielectric spectroscopy [12, 14] and others as a diagnostic parameter, the tangent of the dielectric loss angle in the low-frequency region use, which is quite complexly related to the parameters of the elements of the generalized equivalent insulation replacement circuit, and therefore, taking into account the topic of this work, the results obtained by them may not be considered. So, for this direction as well, the simultaneous determination of all individual parameters of substitution circuits is not relevant.

The first work that analyzed in detail the shortcomings of diagnosing electrical insulation by measuring absorption coefficients, polarization index, dielectric absorption ratio and other interval characteristics is the article [20], where the authors noted the ambiguity of the interpretation of the diagnosis results due to the dependence of the diagnostic criteria on the values of the parameters of several elements of substitution circuits at the same time, which can vary in the process of aging of the insulation, leading to ambiguity of diagnostic parameters, as well as due to the extremity of these diagnostic parameters. There was also a lack of information about the explicit value of the parameters of the resistive elements of the substitution circuit, or their implicit use for diagnostic parameters based on the method of recovery voltage, but a detailed analysis of these methods was not carried out.

In the opinion of the authors of this article, there is an opportunity to significantly increase the informativeness of absorption diagnostic methods and partially eliminate the ambiguity of their interpretation by determining the individual values of the parameters of the elements of the four-component insulation replacement circuits. It is clear that knowledge of the individual values of these parameters will theoretically allow to form, taking into account time and dimensional factors, any diagnostic parameter based on absorption methods.

The goal of the article is to develop the scientific basis of the methodology for determining individual parameter values of four-element insulation replacement circuits with through-conduction.

The article considers the case when the dielectric has only one absorption exponent, taking into account that the generalization of the technique to several absorption exponents is obvious. For this, it is necessary to exclude first the constant component, and then sequentially the exponents with the largest time constant, subtracting the current corresponding to them from the residual curve and rebuilding the new residual curve on a semi-logarithmic scale. The authors understand that the article is of a purely theoretical nature, the determination of the individual values of the parameters of the insulation replacement circuit is carried out for the curve simulating the absorption current in the insulation, but it is obvious that the application of the proposed technique to the real absorption curve will allow to determine the real values of the parameters of the insulation replacement circuit, which is being investigated. The practical use of the technique for real insulation will be demonstrated in the next article.

Use of dielectric equivalent circuits to diagnose insulation. The insulation of electrotechnical and electric power equipment is characterized by heterogeneity of structure and properties, which is caused by the very structure and composition of the electrical insulating material. In addition, the inhomogeneity of the insulation can arise during the operation of the insulation due to the inhomogeneous distribution of the field associated with the geometry of the dielectric structure itself, as a result of which electrical and thermal aging of the insulation will proceed with different intensity in areas with different field strengths. The influence of the heterogeneity of the material and the geometry of the electrical insulating structure on the configuration of the internal field in the insulation can be estimated by calculation only for some of the simplest cases. If non-homogeneous materials are used in a non-homogeneous field, the superimposition of external and internal inhomogeneities greatly complicates the task. One of the simple approaches to bypassing the emerging complications is to model electrical insulating structures with simple electrical substitution circuits consisting of resistors and capacitors and having frequency characteristics corresponding to the frequency characteristics of the insulation under investigation. It is assumed that with such a replacement, it is possible to make a more or less adequate idea of the degree of heterogeneity of the insulation with a certain interpretation of the obtained results. Note that a similar approach, based on replacing dielectrics with equivalent circuits, is used not only to describe the properties of electrical insulation, but also to study the relationship between the structure and electrophysical properties of heterogeneous composite dielectric materials.

Any four-component substitution circuit with through conduction can correspond to this model absorption current curve. For the correct choice of the replacement circuit and the subsequent interpretation of the diagnostic results, it is necessary to have an idea of the composition, structure and peculiarities of the flow of electrophysical processes in the insulation. This is quite a difficult task, and therefore we will give only some possible options for the interpretation of four-element insulation replacement circuits.

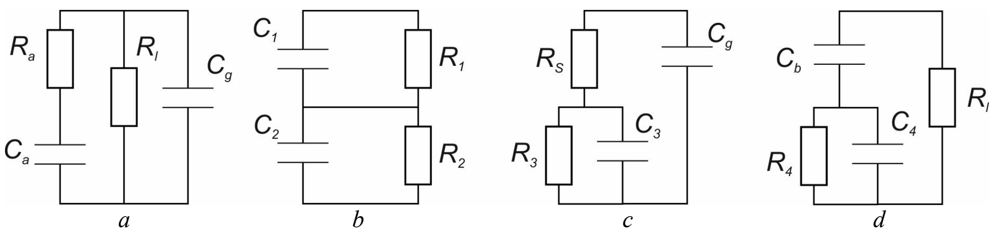

Fig. 1. Four-element insulation replacement circuits with through-conductivity

The interpretation of the generalized insulation replacement circuit (Fig. 1,*a*) was given above.

The layered material, which is a serial connection of two dielectrics with elastic polarization, which is represented by the capacitances C_1 and C_2, and through electrical conductivity, which is represented by the resistances R_1 and R_2, connected in parallel with the corresponding capacances, corresponds to the circuit (Fig. 1,*b*). Provided that $\varepsilon_{r1}\rho_1 \neq \varepsilon_{r2}\rho_2$, the macroscopic inhomogeneity of such two-component insulation leads to the appearance of migration polarization caused by the accumulation of free charges at the interphase boundary, the consequence of which is the exponential decline of current with time at constant voltage and dielectric losses at alternating voltage.

The circuit (Fig. 1,*c*) may correspond to insulation with partially destroyed or broken local inclusions or a composite dielectric material with a subthreshold concentration of a component with much higher electrical conductivity, characterized by the resistance R_b, with which a dielectric (capacitance C_3) with low electrical conductivity is connected in series (resistance R_3), as well as in parallel to this series circuit with capacitance C_g, which reflects fast types of polarization.

And, finally, the circuit (Fig. 1,*d*) can be used for insulation, which is a composition of a high-Q non-polar polymer with very low conductivity (capacitance C_b) and a polar polymer included partly in series with it (circuit C_4, R_4), and partly in parallel (resistance R_l), or for a composite material consisting of an ionic or other low-Q filler in the threshold mode.

Thus, the model curve of the absorption current can be selected for one of the insulation substitution circuits, and it is for this substitution circuit that the individual values of the parameters of its elements can be calculated, but then these values can be recalculated to other substitution circuits as well. First, in the article we will consider how to determine the individual values of the parameters of the elements of the generalized equivalent circuit, and then their recalculation into the individual values of the parameters of the elements of other four-element insulation replacement circuits. Formulas for reverse calculation are also given.

Determination of individual values of the parameters of the elements of the generalized equivalent insulation replacement circuit. Determining the individual values of the parameters of the elements of the generalized equivalent insulation replacement circuit: through resistance, absorption resistance, absorption and geometric capacitances can be implemented in practice by recording and analyzing the transient current in the measuring circuit shown in Fig. 2, with instantaneous supply of constant voltage $U = U_0$.

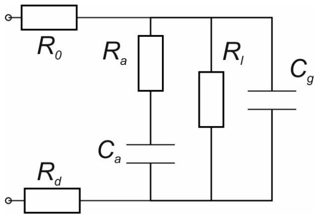

Fig. 2. Equivalent measuring circuit: R_0 – limiting (forming) resistance, R_d – measuring sensor resistance, R_l – through resistance, R_a – absorption resistance, C_a – absorption capacitance, C_g – geometric capacitance

In addition to the insulation, the measuring circuit includes two resistors: the measuring R_d – for measuring the leakage current, and the forming R_0 – for generating an exponent describing the charge of the geometric capacitance of the insulation. The value of the measuring resistance is selected in the range of 10^3 – 10^5 Ω. The forming resistance should be in the range of 10^6 – 10^9 Ω and provide a charge time constant of the geometric capacitance $C_g(R_0+R_d)$ of about a second. Then, in 3-4 s, it will attenuate, and based on later readings of the absorption current, it will be possible to determine the absorption time constant.

The model current through the insulation when the measuring circuit (Fig. 2) is connected to constant voltage U_0 as a function of time will have three components: a constant one and two exponents with the charge for the geometric capacitance $1/a$ and the absorption capacitance $1/b$ time constants:

$$I = C + A \cdot \exp(-at) + B \cdot \exp(-bt). \quad (1)$$

In order to theoretically determine its parameters from the model absorption current curve, we suggest using the three-point method, which makes it possible to determine the constants *a* and *b*, and then calculate the coefficients of the absorption curve. Next, using the formula for the leakage current recorded taking into account the expression for the operator conductivity, it is theoretically possible to determine the parameters of the elements of the equivalent substitution circuit, and then the value of the absorption coefficient or other interval diagnostic parameters.

Within the framework of the proposed theoretical method, at a time interval longer than 10 s, where the charging exponent no longer contributes to the leakage current, three points t_1, t_2 and t_3 are selected such that $t_2 - t_1 = t_3 - t_2$. To be able to calculate the absorption coefficient R_{60}/R_{15}, it is recommended to take t_1 = 15 s, t_2 = 37.5 s and t_3 = 60 s.

The proposed choice of three calculation points allows, due to the subtraction $I(t_2) - I(t_1)$ and $I(t_3) - I(t_2)$, to eliminate the constant component of the absorption current and then, under the condition that the charge time of the geometric capacitance $C_g(R_0+R_d) \approx 1$ s, and the charge time constant of the absorption capacitance C_aR_a >3 s, the constant *b* in the second interval can be calculated with sufficient accuracy by the formula

$$b = \frac{\ln\left(\dfrac{I_4 - I_5}{I_5 - I_6}\right)}{t_5 - t_4}. \quad (2)$$

In the first time interval from 0 to 10 s, three points t_1, t_2 and t_3 should be selected, also observing the requirement that $t_2 - t_1 = t_3 - t_2$. Then the charging constant a at the first time interval is calculated as follows

$$a = \frac{\ln\left(\dfrac{I_1 - I_2}{I_2 - I_3}\right)}{t_2 - t_1}. \quad (3)$$

Coefficients *A*, *B* and *C* are determined from a system of 3 equations taken for three values of the model absorption current curve, preferably at small time values, when the system of equations will be better defined and more accurate coefficient values can be obtained. The system of equations for determining the coefficients of (1) will have the form

$$\begin{cases} a_1 A + b_1 B + C = I_1; \\ a_2 A + b_2 B + C = I_2, \end{cases}, \quad (4)$$

where $a_i = \exp(-at_i)$, $b_i = \exp(-bt_i)$, $I_i = I(t_i)$.

The coefficients of the equation *A*, *B* and *C* according to the solution of system (4) are generally equal to the values given in (5):

$$A = \frac{(I_1 - I_2)\cdot(b_2 - b_3) - (I_2 - I_3)\cdot(b_1 - b_2)}{(a_1 - a_2)\cdot(b_2 - b_3) - (b_1 - b_2)\cdot(a_2 - a_3)};$$
$$B = \frac{I_1 - I_2 - A\cdot(a_1 - a_2)}{(b_1 - b_2)}; \quad (5)$$
$$C = I_1 - a_1 A - b_1 B.$$

To write down the formulas for determining the values of the parameters of the generalized equivalent insulation replacement circuit, we write down its conductivity (6) in operator form. This conductivity corresponds to the following time dependence of the current through the insulation (8)

$$Y_1 = \frac{R_d}{R_0 + R_d} \cdot \frac{p^2 + p(\alpha_{aa} + \alpha_{ga} + \alpha_{gl}) + \alpha_{aa}\alpha_{gl}}{p^2 + p(\alpha_{aa} + \alpha_{ga} + \alpha_{gl} + \alpha_{god}) + \alpha_{aa}(\alpha_{gl} + \alpha_{god})}; \quad (6)$$

$$\alpha_{aa} = \frac{1}{R_a C_a}; \alpha_{ga} = \frac{1}{R_a C_g}; \alpha_{gl} = \frac{1}{R_l C_g}; \alpha_{god} = \frac{1}{C_g (R_0 + R_{god})}; \quad (7)$$

$$I_1 = \frac{U_0}{R_0 + R_d} \cdot \left(\frac{\beta}{ab} + \frac{a^2 - \alpha a + \beta}{a(a-b)} \exp(-at) - \frac{b^2 - \alpha b + \beta}{b(a-b)} \exp(-bt) \right), \quad (8)$$

where α and β are the coefficients of the numerator, a and b are the absolute values of the roots of the denominator of the conductivity of the generalized insulation replacement circuit in operator form, which are equal to the inverse values of the time constants of the leakage current.

The equalities hold for the roots of the denominator according to Vieta theorem

$$a_1 = a + b = (\alpha_{ga} + \alpha_{aa} + \alpha_{gl} + \alpha_{god}); \quad b_1 = ab = \alpha_{aa} \cdot (\alpha_{gl} + \alpha_{god}) \quad (9)$$

The coefficients of the numerator α and β can be determined through the coefficients of the absorption current A and C, taking into account the expressions for a_1 and b_1 according to formula (9)

$$\beta = \frac{b_1 C (R_0 + R_d)}{U_0}; \quad (10)$$

$$\alpha = a + \frac{\beta}{a} - \frac{A a_1 (R_0 + R_d)}{U_0}. \quad (11)$$

Now we can move on to determining the values of the parameters of the generalized substitution circuit. Taken into account that R_0 and R_d are known, and $\alpha_{god} = \alpha_1 - \alpha$, it is possible to determine the geometric capacitance

$$C_g = \frac{1}{(a_1 - \alpha)(R_0 + R_d)}. \quad (12)$$

Next, using equalities

$$\beta = \alpha_{aa} \cdot \alpha_{gl} \quad \text{and} \quad \alpha_{gl} = \frac{\alpha_{god} \cdot \beta}{b - \beta},$$

we have

$$R_l = \left(\frac{b}{\beta} - 1 \right) \cdot (R_0 + R_d), \quad (13)$$

and taking into account that

$$\alpha_{gl} = \frac{(a - \alpha) \cdot \beta}{b - \beta}, \; \alpha_{aa} = \frac{\beta}{\alpha_{gl}} = \frac{b - \beta}{a - \alpha} \; \text{and}$$

$$\alpha_{ga} = \alpha - \alpha_{aa} - \alpha_{gl},$$

we find

$$R_a = \frac{(a - \alpha) \cdot (R_0 + R_d)}{\alpha - \frac{b - \beta}{a - \alpha} - \frac{a - \alpha}{b - \beta} \cdot \beta}, \quad (14)$$

$$C_a = \frac{1}{(R_0 + R_d) \cdot (b - \beta)} \left(\alpha - \frac{a - \alpha}{b - \beta} \beta - \frac{b - \beta}{a - \alpha} \right). \quad (15)$$

It should be noted that, as shown by more detailed model calculations, the correct determination of the parameters of the insulation replacement circuit by the proposed method for the model example is possible only with a certain ratio. The charge time constant of the geometric capacitance $C_g(R_0+R_d)$ must be within $0.2 < C_g(R_0+R_d) < 1$ s, and therefore it is necessary to know or determine the capacitance of the measurement object with the appropriate accuracy in advance. Considering that for the calculation of the absorption coefficient, the absorption current is determined at 15 s and 60 s after applying the voltage, the time constant C_aR_a should be greater than 3 s. In addition, it is necessary that the product C_gR_l is greater than 0.5 s, and the leakage resistance R_l is less than the absorption resistance R_a.

To illustrate the procedure for using the three-point method, consider an example of calculating the parameter values of a model generalized insulation replacement circuit using the calculated absorption current for a circuit with known parameter values. Let's assume that $5 \cdot 10^3$ Ω, $R_0 = 2 \cdot 10^7$ Ω, $C_g = 7 \cdot 10^{-8}$ F, $R_l = 8 \cdot 10^{11}$ Ω, $C_a = 3 \cdot 10^{-8}$ F, $R_a = 6 \cdot 10^9$ Ω.Then, using (7) – (9) for the absorption current flowing through the model circuit of the replacement of the insulation, we have an expression by which it is necessary to determine the individual values of the parameters of the elements of the model replacement circuit

$$I = 1{,}69 \cdot 10^8 e^{(-0{,}0055t)} + 4{,}98 \cdot 10^6 e^{(-0{,}716t)} + 1{,}25 \cdot 10^{-10}. \quad (16)$$

To determine the values of the time constants of the exponent of the model absorption curve in the first interval, we choose the time values of 1, 2, and 3 s, and in the second – 15, 37.5, and 60 s. Using (2), (3), we find that $a = 5.5 \cdot 10^{-3}$, $b = 0.7164$, which practically coincides with the values of the time constants in (16). Now we can find the calculated coefficients of the equation, which are equal to $A = 1.686 \cdot 10^{-8}$, $B = 4.982 \cdot 10^{-6}$ and $C = 1.25 \cdot 10^{-10}$, respectively, and exactly match the actual values of the coefficients. After calculating a_1 and b_1, we find by (10), (11) $\alpha = 8 \cdot 10^{-3}$, which exactly corresponds to the original value, and a slightly underestimated $\beta = 9.9196 \cdot 10^{-8}$ at an exact value $9.9206 \cdot 10^{-8}$. Having all the necessary values, we calculate the values of the parameters of the insulation replacement circuit using (12) – (15): $C_g = 7 \cdot 10^{-8}$ F, $R_l = 8 \cdot 10^{11}$ Ω, $C_a = 3 \cdot 10^{-8}$ F, $R_a = 8 \cdot 10^{11}$ Ω, which coincide with the original values to the fourth decimal place.

The given calculation example can also be used to theoretically illustrate the advantage of knowing the individual values of the individual parameters of the insulation replacement circuit before the formal use of the absorption coefficient. The absorption coefficient for the model calculation circuit is equal to 1.18, which in practice would give formal grounds for decommissioning the insulation due to unsatisfactory characteristics. However, if we take into account that the through-flow resistance has a value of $8 \cdot 10^{11}$ Ω, and the calculated tgδ for electrical conductivity has a value of $5.7 \cdot 10^{-8}$, then we can come to the opposite conclusion – the insulation has satisfactory characteristics and is not at risk of breakdown.

Thus, the theoretical verification of the proposed model methodology shows that only in the case when the necessary relationships between the values of the insulation parameters and, accordingly, the circuit of its replacement, take place, the calculations of individual values give good accuracy. But it is necessary to keep in mind that when going beyond the above limits of parameter values, the accuracy deteriorates quite sharply.

Theoretically, it is possible to increase the accuracy of determining the values of the parameters of the substitution circuit by performing two calculations. The first calculation should be carried out under the condition that R_0 and $R_d \ll R_a$ and R_l, and the influence of external resistances on the absorption current can be neglected. Here

$$I = U_0\left(\frac{1}{R_l} + \frac{1}{R_a}\exp\left(-\frac{t}{\tau_a}\right)\right),$$

where $\tau_a = C_aR_a$ is the absorption time constant.

Having chosen three time values in the region of the decline of the absorption curve as before so that $t_2 - t_1 = t_3 - t_2 = \Delta t$, using the current values I_1, I_2 and I_3, we find their differences $\mathrm{d}I_{12} = I_1 - I_2$, $\mathrm{d}I_{23} = I_2 - I_3$ and the value of absorption time constant

$$\tau_a = \frac{\Delta t}{\ln(\mathrm{d}I_{12}/\mathrm{d}I_{23})}. \quad (17)$$

Now we can calculate the absorption resistance

$$R_a = \frac{U_0}{\Delta I_{12}}\left(\exp\left(-\frac{t_1}{\tau_a}\right) - \exp\left(-\frac{t_2}{\tau_a}\right)\right), \quad (18)$$

absorption capacitance

$$C_a = \tau_a / R_a, \quad (19)$$

and through resistance

$$R_l = \frac{U_0}{I(t_1) - \frac{U_0}{R_a}\exp\left(-\frac{t_1}{\tau_a}\right)}. \quad (20)$$

At the second stage, we need to make a calculation, choosing R_0 approximately 10^6 Ω to form the charging exponent, using (2), (3) to find the time constants a and b, and then, taking into account that the other parameters are already known almost exactly, calculate the approximate value C_g according to the formula

$$C_n = \left(abC_aR_a(R_0 + R_d)\right)^{-1}. \quad (21)$$

If the charging time constant $C_g(R_0+R_d)$ is in the range from 0.2 s to 1 s, then C_g will be determined with an accuracy no worse than a few percent, if not, then a new value of R_0 that satisfies the given condition is chosen and the calculation is repeated . Thus, in this case, despite the greater amount of work, it is possible to obtain the exact values of the three parameters that determine the absorption coefficient, and the approximate value of the fourth one.

Theoretically, it is possible to determine all values of the parameters of the insulation replacement circuit by the three-point method even with a single calculation by using, in addition to the absorption curve, also the recovery voltage. To do this, first the first stage of the preliminary calculation is repeated and the absorption current values necessary for the accurate determination of R_l, R_a and C_a are fixed, and then when simulating the method of recovery voltage (short-term insulation shorting for the discharge of the geometric capacitance to a low resistance and measurement with an electrostatic voltmeter or a voltmeter with a resistance, which significantly exceeds the resistance of the insulation, the recovery voltage on the insulation, which arises as a result of the charge of the geometric capacitance from the absorption capacity) the capacitive absorption coefficient is determined

$$k_c = \frac{U_{v\max}}{U_0} = \frac{C_a}{C_g + C_a},$$

where $U_{v\max}$ is the maximum value of the recovery voltage, and the geometric capacity

$$C_g = C_a\left(\frac{1}{k_c} - 1\right). \quad (22)$$

Note that with this model determination of the recovery voltage, the capacitive coefficient of absorption and the geometric capacitance, the possible discharge of the insulation capacitances due to its through resistance in the process of charging the geometric capacitance from the absorption one is neglected, which may lead to some overestimation of the value of the found geometric capacitance.

A more detailed theoretical study of the recovery voltage can be carried out knowing the values of the parameters of the insulation replacement circuit. Consider the case with the inclusion of R_d and R_0 in the discharge circuit, when after charging the insulation and disconnecting the voltage source, a short-term short circuit occurs. Assuming that R_d is so small (less than or equal to 10^4 Ω) that it can be neglected, consider the redistribution of charge between the capacitances C_a and C_g, as well as the discharge of C_a through R_a, R_0 and R_l and C_g through R_l and R_0 under the condition that C_a is charged to U_{ca}, and the charge on C_g is zero. Marking

$$\frac{R_lR_0}{R_l + R_0} = R_{de},$$

from the system of equations for currents I_1 and I_2 in the operator form, taking into account that $U_{rg} = I_2/(pC_g)$, we write down the expression for I_2:

$$I_2(R_{de} + R_a)\left[\frac{(p+\alpha_{gde})}{p}\frac{(p+\alpha_{aade})}{p} - \frac{R_{de}}{(R_{de}+R_a)}\right] = -U_{ca},$$

where $\alpha_{gde} = C_gR_{de}$, $\alpha_{aade} = C_a(R_a+R_{de})$, and for the recovery voltage in the operator form we have

$$U_{rg} = \frac{I_2}{pC_g} = -\frac{U_{ca}}{C_gR_{de}}\frac{p}{(p+\alpha_{aa})\cdot(p+\alpha_{gdee})},$$

or as the function of time

$$U_{rg} = \frac{U_{ca}}{C_gR_{de}}\frac{\exp(-\alpha_{aa}t) - \exp(-\alpha_{gdee}t)}{\alpha_{aa} - \alpha_{gdee}}.$$

Now we can calculate the time at which the recovery voltage has an extremum

$$t_{\max} = \frac{\ln(\alpha_{aa}) - \ln(\alpha_{gdee})}{\alpha_{aa} - \alpha_{gdee}},$$

the maximum value of the recovery voltage

$$U_{r\max} = -\frac{U_{ca}}{\alpha_{gdee}C_gR_a}\left(\frac{\alpha_{gdee}}{\alpha_{aa}}\right)^{\frac{\alpha_{gdee}}{\alpha_{aa}-\alpha_{gdee}}}$$

and the rate of recovery of the voltage on the geometric capacitance, which at $t = 0$ is

$$\frac{dU_r}{dt}\Big|_{t=0} = \frac{U_{ca}}{C_g R_a}$$

and depends not only on the parameters of the insulation replacement circuit, but also on the value of the voltage U_{ca}, to which the capacitance C_a is charged. For the classic variant of determining the recovery voltage, when initially the geometric and absorption capacitances are charged to the maximum value of the voltage U_0, the obtained formulas will be valid if $U_{ca}=U_0$ is accepted. We note that the characteristics of the recovery voltage used for diagnosis in [4] and in other works can also be calculated based on the determined individual values of the parameters of the elements of the substitution circuit, without conducting additional measurements.

To make sure of this, we consider that the voltage U_{ca} on the absorption capacitance can be obtained with an incomplete charge of the insulation. If a geometric capacitance is charged through a small resistance (10^6 – 10^7) Ω, so that its charge constant is less than 0.1 s, then with such an absorption constant time, the voltage equal to the applied U_0 will actually occur on the insulation after a second, and the absorption capacitance will be charged with an absorption time constant and the voltage on it will be

$$U_a = U_0\left(1-\exp(-\alpha_{aa}t)\right).$$

If we limit the process of applying the constant voltage to the insulation due to a small limiting resistance by time

$$\Delta t = -\frac{1}{\alpha_{aa}}\ln\left(1-\frac{U_{ca}}{U_0}\right),$$

the absorption capacitance will charge up to the voltage U_{ca}. Then it is necessary to discharge the geometric capacitance to low resistance to zero voltage in a short time and record the increase in voltage on the geometric capacitance due to its charge from the absorption capacitance, which is described above.

Recalculation of the parameters of the generalized equivalent circuit to other insulation replacement circuits. Using the parameter values found above for the generalized equivalent insulation replacement circuit, it is possible to find individual parameter values for other four-element circuits reflecting the possibility of through-current flow (see Fig. 1). Theoretically, the conditions of identity of the response to the action of an external constant electric field can be obtained, for example, by equating their transient characteristics in operator form.

Having chosen as the main one the generalized substitution circuit considered above, shown in Fig. 1,*a*, we will find the relationship between the parameters of different equivalent circuits corresponding to the same time dependence of the current through the dielectric by solving the systems of equations obtained by equating the corresponding coefficients of transient conductances in the operator form at different powers of the operator *p*. In parallel we will also consider the transition from the parameter values of equivalent insulation replacement circuits to the parameter values of the generalized replacement circuit and present formulas for calculating the absorption coefficient for different insulation replacement circuits. For the equivalent circuit of a two-layer dielectric (Fig. 1,*b*), the conductivity in the operator form is equal to

$$Y_2 = \frac{C_1C_2}{C_1+C_2}\,\frac{p^2+p(\alpha_{11}+\alpha_{22})+\alpha_{11}\alpha_{22}}{p+\alpha_{2e}}, \qquad (23)$$

where

$$\alpha_{11} = \frac{1}{R_1C_1};\quad \alpha_{22} = \frac{1}{R_2C_2};\quad \alpha_{2e} = \frac{R_1+R_2}{R_1R_2(C_1+C_2)}.$$

From a comparison of formulas (6) for Y_1 and (23) for Y_2, we write down a system of equations for the transition from the substitution circuit in Fig. 1,*b* to the substitution circuit in Fig. 1,*a* and vice versa, using the parameters of the elements of the equivalent circuits:

$$C_g = \frac{C_1C_2}{C_1+C_2}; \qquad (24)$$

$$\frac{1}{C_aR_a}\,\frac{1}{C_gR_l} = \frac{1}{C_1R_1}\,\frac{1}{C_2R_2}; \qquad (25)$$

$$\frac{1}{C_gR_a}+\frac{1}{C_aR_a}+\frac{1}{C_gR_l} = \frac{1}{C_1R_1}+\frac{1}{C_2R_2}; \qquad (26)$$

$$\frac{1}{C_aR_a} = \frac{R_1+R_2}{R_1R_2(C_1+C_2)}. \qquad (27)$$

Equation (24) immediately gives the expression for C_g in terms of C_1 and C_2. From (25), taking into account (24), (27), we have

$$R_l = R_1 + R_2. \qquad (28)$$

Substituting the appropriate values into (26) and performing the necessary transformations, as well as taking into account (7) for α_{aa}, we obtain

$$R_a = \frac{R_1R_2(R_1+R_2)\cdot(C_1+C_2)}{(C_1R_1-C_2R_2)^2}; \qquad (29)$$

$$C_a = \frac{(C_1R_1-C_2R_2)^2}{(C_1+C_2)(R_1+R_2)^2}. \qquad (30)$$

The reverse determination of the coefficients for the transition from the circuit in Fig. 1,*a* to the circuit in Fig. 1,*b* is better carried out by first determining α_{11} and α_{22}. To find α_{11} and α_{22}, we use the system of two equations (25), (26), written in the form

$$\begin{cases}\alpha_{11}\alpha_{22} = \alpha_{aa}\alpha_{gl} = A;\\ \alpha_{11}+\alpha_{22} = \alpha_{aa}+\alpha_{ga}+\alpha_{gl} = B.\end{cases} \qquad (31)$$

Having found α_{11} and α_{22}, as well as taking into account equations (27), (28), it is possible to write the parameters of the elements of the insulation replacement circuit in Fig. 1,*b* through the parameters of the elements of the replacement circuit in Fig. 1,*a*, as well as the expression for the absorption coefficient:

$$C_1 = \frac{\alpha_{aa}(\alpha_{11}-\alpha_{22})}{R_l\alpha_{11}\alpha_{22}(\alpha_{11}-\alpha_{aa})};\quad C_2 = \frac{\alpha_{aa}(\alpha_{22}-\alpha_{11})}{R_l\alpha_{11}\alpha_{22}(\alpha_{22}-\alpha_{aa})}.$$

The absorption coefficient for the circuit in Fig. 1,*b* is equal to

$$k_a = \frac{1+d_{1b}\exp(-60\alpha_{1b})}{1+d_{1b}\exp(-15\alpha_{1b})},$$

where $d_{1b} = \dfrac{(R_1C_1-R_2C_2)^2}{R_1R_2(C_1+C_2)^2}$, $\alpha_{1b} = \dfrac{R_1+R_2}{R_1R_2(C_1+C_2)}$.

For the substitution circuit in Fig. 1,*c*, we have the transient characteristic in the form

$$Y_3 = C_g \frac{p^2 + p(\alpha_{gs} + \alpha_{3s} + \alpha_{33}) + \alpha_{gs}\alpha_{33}}{p + \alpha_{3e}}, \quad (32)$$

where $\alpha_{gs} = \frac{1}{R_s C_g}$; $\alpha_{3s} = \frac{1}{R_3 C_s}$; $\alpha_{3e} = \frac{R_s + R_3}{R_s R_3 C_1}$.

After comparing the coefficients at different degrees of the operator p in the numerator and denominator for (32) and (6), we obtain formulas for recalculating the coefficients of the generalized insulation replacement circuit (Fig. 1,*a*) to the coefficients of the circuit (Fig. 1,*c*) and vice versa. Taking into account that C_g remains unchanged, we have:

$$C_g = C_g, R_l = R_3 + R_s, R_a = \frac{R_s}{R_3}(R_3 + R_s), C_a = C_3\left(\frac{R_3}{R_3 + R_s}\right)^2.$$

The reverse transition from the circuit in Fig. 1,*a* to the circuit in Fig. 1,*c* corresponds to the formulas:

$$C_g = C_g, R_3 = \frac{R_l^2}{R_a + R_l}, R_s = \frac{R_a R_l}{R_a + R_l}, C_3 = C_a\left(1 + \frac{R_a}{R_l}\right)^2,$$

and the absorption coefficient, expressed in terms of the parameter values of the circuit elements (Fig. 1,*c*), is equal to

$$k_a = \frac{R_s + R_3\exp(-60\alpha_{1v})}{R_s + R_3\exp(-15\alpha_{1v})}, \; \alpha_{1v} = \frac{R_s + R_3}{R_s R_3 C_3}.$$

For the circuit (Fig. 1,*d*), the transient conductivity in operator form is equal to

$$Y_4 = \frac{C_4 C_s}{C_4 + C_s} \cdot \frac{p^2 + p(\alpha_{sl} + \alpha_{4l} + \alpha_{44}) + \alpha_{sl}\alpha_{44}}{p + \alpha_{4e}}, \quad (33)$$

where $\alpha_{sl} = \frac{1}{R_l C_s}$; $\alpha_{4s} = \frac{1}{R_l C_4}$; $\alpha_{4e} = \frac{1}{R_4(C_4 + C_s)}$.

The transition from the circuit in Fig. 1,*d* to the circuit in Fig. 1,*a*, taking into account (33) and the obvious equality of R_l, is possible according to the formulas obtained as a result of solving the corresponding system of equations:

$$R_l = R_l, C_g = \frac{C_s C_4}{C_s + C_4}, R_a = R_4\left(1 + \frac{C_4}{C_s}\right)^2, C_a = \frac{C_s^2}{(C_s + C_4)}.$$

The transition from the circuit in Fig. 1,*a* to the circuit in Fig. 1,*d* and the absorption coefficient is described by the formulas

$$R_l = R_l, C_s = C_g + C_a, C_4 = C_g\left(1 + \frac{C_g}{C_a}\right), R_4 = R_a\left(\frac{C_a}{C_a + C_g}\right)^2.$$

Absorption coefficient for the circuit in Fig. 1,*d*

$$k_a = \frac{R_4 + d_{1g}\exp(-60\alpha_{1g})}{R_4 + d_{1g}\exp(-15\alpha_{1g})},$$

where $d_{1g} = \frac{C_b^2 R_b}{(C_b + C_4)^2}$; $\alpha_{1g} = \frac{1}{(C_b + C_4)R_4}$.

To illustrate the equivalence of insulation replacement circuits, consider, as an example, the case when the determined values of the parameters of the elements of the generalized equivalent insulation circuit are equal to $C_g = 10^{-9}$ F, $C_a = 10^{-10}$ F, $R_l = 10^{12}$ Ω, $R_a = 2 \cdot 10^{11}$ Ω. Then the calculated values of the parameters of the elements of other equivalent circuits will be: for the circuit in Fig. 1,*b* – $C_1 = 1.098 \cdot 10^{-9}$ F, $C_2 = 1.114 \cdot 10^{-8}$ F, $R_1 = 9.968 \cdot 10^{11}$ Ω, $R_2 = 1.557 \cdot 10^{9}$ Ω; for the circuit in Fig. 1,*c* – $C_g = 9.997 \cdot 10^{-9}$ F, $C_3 = 1.353 \cdot 10^{-10}$ F, $R_p = 1.69 \cdot 10^{11}$ Ω, $R_3 = 8.31 \cdot 10^{11}$ Ω; for the circuit in Fig. 1,*d* – $C_b = 1.093 \cdot 10^{-9}$ F, $C_2 = 1.169 \cdot 10^{-8}$ F, $R_b = 9.999 \cdot 10^{11}$ Ω, $R_2 = 1.486 \cdot 10^{9}$ Ω.

As the calculation based on the listed values of the parameters shows, different substitution circuits give practically the same absorption curves and the same absorption coefficient, which for this case is equal to 2.156. At the same time, the interpretation of the results depending on the insulation replacement circuit will be different due to, as already noted, the different structure of the circuits.

The authors would like to make a few remarks regarding the practical application of the methodology for determining the individual values of the parameters of the elements of the insulation replacement circuits proposed in this article.

In practice, even knowing the values of the parameters of the substitution circuit does not lead to an unambiguous interpretation of the results obtained in the process of diagnosis. When assessing the technical condition of the electrical insulation, it should be taken into account that the change in R_l will correspond to both reversible and irreversible changes in the insulation. Of the reversible changes, it is necessary to distinguish, first of all, heating and moistening of the insulation. Irreversible changes in the insulation can occur as a result of diffusion, chemical, electrochemical processes or as a result of mechanical destruction by the thermal fluctuation mechanism. First of all, the leakage resistance should be affected by the carbonization of organic components during significant overheating, the formation of conductive channels (tracking or treeing) as a result of the action of partial discharges on organic materials or the reduction of metal oxides due to electrolysis, especially at constant voltage, in the case of inorganic materials.

An increase in C_a will indicate an increase in the degree of macroinhomogeneity (the formation of macroscopic defects in the insulation, such as cracks, cavities, delamination, etc., as well as a local change in electrophysical characteristics due to aging in an inhomogeneous field), and a decrease in R_a will indicate an increase in the defectivity of the insulation on microscopic level.

With the practical use of our proposed method, knowledge of the individual values of the parameters of the a priori selected insulation replacement circuits in the presence of information about the composition, properties and operation mode of the insulation will also allow to determine the contribution of different phases to the properties of heterogeneous or composite insulation and to orientate in the physical essence of the processes occurring at its aging in operation. However, due to the wide variety of structures and combinations of properties of insulation components, the question of interpretation of measurement results requires a separate consideration in each specific case.

Conclusions. The article describes the scientific basis of the method of determining the individual values of the parameters of the four-element insulation replacement circuits using the example of the generalized replacement circuit. To calculate these values, a three-point method was used, when readings of absorption current values are selected so that $t_2 - t_1 = t_3 - t_2$, while the constant component of the current is eliminated, and the parameters of the exponential components used in the calculation of the parameter values are consistently determined without error. The formulas for the mutual recalculation of the individual values of the parameters of the elements of the four-element insulation replacement circuits with through conductivity are given and it is shown that the accuracy of the calculation is satisfactory. The possibility of constructing known diagnostic parameters using individual parameter values of the elements of the generalized insulation replacement circuit is shown.

It is noted that within the framework of absorption diagnostic methods, the problem of determining the technical condition of insulation based on the results of the step voltage response study does not have an unambiguous solution. The choice of the substitution circuit and the interpretation of the measurement results should be based on a priori information about the processes taking place in the insulation, or a hypothesis about its structure and properties.

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REFERENCES

1. Protsenko O.R. *Diagnostics of the electrical equipment condition. Course of lectures*. Kyiv, Igor Sikorsky Kyiv Polytechnic Institute Publ., 2022. 162 p. (Ukr).

2. Németh B., Csépes G., Vörös C. Applicability of the dielectric response methods of diagnostics of power transformers: Hungarian experiences. *2011 Electrical Insulation Conference (EIC)*, 2011, pp. 49-53. doi: https://doi.org/10.1109/EIC.2011.5996114.

3. Saha T.K., Purkait P., Muller F. Deriving an Equivalent Circuit of Transformers Insulation for Understanding the Dielectric Response Measurements. *IEEE Transactions on Power Delivery*, 2005, vol. 20, no. 1, pp. 149-157. doi: https://doi.org/10.1109/TPWRD.2004.835436.

4. Soni G., Dutta S., Baral A. Condition Monitoring of Power Transformer Insulation by Return Voltage Measurement. *2021 IEEE 5th International Conference on Condition Assessment Techniques in Electrical Systems (CATCON)*, 2021, pp. 108-112. doi: https://doi.org/10.1109/CATCON52335.2021.9670485.

5. Sarkar S., Sharma T., Baral A., Chatterjee B., Dey D., Chakravorti S. A new approach for determination of moisture in paper insulation of in-situ power transformers by combining polarization-depolarization current and return voltage measurement results. *IEEE Transactions on Dielectrics and Electrical Insulation*, 2013, vol. 20, no. 6, pp. 2325-2334. doi: https://doi.org/10.1109/TDEI.2013.6678886.

6. Gavrilă D.E., Ciprian I., Gavrilă H.C. Applying the Recovery Voltage Method (RVM) to Study the Degradation of High Power Transformer Insulation. *Advanced Materials Research*, 2014, vol. 911, pp. 260-265. doi: https://doi.org/10.4028/www.scientific.net/amr.911.260.

7. Martinez M., Pleite J. Improvement of RVM Test Interpretation Using a Debye Equivalent Circuit. *2019 6th International Advanced Research Workshop on Transformers (ARWtr)*, 2019, pp. 105-110. doi: https://doi.org/10.23919/ARWtr.2019.8930187.

8. Hubarevych O.V. *Reliability and diagnostics of electrical equipment*. Syevyerodonetsk, V. Dahl EUNU Publ., 2016. 248 p. (Ukr).

9. Khamevko O.N., Sushko D.L. Analysis of methods control and diagnostic parameters isolation the traction engine of direct current. *Collected scientific works of Ukrainian State University of Railway Transport*, 2014, no. 147, pp. 152-155. (Ukr). doi: https://doi.org/10.18664/1994-7852.147.2014.75121.

10. *IEEE Std 43-2000. Recommended Practice for Testing Insulation Resistance of Rotating Machinery*, 2000, 28 p. doi: https://doi.org/10.1109/IEEESTD.2000.91301.

11. Stone G.C., Sasic M. Experience with DC polarization-depolarization measurements on stator winding insulation. *2013 IEEE Electrical Insulation Conference (EIC)*, 2013, pp. 7-10. doi: https://doi.org/10.1109/EIC.2013.6554191.

12. Tamus Z.A., Berta I. Application of voltage response measurement on low voltage cables. *2009 IEEE Electrical Insulation Conference*, 2009, pp. 444-447. doi: https://doi.org/10.1109/EIC.2009.5166387.

13. Filipović-Grčić B., Filipović-Grčić D., Uglešić I. Modeling of polarization in oil-paper insulation using recovery voltage measurements. *International Review of Electrical Engineering*, 2011, vol. 6, no. 1, pp. 430-437.

14. Bezprozvannych G.V., Kostukov I.O., Moskvitin E.S. Differentiation of absorption processes in inhomogeneous insulation by curve of recovering voltage of power high voltage cables. *Technical Electrodynamics*, 2021, no. 6, pp. 13-19. doi: https://doi.org/10.15407/techned2021.06.013.

15. Bezprozvannych, G. V., Moskvitin, E. S., & Kyessayev, A. G. The absorption characteristics of the phase and zone paper-impregnated insulation of power cable at direct voltage. *Electrical Engineering & Electromechanics*, 2015, no. 5, pp. 63-68. doi: https://doi.org/10.20998/2074-272X.2015.5.09.

16. *SOU-N-EE-20.302:2007. Testing norms for electrical equipment*. Kyiv, DP MOU «Voienne vydavnytstvo Ukrainy «Varta», 2007. 262 p. (Ukr).

17. Bezprozvannych G.V. Physical interpretation of the recovery voltage curves based on the equivalent circuits of an inhomogeneous dielectric. *Technical Electrodynamics*, 2009, no. 6, pp. 23-27. (Rus).

18. Bezprozvannych G.V., Kostiukov I.A. Error of control of electrical insulation structures by dielectric absorption parameters according to the concept of uncertainty of measurements. *Electrical Engineering & Electromechanics*, 2020, no. 1, pp. 47-51. doi: https://doi.org/10.20998/2074-272X.2020.1.07.

19. Bezprozvannych G.V., Kostiukov I.A. A method of wavelet analysis of time series of parameters of dielectric absorption of electrical insulating structures. *Electrical Engineering & Electromechanics*, 2020, no. 2, pp. 52-58. doi: https://doi.org/10.20998/2074-272X.2020.2.08.

20. Kyrylenko V.M., Kyrylenko K.V., Budko M.O., Denysiuk P.L. Reasoning of additional diagnostic parameters for electric insulation diagnostics by absorption methods. *Electrical Engineering & Electromechanics*, 2021, no. 6, pp. 39-45. doi: https://doi.org/10.20998/2074-272X.2021.6.06.

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V.M. Kyrylenko[1], *PhD, Assistant Professor,*
K.V. Kyrylenko[1], *PhD,*
[1] National Technical University of Ukraine
«Igor Sikorsky Kyiv Polytechnic Institute»,
37, Prospect Peremohy, Kyiv-56, 03056, Ukraine,
e-mail: vsemychkirg@gmail.com (Corresponding Author)

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