KAUNAS UNIVERSITY OF TECHNOLOGY

LITHUANIAN ENERGY INSTITUTE

Kęstutis Jasiūnas

QUALITY AND RESOURCE INVESTIGATION OF HIGH VOLTAGE EQUIPMENT COMPLEX INSULATION

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The scientific work was carried out in 1999-2004 at Kaunas University of Technology, Department of Electric Power Systems.

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AUKŠTOSIOS ĮTAMPOS ĮRENGINIŲ KOMBINUOTOSIOS IZOLIACIJOS KOKYBĖS IR RESURSO TYRIMAI

Daktaro disertacijos santrauka
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Su disertacija galima susipažinti Kauno technologijos universiteto (K. Donelaičio g. 20, Kaunas) ir Lietuvos energetikos instituto (Breslaujos g. 3, Kaunas) bibliotekose.

Relevance of the problem

Complex insulation is used in transformers (power, measuring, voltage regulation), capacitors and bushings, therefore it plays an important role in the operation of electric equipment. The reliability and lifetime of the aforesaid equipment is highly dependent on the quality of insulation. The advantage of oil-paper insulation lays in the possibility of complete restoration of its quality in the cases of timely identified defects.

In the operation of electric equipment the quality of complex insulation is dependent on various factors; among these the most important is the water, which might accumulate in the paper, barriers and oil, hence influencing dielectric properties, lifetime and obsolescence.

The quality assessment of complex insulation is an actual problem; various methods are being applied for its solution. New methods, which would enable to more efficiently assess the quality of insulation, are being searched for.

The assessment of water quantity and the analysis of its variation enables to more precisely identify the nature of defects and to carry out the prevention of operation failures, high quality restoration of resource and, respectively, to extend the equipment's lifetime.

According to the statistical data, in the period of 1998-2002 about one fifth of all faults occurred in high voltage equipment with oil-paper insulation. The losses in the transmission grid, incurred resultant of these faults were rather high. An irreparable fault in the insulation of 200 MVA power transformers might cost up to LTL 10 million. In this context we face a complicated task: to assess the quality and resource of insulation mainly depending on the water quantity, however, without deteriorating its quality.

In 1990-2001, in the electricity industry of Lithuania the electricity consumption and transformers load dropped nearly three times. The increase of water content in oil – paper insulation was observed. Apart from other factors, this process was influenced by the aging of equipment.

In the transmission grid 56 % of power transformers (total capacity - 3159 MVA) have been operated for more than 20 years, 31 % of them have been operated for more than 25 years. In the distribution networks 37 % of power transformers are older than 20 years, their total capacity equals 1999 MVA.

Subsequent to the analysis of the research models on the moisture content and worked out method of their application, it is possible, without causing damage to the insulation itself, to more precisely assess the quality of transformer insulation and its resource. Both in the transmission and in the distribution systems it would be possible to reach higher quality in transformers' operation and to use more efficiently the funds allocated for investments and maintenance by applying the prepared method of the water quantity assessment.

Aim of the work

1. To analyze the methods used for the quality and resource assessment of complex insulation;

2. To develop the models for the assessment and analysis of polarization features, dielectric parameters and moisture content in oil- paper insulation;

3. To develop the method for the assessment of moisture quantity by measuring the polarization characteristics;

4. To analyze the impact of water quantity on dielectric parameters of transformer insulation;

5. To classify the quality criteria of oil-paper insulation;

6. To identify the tendencies in variation of insulation's dielectric parameters and moisture quantity;

7. To implement the developed models and methods in the electricity industry of Lithuania for the assessment of the transformers' insulation quality and resource.

Scientific novelty of the work

The transformer insulation defects occurring during transformer operation because of its moistened components were analyzed and classified. The methods used in the quality assessment of complex insulation with regard to the moisture content in paper layer, barriers and oil channels were analyzed and classified.

The models of triple-layer complex insulation (two layers – of solid state, and one- of liquid state) were developed to calculate the polarization characteristics and recovery voltage. The peculiarities of algorithms used in the models were analyzed. The investigation method of the aforesaid models was developed for the assessment of moisture content in oil-paper insulation (paper layer, barriers and oil channels).

The model was developed for the evaluation of moisture content in the layers of complex insulation by means of analysis of dielectric properties and their variation. The research method was worked out. The methodology for the research model of transformer insulation's dielectric properties and for the compilation of databases of respective measurements was compiled.

The influence of the moisture content in oil-paper insulation layers on the polarization characteristics and dielectric parameters was analyzed. The functional dependencies between the complex insulation's dielectric parameters and the moisture content in paper layers, barriers and oil channels were identified.

Practical value of the work

The method of measurement of the polarization characteristics and recovery voltage has been applied in the assessment of moisture content and variation of water quantity in the transformer insulation components (paper layer, barriers and oil channels).

The method used for the development of the calculation models of polarization characteristics and recovery voltage has been applied in the real model of transformer insulation and for the calculation of its parameters.

The model of the variation analysis of dielectric parameters and the respective method has been applied in the examination of the variation tendencies of moisture content in transformer insulation. The polarization characteristics and dielectric parameters of oil-paper insulation components have been classified depending on their moisture content.

Investigation of variation tendencies of the water quantity, the application of the aforesaid models and method enables to assess more accurately the quality and resource of transformer insulation. The examined functional dependence of the polarization time constant on the temperature has enabled to more accurately determine the moisture content in transformer insulation.

Presents for the pleading

1. The triple-layer models of oil-paper insulation to calculate the characteristics of recovery voltage and polarization. The creation methods of above mentioned models.
2. The methods to be used for the quality assessment of complex insulation by analyzing its dielectric parameters, defining polarization characteristics and the moisture content.
3. The impact of moisture on the quality of paper layer, barriers and oil layer was investigated by applying the method for the evaluation of polarization characteristics of complex insulation and moisture content. The criteria to be used for the quality assessment of complex insulation were grouped and classified depending on the moisture content in the paper layer, barriers and oil.
4. The variation tendencies of transformer's dielectric parameters were investigated and the consistent patterns were established by using the method for the analysis of complex insulation dielectric parameters.
5. The experimental results of investigation on the oil-paper insulation quality, polarization characteristics and water content established by measuring the recovery voltage was carried out.
6. The functional dependencies of dielectric parameters on the water quantity in transformer insulation (in paper layer, barriers and oil layer).
7. The resource of transformers insulation and patterns of its variation was established with regard to the variation tendencies of dielectric parameters and their functional dependencies on the water quantity.

Approval of the work

The material of the dissertation was presented at five international scientific conferences: "XI International Conference on Electromagnetic Disturbances", Bialystok Technical University, 2001; "XII International Conference on Electromagnetic Disturbances", Kaunas University of Technology, 2002; „Power and electrical engineering", Sejums 5, Riga

Technical University, 2002; “XIII International Conference on Electromagnetic Disturbances”, Bialystok Technical University, 2003; International conference of power transformer „Transformer 03“, Pieczyska, 2003.

In Lithuania the material of the dissertation was presented at five scientific conferences: “Energy and Electric Engineering Technologies”, Kaunas, KTU, 1999, 2000, 2001, 2003; „Electronics and Electric Engineering“, Vilnius, VGTU, 2000.

The subject of the dissertation was publicized in 14 scientific publications, 5 of them - in the publications assigned for the Doctor’s dissertation by the Science Council of Lithuania. Five publications were publicized in the international scientific journals, nine - published in Lithuania.

Structure of the dissertation

The constituent parts of the dissertation are: Introduction, 4 Chapters, Conclusions and List of References. The dissertation is comprised of 118 pages, 47 figures and 12 tables. The List of References includes 90 titles.

1. Methods and criteria of quality and resource assessment of complex insulation

The survey of the methods used in the quality and resource assessment of complex insulation illustrates the importance of the evaluated characteristics and criteria as well as the efficiency of the already used diagnostic structures. The aim of the aforesaid survey is to establish the drawbacks of the current methods of quality and resource assessment as well as to provide proposals for the improvement of diagnostic efficiency.

The characteristics (Fig. 1) classified under the category *Quality Characteristics of Liquid Oil Insulation* define the quality of an oil layer in complex insulation. The most efficient application of the assessment of the oil layer’s quality characteristics is the observation of the transformers’ status and its variation. The observation of the status of 330-110 kV transformer insulation enables to identify the deterioration of the oil’s quality and the internal transformer’s faults. The above-mentioned observation system of the oil quality characteristics is not suitable for hermetic transformers.

The drawback of the assessment of the oil layer’s quality characteristics and observation system is such that during frequent oil sampling (as well as in refilling its quantity in the transformer up to the required oil level) the oxidation process is accelerated, air and moisture penetrate inside and the insulation resource decreases.

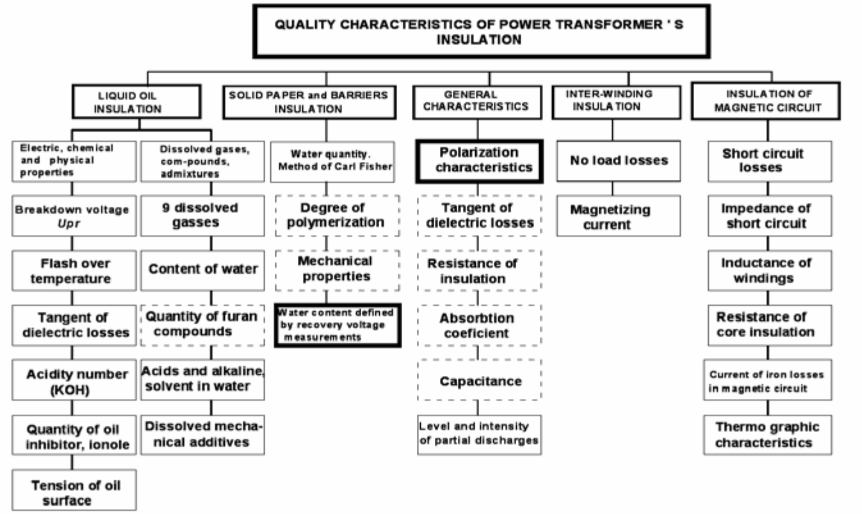

Fig. 1. Quality characteristics of power transformers insulation

The characteristics (Fig. 1) classified under the category *Quality Characteristics of Solid Paper Insulation* for a long time were inspected during maintenance and internal overhaul of power transformers, with discharged insulating oil. Pieces of paper insulation were sampled from the surface of the windings' insulation. Thus in the course of operation (between or prior to the maintenance works) the moisture content in paper insulation and barriers remained unknown.

The complex insulation characteristics (Fig. 1) defining the general quality parameters are classified under the category *General Quality Characteristics of Insulation.* These characteristics are measured: 1) prior to the start-up of the equipment's operation (to establish compliance with the requirements of normative documents and to measure the initial values); 2) in the course of operation, in the time periods prescribed by the normative documents; 3) when the properties of liquid insulation deteriorate; 4) in the case of short circuit occurring close to or inside the transformer; 5) in the cases of the transformer's gas relay operating or uncertainties regarding the quality of insulation; 6) prior to the transformer's maintenance or renovation of insulation (to project the scope of maintenance works, to establish the quality of insulation in order not to deteriorate it during the maintenance or renovation works); 7) after the transformer's maintenance or renovation of insulation (to examine the quality of maintenance or renovation and impact on the properties).

Under the category "Quality characteristics of inter-winding insulation" (Fig. 1) the respective characteristics representing the quality of inter-winding oil-paper insulation have been analyzed. They are measured after the manufacturing, prior to start-up of operation and maintenance.

Under the category Quality Characteristics of Magnetic Circuit Insulation (Fig. 1) the respective quality characteristics of the quality of magnetic circuit insulation have been analyzed. They are measured after the manufacturing, prior to start-up of operation and maintenance.

Recently some common global tendencies in searching for the assessment methods of the transformer insulation quality, which would enable to more explicitly evaluate the insulation quality and subsequently – to carry out its monitoring, have been observed. The method of recovery voltage, assigned to the group of capacitance – time methods has been investigated. In Lithuania as well as in other countries in Europe and the world this method is making the very first steps from theoretical models to more complex ones, complying with the specifics of actual measurements. The polarizations of water molecules in the components of complex insulation under the conditions of direct voltage constitute the physical basis of the aforesaid method.

In compiling the research models of polarization characteristics and moisture content in transformer insulation, the following elements described in scientific literature have been used.

C_G and R_G – capacitance – resistance of complex insulation exclusively depending on geometrical dimensions of the insulation's construction and not related to the insulation's polarization properties.

C_{pi} and R_{pi} – capacitance and resistance of the transformer insulation's layer *i,* the value of which depends on the polarization properties.

The polarization process of water molecules in the insulation layer is represented by the model of R_{pi} and C_{pi} circuit connected in series. The constant of polarization time τ_{pi} is directly dependent on the water quantity in paper layers, barriers and oil channels. The relationship among R_{pi}, C_{pi} and τ_{pi} is represented by the equation often found in scientific literature:

$$\tau_{pi} = R_{pi} \cdot C_{pi} . \qquad (1)$$

When the method of recovery voltage is applied, the insulation of one winding in the transformer is charged with a positive charge during the time t_C, and it attracts electrons from the outer layers of water molecules. When the electrons are shifted, the water molecules become polarized. Polarized molecules move towards the electric field. The polarized water molecules gain a respective total charge. When the voltage supply is terminated, the charge is partially discharged (when the winding with a positive charge is interconnected with the uncharged one). When this interconnection is separated, the voltage (charge) U_r appears between the polarized windings, and is called a recovery voltage.

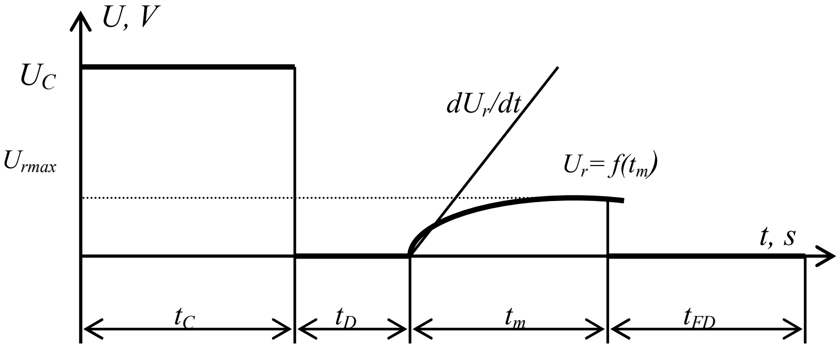

Fig. 2. Measurement diagram of recovery voltage

When the discharge time of a winding with a positive charge is $t_D = t_C / 2$, the transformer insulations τ_p will be approximately equal to the same value of the paper layers and the value t_C. During the partial discharge, the water molecules accumulated in oil loose their charge. When the recovery voltage is measured, its value increases from 0 up to $U_{r\,max}$. $U_{r\,max}$, this being the maximum measured value of the recovery voltage depending on the number of water molecules accumulated in water. By adjusting t_C and, respectively, its duration t_D, the most important polarization characteristic – the spectrum of polarization, the curve $U_{rmax}=f(t_C)$ - is measured.

The value τ_p described by the equation (1) represents a certain time period t_C, during which the transformer's insulation is charged, the biggest number of water molecules becomes polarized and the value $U_{r\max}$ is measured.

The set of the cycles t_C, t_D, t_m and t_{FD} (Fig. 2) represent the procedure of recovery voltage measurement and moisture content assessment by: 1) charging the insulation with the direct voltage charge U_C during the time period t_C; 2) electric discharge during the time $t_D=t_C/2$; 3) measurement of recovery voltage U_{rmax} during the time t_m; 4) complete electric discharge during t_{FD}.

2. Quality research models in complex insulation and method of the calculation

The calculation models have been compiled to make an analytical research regarding the impact of moisture content in the paper layer, barriers and oil channels on the quality of complex insulation and the polarization characteristics.

The above mentioned models simulate the measurement of recovery voltage in the oil-paper insulation.

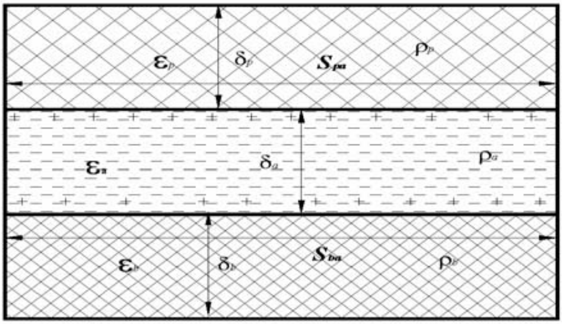

Fig. 3. Composition of a complex insulation layers

The method systematizes the compilation of complex insulation models and facilitates the mathematical calculations and research.

The transformer insulation represents a complicated complex of oil, barriers and paper. Therefore it is important not only to examine the status of a paper layer, but also the quality of barriers and an oil layer. The layers of the complex insulation are shown in (Fig. 3).

The parameters of triple-layer complex insulation (Fig. 3): S_{pa} – the overlaying area of oil and paper layers, S_{ba} – the overlaying area of oil and barrier layers, ρ_p – specific resistivity of paper layer; ρ_a – specific resistivity of oil layer, ρ_b - specific resisitivity of barriers, ε_p – dielectric permeability of paper layer, ε_a – dielectric permeability of oil layer, ε_b – dielectric permeability of barriers, δ_a – thickness of oil layer, δ_b – thickness of paper layer, δ_b – thickness of barriers.

For the research of quality characteristics in transformer insulation (the polarization characteristics and moisture content) by measuring the recovery voltage in accordance with the composition of a complex insulation layer provided in Figure 3 herein, the oil-paper insulation model consisting of capacitances and resistances has been compiled and examined, and it is illustrated by (Fig. 4).

In the model illustrated by (Fig. 4): C_{pbag} – geometric capacitance of oil-paper insulation, R_{pg} – geometric resistance of complex insulation, C_{pp} – polarization capacitance of paper layer, R_{pp} – polarization resistance of paper layer, C_{ap} – polarization capacitance of oil layer, R_{ap} – polarization resistance of oil layer, C_{bp} – polarization capacitance of barriers, R_{bp} – polarization capacitance of barriers.

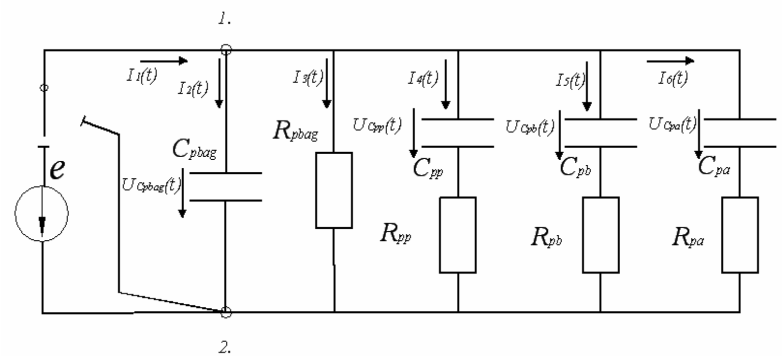

Fig. 4. General model for research of polarization characteristics and moisture content in oil-paper insulation by measuring the recovery voltage

For the research of oil-paper insulation model the electric circuit provided hereunder has been compiled; It's branches consist of the parts of the circuit with a DC supply source e, and capacitances C_{pbag}, C_{pp}, C_{ap}, C_{bp} (Fig. 4). The part of the model with the resistance R_{pbag} is selected as the additional branch of the circuit.

The research model of oil-paper insulation polarization characteristics will comply with the model provided in (Fig. 4), if the following conditions are satisfied:

– the specific resistance and dielectric permeability of a paper layer is not equal to the specific resistance and dielectric permeability of barriers – $\rho_p \neq \rho_b$ and $\varepsilon_p \neq \varepsilon_b$ (the moisture content is not the same);

– the specific resistance and dielectric permeability of an oil layer surrounding the paper layer is not equal to the specific resistance and dielectric permeability of an oil layer surrounding the barriers – $\rho_{ap} \neq \rho_{ab}$ and $\varepsilon_{ap} \neq \varepsilon_{ab}$ (emulsified moisture accumulated in oil channels, between the barriers);

– the polarization capacitance of a paper layer is not equal to the polarization capacitance of the barriers (the moisture content is not the same) – $C_{pp} \neq C_{bp}$;

– the polarization capacitance of an oil layer surrounding the paper layer is not equal to the polarization capacitance of an oil layer surrounding the barriers (emulsified moisture accumulated in oil channels, between the barriers) – $C_{ap} \neq C_{ab}$;

– the polarization resistance of a paper layer is not equal to the polarization resistance of barriers (the moisture content is not the same) – $R_{pp} \neq R_{bp}$;

– the polarization resistance of oil surrounding the paper layer is not equal to the polarization resistance of oil surrounding the barriers (emulsified moisture accrued in oil channels, between the barriers) – $R_{ap} \neq R_{ab}$;

– the polarization time constant of a paper layer is not equal to the polarization time constant of barriers – $t_{cp} \neq t_{cp}$ (the moisture content is not the same);

– the polarization time constant of oil around the paper layer is not equal to the polarization time constant of oil around the barriers – $t_{cap} \neq t_{cab}$ (emulsified moisture accrued in oil channels, between the barriers).

For the analysis of the general model (Fig. 4), node 1. and single loops I, II, III, IV and V of the electric circuit (Figure 4), by applying the first and the second Kirchhof laws, the following system of differential equations was made:

$$\left.\begin{aligned}
&\frac{dU_{C_{pbag}}}{dt}=\frac{1}{C_{pbag}}\cdot\left[\frac{1}{R_{pp}}(U_{C_{pbag}}(t)-U_{C_{pp}}(t))+\frac{1}{R_{pb}}(U_{C_{pbag}}(t)-U_{C_{pb}}(t))+\frac{1}{R_{pa}}(U_{C_{pbag}}(t)-U_{C_{pa}}(t))+I_3(t)-I_1(t)\right],\\
&U_{C_{pbag}}(t)=\left[k\right]\cdot e,\\
&\frac{dU_{C_{pp}}}{dt}=\frac{1}{C_{pp}\cdot R_{pp}}\cdot(U_{C_{pbag}}(t)-U_{C_{pp}}(t)),\\
&\frac{dU_{C_{pb}}}{dt}=\frac{1}{C_{pb}\cdot R_{pb}}\cdot(U_{C_{pbag}}(t)-U_{C_{pb}}(t)),\\
&\frac{dU_{C_{pa}}}{dt}=\frac{1}{C_{pa}\cdot R_{pa}}\cdot(U_{C_{pbag}}(t)-U_{C_{pa}}(t)).
\end{aligned}\right\}\quad(2)$$

Various methods may be applied in the mathematical research of the compiled model (analytical, operational and digital). Presently the most frequently used are the digital integration methods.

3. Theoretical research of complex insulation quality parameters

During the examination of quality parameters in the general model of transformer insulation by making the assessment of polarization characteristics and moisture content: 1) the method for the assessment of moisture quantity by measuring the polarization characteristics has been developed; 2) the quality criteria of oil-paper insulation have been classified; 3) the impact of water quantity on the quality of transformer insulation has been theoretically investigated; 4) the method has been worked out for the assessment of moisture content in the insulation by examining its dielectric parameters.

For the analytical research of polarization characteristics and moisture content of the transformer insulation model (Fig. 4) by the method of recovery voltage based on the equation system (2) we have drawn the matrix system (3) of differential equations:

$$\frac{d}{dt}\left|U(t)\right| = A \cdot \left|U_i(t)\right| + B \cdot \left|Y_j(t)\right|, \qquad (3)$$

where $\left|U_i(t)\right| = \begin{pmatrix} U_{C_{pbag}}(t) \\ U_{C_{pp}}(t) \\ U_{C_{pb}}(t) \\ U_{C_{pa}}(t) \end{pmatrix}$ – the matrix-column of charging voltages (as time functions) of model's capacitances C_{pbag}, C_{pp}, C_{pb} and C_{pa}; A – the square matrix of coefficients depending on the parameters of the model. $\left|Y_j(t)\right| = \begin{pmatrix} I_1(t) \\ I_3(t) \\ E(t) \end{pmatrix}$ – the matrix-column (Fig. 5) of currents in oil-paper insulation model and charge voltage as time functions; B – the rectangular matrix of coefficients depending on the parameters of the model.

The best way to solve the differential-matrix equation (3) is by applying the digital integration methods. One of the possible solution methods is the Runge-Kutto method of the 4th order. The following peculiarities of the Runge-Kutto method should be mentioned: 1) the error Δx^4 , 2) the unnecessary previous information regarding variable and derivative changes.

For the analysis of the transformer insulation model and the calculations of recovery voltage in examining the polarization characteristics and moisture content it would be reasonable to apply the accelerated digital methods for the solution of differential equations. For this purpose the property of equivalence of increments enables to efficiently apply the recurrent calculation method of transitional processes. The advantage of the method is such that it enables to conciliate the calculations of relatively long processes (in polarization capacitances C_{pp} , C_{pb} and C_{pa} , which take from 1s up to 10000 s) with the accelerated ones (in the geometric capacitance – C_{pbag} , which is loaded in less than 1 s).

In solving the differential matrix equation (4) (when $U_{C_{pbag}}(t)$, $U_{C_{pp}}(t)$, $U_{C_{pb}}(t)$ and $U_{C_{pa}}(t)$ remains unchanged in the integration pitch) at the time moment $t = (k+1) \cdot h$ (integration pitch) the recurrent formula shall be expressed as follows:

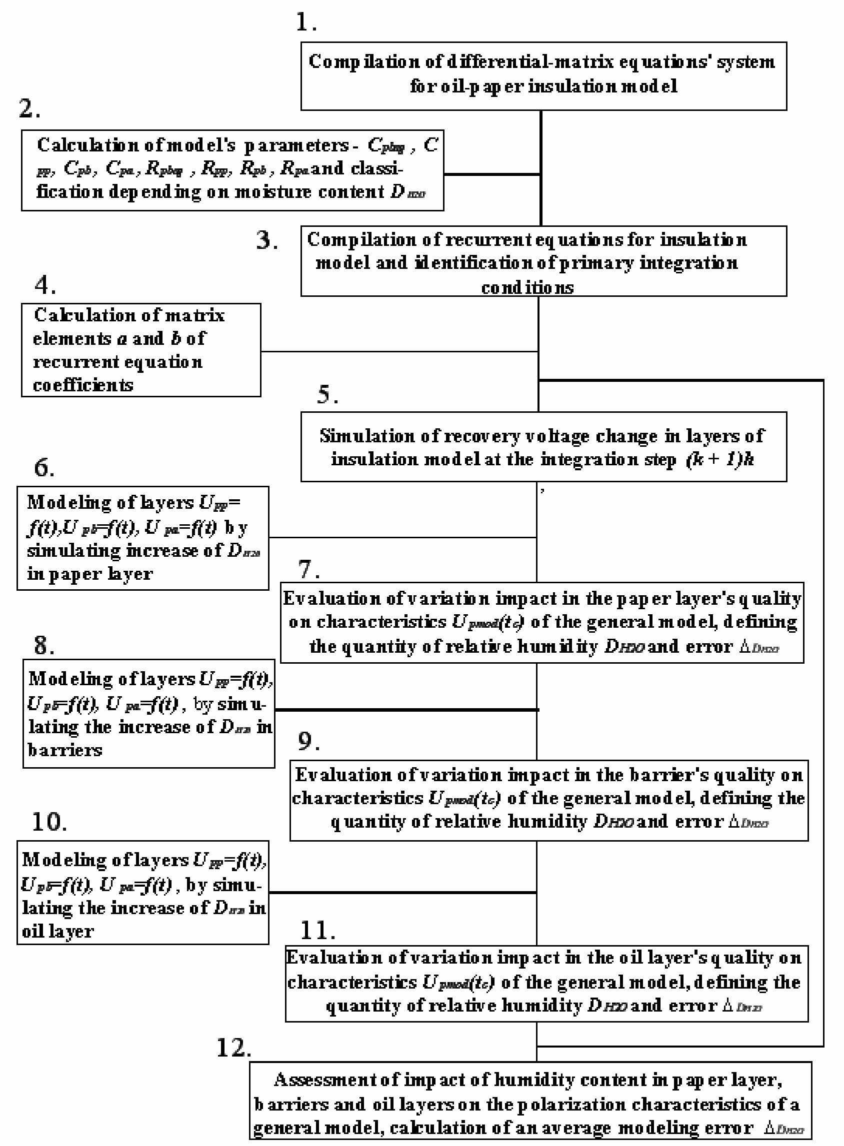

Fig. 7. Method of the model compilation of polarization characteristics and moisture content in 110-330 kV transformer insulation established by modeling the recovery voltage

$$U_{k+1} = a \cdot U_k + b \cdot Y_{k+1}, \qquad (4)$$

where $U_{k+1} = \begin{pmatrix} U_{C_{pbag}} \\ U_{C_{pp}} \\ U_{C_{pb}} \\ U_{C_{pa}} \end{pmatrix}_{k+1}$ – the matrix–column of voltages at the time moment (k+1);

$U_k = \begin{pmatrix} U_{C_{pbag}} \\ U_{C_{pp}} \\ U_{C_{pb}} \\ U_{C_{pa}} \end{pmatrix}_k$ – the matrix–column of voltages at the time moment k; a – square matrix of coefficients;

$Y_{k+1} = \begin{pmatrix} Y_1 \\ Y_3 \\ E \end{pmatrix}_{k+1}$ – the matrix-column of node currents and charge voltage; b – the rectangular matrix of coefficients.

The charging and discharging regimes of oil-paper insulation model (Fig. 4) by direct voltage are modeled by the commutation matrix-column $[k] = \begin{vmatrix} 1 \\ 0 \end{vmatrix}$.

The principle of super-position is applied for the calculation of *a* and *b* elements in the matrix of recurrent formulas. By allocating „1“ to one of the variable parameters, and by setting “0” values of the other ones, the transitional process of charging and discharging with direct voltage of one integration step *h* of complex insulation is calculated. In the analysis of the aforesaid process, the function of dependence of the recovery voltage on the charging duration $U_r = f(t_C)$.

By applying the matrix equation system of the insulation model (5) to set the matrix parameters in one integration pitch *a* and *b* the Runge-Kut method has been used (it is also possible to apply the Euler or any other digital integration method). The solution is one column of matrix elements. The accuracy of the recurrent method complies with the accuracy of the selected integration method.

The polarization characteristics $U_p = f(t_C)$, $\frac{dU_p}{dt} = f(t_C)$ and $\frac{dU_p}{dt} = f(U_p)$ have been modeled by calculating the recovery voltage and with regard to the dry, moderately wet and wet state of transformer insulation (by using MATLAB software for modeling purposes).

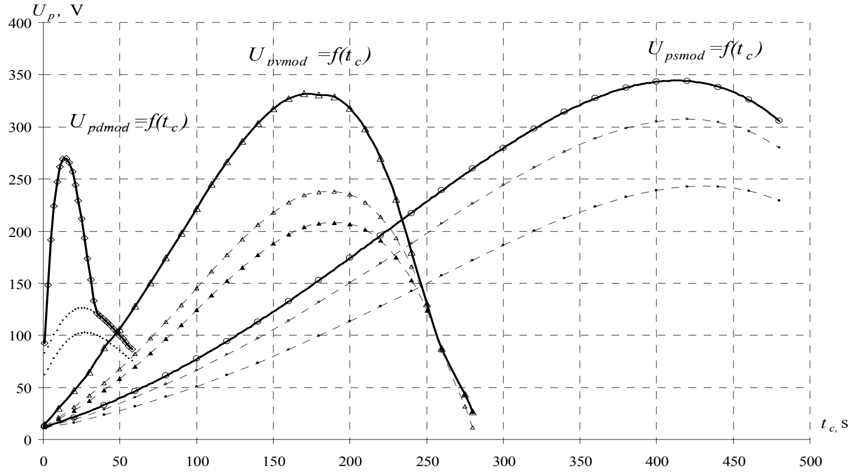

Fig. 8. Modeling of transformer's insulation polarization characteristics $U_{pmod}=f(t_C)$ in a general transformer insulation model with dry, moderately wet and wet oil layer

The deviation of paper layer's relative humidity $\Delta_{Dsk\ /\ mod}$ (Table 1) in theoretical calculations by applying the equation (1) and in modeling shall be calculated as follows:

$$\Delta_{D_{sk\ /\ mod}} = \frac{(D_{H_2Osk} - D_{H_2O\ mod})}{D_{H_2O\ mod}} \cdot 100 \qquad (5)$$

The average modeling deviation in determining the moisture content shall be calculated as follows:

$$\Delta_{D_{vid}} = \frac{\sum_{1}^{j} \left| \Delta_{D_{sk\ /\ mod}} \right|}{j}, \qquad (6)$$

where j – number of investigated models with different moisture content and different integration coefficients (In Table 1 – 15).

The calculation of polarization characteristics in a general insulation model has proved:

– the functional relationship between the moisture content in the transformer insulation's paper layer, barriers and oil layer and the polarization characteristics established by measuring the recovery voltage,

Table 1. Modeling results of transformers' insulation polarization characteristics and dependence of the moisture content on quality

Model	1	3	4	5	7	8	9	10	11	13	14	15
Changing moisture content in paper layers												
t_{psk}, s	421,0	254,7	212,8	172,7	98,0	63,2	30,2	23,3	16,8	7,5	4,6	1,9
D_{H2Osk}, %	1,44	1,68	1,77	1,87	2,14	2,35	2,70	2,83	2,99	3,37	3,61	4,04
t_{pmod}, s	460	291	244	203	115	74	37	26	19	9	5,5	2,6
D_{H2Omod}, %	1,40	1,62	1,70	1,79	2,06	2,27	2,61	2,78	2,93	3,29	3,52	3,88
$\Delta_{Dsk/mod}$, %	2,95	3,80	3,72	4,16	3,60	3,21	3,59	1,84	2,01	2,65	2,48	3,90
Δ_{Dvid}, %	±3,11											
Changing moisture content in barriers												
t_{bsk}, s	510,0	448,8	418,1	387,5	326,3	295,7	265,1	234,5	203,9	142,7	112,1	*81,5*
D_{H2Osk}, %	1,44	1,50	1,54	1,58	1,72	1,87	2,03	2,21	2,42	2,95	3,30	*3,77*
t_{bmod}, s	520	420	370	320	270	220	170	120	100	50	35	*25*
D_{H2Omod}, %	1,39	1,46	1,53	1,56	1,69	1,82	1,97	2,16	2,30	2,83	3,15	*3,67*
$\Delta_{Dsk/mod}$, %	3,67	2,58	0,62	1,20	1,78	2,52	3,15	2,28	5,03	*3,87*	*4,70*	*2,47*
Δ_{Dvid}, %	±2,75											
Changing moisture content in oil channels												
t_{ask}, s	967,6	642,4	513,1	403,2	234,5	172,3	122,5	83,7	54,3	18,1	8,7	3,3
D_{H2Osk}, %	1,44	1,50	1,54	1,58	1,72	1,87	2,03	2,21	2,42	2,95	3,30	3,77
t_{amod}, s	550	430	380	330	250	190	140	93	70	23	12	4
D_{H2Omod}, %	1,39	1,46	1,53	1,56	1,69	1,82	1,97	2,16	2,30	2,83	3,15	3,67
$\Delta_{Dsk/mod}$, %	3,67	2,58	0,62	1,20	1,78	2,52	3,15	2,28	5,03	3,87	4,70	2,47
Δ_{Dvid}, %	±2,75											

– the highest recovery voltage has been modeled in the layer with the highest moisture content (in simulated polarization capacity), therefore, by applying the method of recovery voltage, the quality of layer with the highest moisture content has been assessed),

– the best way to assess the moisture content (by measuring the recovery voltage) is by the polarization curve's (spectrum) $U_{p(r)}=f(t_C)$ constant value $t_C \approx t_p$,

– non-uniform $U_p=f(t_C)$ and $\frac{dU_p}{dt}=f(t_C)$ characteristics confirm the uneven moisture distribution throughout insulation layers (the bigger un-uniformity, the higher difference between the moisture content in insulation components; the biggest impact on the aforesaid un-uniformity is made by the moisture accumulated in the oil channels),

– $\dfrac{dU_p}{dt} = f(t_C)$ and $\dfrac{dU_p}{dt} = f(U_p)$ characteristics analysis enables to identify the transformer insulation's layer of the worst quality and the highest moisture content.

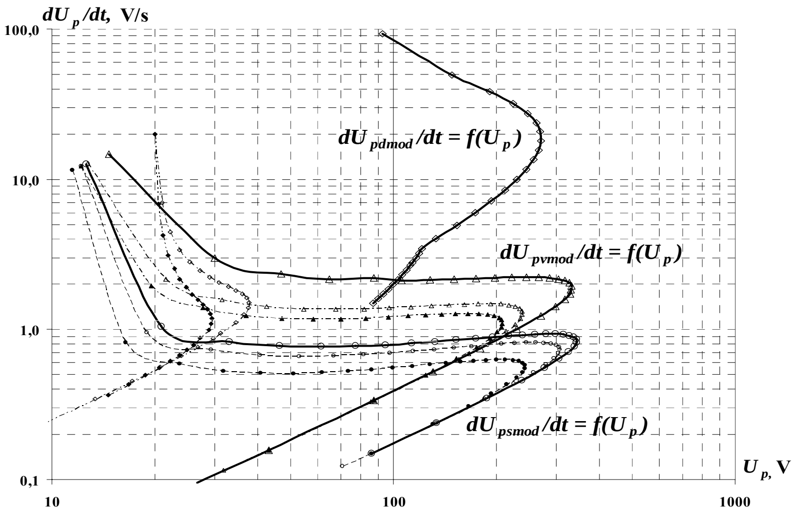

Fig. 9. Polarization characteristics in a general insulation model with dry, moderately wet and wet oil channels

4. Experimental research of transformers' insulation quality

The experimental researches on oil-paper insulation provide a possibility to:

– use the model and method developed for determining the moisture content by measuring the recovery voltage in the quality assessment of transformer insulation and its resource;

– apply the model and method for determining the moisture content by the examination of dielectric parameters in the analysis of insulation quality and resource variation tendencies in the insulation of operated transformers.

– evaluate the relevance of models and methods of recovery voltage measurement in the contemporary diagnostic tools used in the research of moisture content and resource variation tendencies in a complex insulation.

The experimental research of 25 – 400000 kVA power transformers' insulation has been carried out by applying the testing method described in Chapter 3. The aforesaid tests were carried out in the transmission grid, distribution networks and the Lithuanian Power Plant. By applying the method of recovery voltage as well as other assessment methods, the insulation quality in transformers manufactured in 1972 – 1999 was tested. The data of experimental tests is provided in (Table 2).

Table 2. Results of experimental tests of transformer insulation quality carried out by analyzing polarization characteristics, moisture content and dielectric parameters

Tested equipment	***T₁***	***T₂***	***T₃***	***T₄***	***T₅***	***T₆***
Nominal voltage, kV	20/330	330/ 110/10	10/0,4	110/ 10	20/ 330	10/10
Nominal capacity, kVA	400000	125000	25	16000	250000	16000
Insulation's temperature, ^{0}C	13	24	9	19	19	17
Insulation's resistance R_{15}, MΩ	4182	1500	477,7	1078	5500	210
Insulation's resistance R_{60}, MΩ	6184	2600	701,7	1230	7500	230
Absorption coefficient k_{abs}	1,478	1,73	1,468	1,141	1,36	1,09
Insulation's dielectric losses $tg\delta,\%$	0,16	0,21	0,28	0,48	0,69	2,1
Water quantity in oil, g/t	15	7,09	-	14,07	1,36	42
Duration of measurements, s	11837	9540	11940	10140	10210	10080
Voltage of insulation charging U_c, V	1500	2000	200	1500	1500	1500
Maximum measured recovery voltage $U_{r\,max}$, V	328	415	140	100	98,3	108
Measured constant of polarization time t_{pmat}, s	428	333	194	171	94	1,6
Experimentally determined moisture content in solid insulation D_{H_2Omat}, %	1,4	1,5	2,0	2,1	2,4	4,6
Constant of polarization time $t_{p\,mod}$, s established during the modeling	486	362	178	159	86	1,8
Average moisture content in solid insulation, $D_{H_2O\,mod}$, % established during the modeling	1,45	1,56	1,93	2,03	2,31	4,2
Deviation of relative humidity established in paper layers and barriers $\Delta_{Dmod/mat}$, %	3,4	3,9	-3,5	-3,3	-3,7	-8,7
Deviation in setting the constant of polarization time $\Delta_{t_p mod/mat}$, %	11,9	8,01	-8,9	-7,5	9,3	11,1
Average deviation in establishing the water content in solid insulation Δ_{Dvid} = ± 3,6 %						
Average deviation in establishing the constant of polarization time $\Delta_{t_p vid}$ = ± 9,4 %						

The duration of electric charging during tests – t_c lasted from 20 ms up to 10000 s, direct charge voltage – U_C from 1500 V up to 2000 V, electric discharge $-t_d = \frac{t_c}{2}$. The measurement cycles t_C, t_D, t_m and t_{FD} (Fig. 2) constituted the measurement procedure of recovery voltage U_r and of polarization characteristics. Apart of polarization characteristics, the dielectric quality characteristics R_{15}, R_{60}, k_{abs} and $tg\delta$ were measured.

The water quantity in oil was also established. During the tests, the dependence of recovery voltage U_r on the charging time's t_C curve – polarization spectrum $U_r = f(t_C)$ (Figure 10) was measured.

The measured polarization spectrums of transformer insulation per one time constant $\tau_p = t_p \approx t_{C_{U_{r\,max}}}$ illustrated uniform distribution of moisture (from 1,4 % up to 4,6 % paper mass) in the transformers' paper insulation and barriers (T_1 – 1,4 %, T_2 – 1,5 %, T_3 – 2 %, T_4 - 2,1 %, T_5 – 2,4 %, T_6 – 4,6 %). In the transformers T_1 and T_2 the established moisture content according to the value of polarization time constant (T_1 – $t_{pT1} = 428$ s and T_2 – $t_{pT2} = 233$ s) was, respectively, from 1,4 % up to 1,5 % - low; In T_3, T_4 and T_5 – average (T_3 – $t_{pT3} = 224$ s, T_4 – $t_{pT4} = 104$ s and T_5 – $t_{pT5} = 98$ s), from 2 % up to 2,4 %, and in T_6 – 16 MVA voltage regulation transformer high the moisture content in insulation and barriers was 4,6 % (T_6 – $t_{pT6} = 0{,}6$ s).

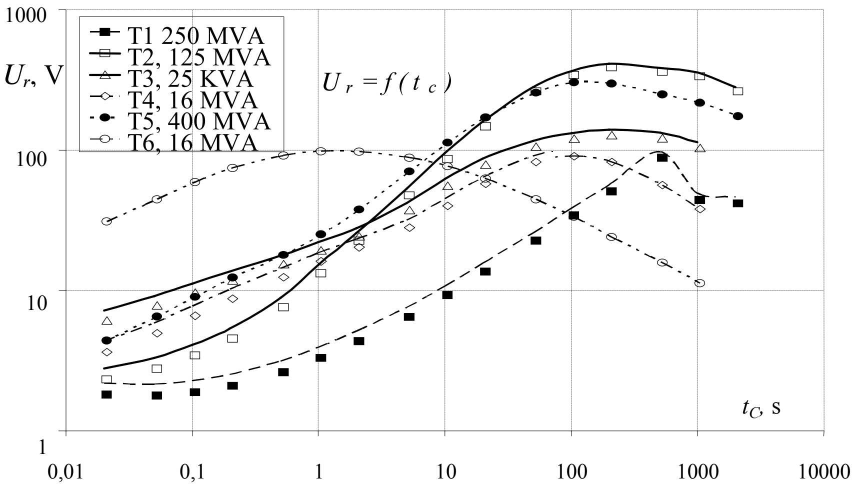

Fig. 10. Curves of experimental transformer polarization spectrum complying with moisture content in paper layers and barriers

According to the established moisture content in the transformer T_5 – 400 MVA, U_n =20/330 kV, and by taking into consideration its importance (step-up transformer installed in power generation unit in the Lithuanian Power Plant), the drying of windings (of paper layer) has been scheduled during its nearest maintenance. According to the established moisture content and the importance of the regulating transformer (T_6 – 16 MV, U_n=10/10 kV, regulating transformer, connected with 125 MVA, U_n=330/110/10 kV autotransformer's 10 kV bus bar bridge in 330/110/10 kV Jonava substation) the immediate drying of T_6 windings has been carried out.

The variation tendencies of insulation's dielectric parameters during the operation of the 330/110/10 kV autotransformers of the transmission grid have been investigated. During the analysis of variation of dielectric characteristics in the autotransformer insulation layers, the databases of measuring data were compiled based on the general measurement data. After the assessment of the impact of the temperature, the general insulation's resistance values have been revised.

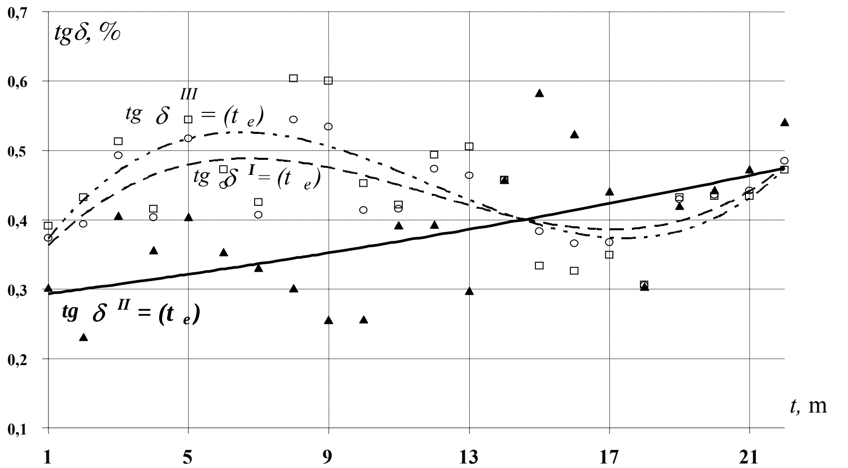

Fig. 11. Long-term variation curves of dielectric losses in 330 kV transformer insulation, zones *I*, *II* and *III*

The research of dielectric quality characteristics proved that the quality variation of paper layers and barriers insulation (during the time period t_e) is expressed by the equation system of dielectric parameters variation:

$$\left.\begin{aligned} R &= R_t^{II} = f(t_e) = R_{t0}^{II} \cdot e^{-a \cdot t_e}, \\ k_{abs} &= k_{abs}^{II} = f(t_e) = k_{abs_0}^{II} \cdot t_e^{-b}, \\ tg\delta &= tg\delta^{II} = f(t_e) = tg\delta_0^{II} \cdot e^{c \cdot t_e}, \\ C &= C^{II} = f(t_e) = C_0^{II} \cdot e^{d \cdot t_e}, \end{aligned}\right\} \quad (7)$$

were accuracy of the approximation R^2 is from 0,65 till 0,77.

The coefficients a, b, c and d illustrate the deterioration rate of dielectric quality characteristics and water accumulation rate in the paper layer and barriers.

The analysis of dielectric parameters variation has proved that:

– the worked-out method for the variation analysis of transformers' insulation dielectric characteristics enables to assess the variation of the insulation quality during operation;

– the established functional dependencies enable to apply the variation regularities of dielectric characteristics for the investigations of insulation resource and its dependence on the accumulated quantities;

– during the analysis of regularities of transformer insulation's dielectric characteristics it has been established that the lower are the values of the coefficients a, b, c and d, the higher is the quality of complex insulation.

The research of correlation between the dielectric characteristics and the moisture content enabled to establish functional dependence between the moisture content in oil-paper insulation and dielectric parameters.

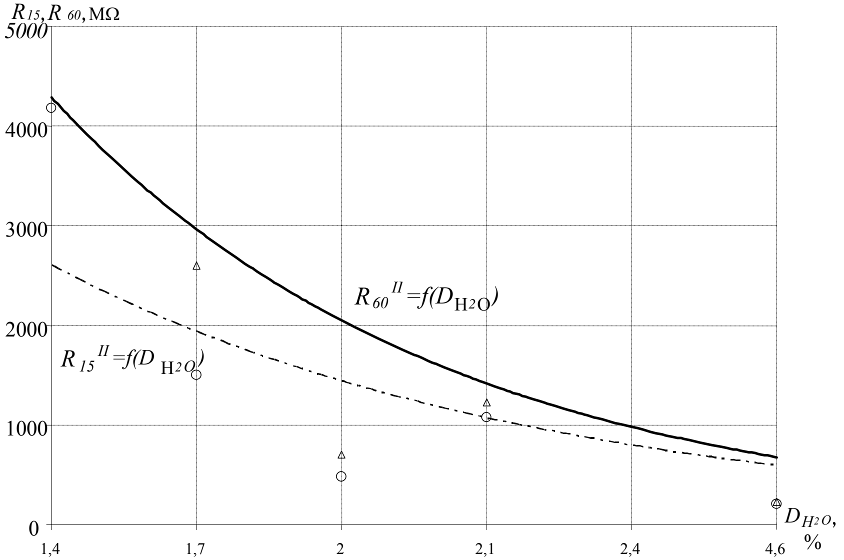

Fig. 12. Impact of moisture content of transformer insulation's paper layer and barriers on the parameters R_{15} and R_{60}

The research of the impact of moisture accumulated in transformer insulation's paper layer and barriers on the quality characteristics has shown, that the dependence between moisture content and dielectric parameters may be illustrated by the set of exponent curves of a general type:

$$
\left.
\begin{aligned}
R_{15} &= f(D_{H_2O}) = R_{15_0}{}^{II} \cdot e^{-g \cdot D_{H_2O}}, \\
R_{60} &= f(D_{H_2O}) = R_{60_0}{}^{II} \cdot e^{-h \cdot D_{H_2O}}, \\
tg\delta &= f(D_{H_2O}) = tg\delta_0{}^{II} \cdot e^{i \cdot D_{H_2O}}, \\
k_{abs} &= f(D_{H_2O}) = k_{abs0}{}^{II} \cdot e^{-j \cdot D_{H_2O}}.
\end{aligned}
\right\} \quad (8)
$$

Table 3. Results of research on variation of moisture content in transformer insulation’s paper layers and barriers

Calculated dielectric quality characteristics of the insulation zone II										
R_{60}, MΩ	3094	2922	4548	11160	2596	2664	2646	2961	3033	2945
R_{15}, MΩ	1288	1662	2576	5412	1276	1566	2115	1905	2186	2013
$tg\ \delta$, %	0,30	0,23	0,41	0,36	0,40	0,35	0,33	0,30	0,26	0,26
k_{abs}	2,40	1,76	1,77	2,06	2,03	1,70	1,25	1,55	1,39	1,46
t_e, m	1	2	3	4	5	6	7	8	9	10
Calculated moisture quantity paper layers and barriers										
$D_{H2O}{}^{R}{}_{60}$, %	1,95	1,98	1,7	1,14	2,06	2,04	2,04	1,97	1,95	1,98
$D_{H2O}{}^{R}{}_{15}$, %	2,31	2,15	1,88	1,42	2,32	2,19	2	2,07	1,98	2,03
$D_{H2O}{}^{tg\delta}$, %	1,86	1,65	2,14	2,02	2,11	1,99	1,94	1,86	1,74	1,74
$D_{H2O}{}^{k}{}_{abs}$, %	1,24	1,97	1,95	1,55	1,59	2,07	3,2	2,3	2,8	2,6
D_{H2Ovid}, %	1,84	1,94	1,92	1,53	2,02	2,07	2,30	2,05	2,12	2,09
Calculated dielectric quality characteristics of the insulation zone II.										
R_{60}, MΩ	2865	1976	2301	1866	1534	1419	1160	1283	1342	1594
R_{15}, MΩ	1840	1295	1533	1302	967	910	805	835	796	948
$tg\ \delta$, %	0,30	0,46	0,58	0,52	0,44	0,30	0,42	0,44	0,47	0,54
k_{abs}	1,56	1,53	1,50	1,43	1,59	1,56	1,44	1,54	1,69	1,68
t_e, m	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*
Calculated moisture quantity paper layers and barriers										
$D_{H2O}{}^{R}{}_{60}$,%	2	2,23	2,13	2,26	2,39	2,44	2,56	2,5	2,47	2,36
$D_{H2O}{}^{R}{}_{15}$, %	2,09	2,31	2,2	2,3	2,49	2,52	2,6	2,58	2,6	2,5
$D_{H2O}{}^{tg\delta}$, %	1,86	2,27	2,52	2,4	2,22	1,9	2,2	2,22	2,3	2,44
$D_{H2O}{}^{k}{}_{abs}$, %	2,3	2,4	2,5	2,69	2,29	2,3	2,66	2,4	2,1	2,1
D_{H2Ovid}, %	2,06	2,30	2,34	2,41	2,35	2,29	2,51	2,43	2,37	2,35

The analysis of experimental research has shown that:

– by using the method described in Chapter 3, the functional dependencies between the moisture content in transformer insulation (paper layer and barriers) and dielectric characteristics have been established, average accuracy of the approximation R^2=0,7;

– the established functional dependencies $R_{15}=f(D_{H_2O})$, $R_{60}=f(D_{H_2O})$, $tg\delta = f(D_{H_2O})$ and $k_{abs} = f(D_{H_2O})$ enable to make a research of long-term variation of moisture quantity in the transformer insulation's paper layer and the barriers, average accuracy of the approximation R^2=0,68;

– the coefficients g, h, i and j, established during the investigation, have experimentally confirmed a significant deterioration in dielectric quality characteristics when the moisture content in the oil-paper insulation (paper layer and the barriers) has been increasing.

In order to investigate the insulation resource of 330/110/10 kV transformers operated in the transmission system of Lithuania, the research of water content variation in the paper layer and barriers was carried out.

Based in the calculation results provided in Table 3, we have drawn the curves illustrating the increase of moisture content in complex insulation (in paper layer and barriers) up to the marginal value of 4 %.

The curves of the increasing moisture content in paper layer and the barriers of 330/110/10 kV transformers (Table 3) have been drawn according to the following operation time of the transformer:

1) 30 years, 2) 35 years, 3) 40 years and 4) 45 years.

1), 2), 3) and 4) curves on the increase of moisture content provided in (Figure 13).

The monitoring of moisture content in the insulations' paper layer and barriers as well as timely removal of moisture enables to increase the insulation's resource up to 35 – 45 years.

The increase of moisture quantity (in the paper layer and the barriers of transformer insulation) during the operation time t_e, in the general case is expressed by an exponent equation:

$$D_{H_2O} = f(t_e) = D_{H_2O_0} e^{K \cdot t_e}, \qquad (9)$$

where $D_{H_2O_0}$ – initial moisture content in paper layers and barriers calculated based on initial experimental data (at the beginning of operation), K – coefficient representing the rate of moisture increase during operation. The bigger is the K value, the more accelerated is the moisturizing of insulation and its obsolescence. Accuracy of the approximation R^2 no less than 0,65.

The analysis of the results of the research carried out in this Chapter has proven that:

- by using the method described in Chapter 3, the functional dependencies between moisture content in transformer insulation (paper layer and barriers) and operation time have been established;

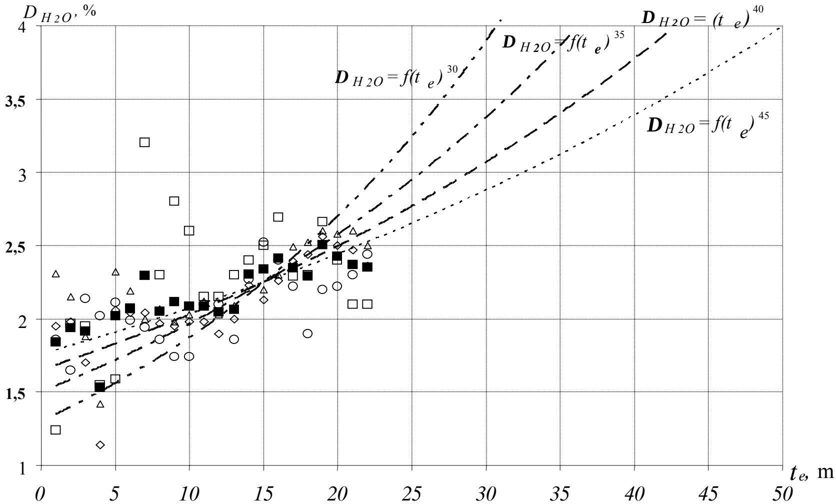

Fig. 13. Curves of increasing moisture content in 330/110/10 kV transformer insulation paper layers and barriers when the estimated lifetime equals 30, 35, 40 and 45 years

- the established functional dependencies $D_{H_2O} = f(t_e)$ revealed the regularities in variation of moisture content in the transformer insulation's paper layer and the barriers;
- resultant of the analysis of $D_{H_2O} = f(t_e)$ curves, the resource (life time) of 330/110/10 kV transformers (illustrated by Table 3) has been established.

Resultant of the experimental research, the analysis has been made of the temperature variation impact on the value of time constant of the transformer's insulation polarization, which is calculated by the following formula:

$$t_C^{T_{sk}} = t_C^{T_{mat}} \cdot 1,105^{\Delta T_W}, \tag{10}$$

where $t_C^{T_{sk}}$ – the value of polarization time constant, recalculated at the temperature T_{sk} (most often 20°C); $t_C^{T_{mat}}$ – the value of polarization time constant measured by applying the method of recovery voltage, at a certain insulation temperature at the moment of measurement T_{mat}; $\Delta T_W = T_{mat} - T_{sk}$ - the difference between the measurement temperature and recalculation temperature ($\Delta T_W > 0$, when $T_{mat} > T_{sk}$ and $\Delta T_W < 0$, when $T_{mat} < T_{sk}$). Accuracy of the approximation R^2 is not less than 0,96.

Conclusions

1. The analysis of the impact of moisture content on dielectric properties, acceleration of obsolescence and resource of complex insulation (as well as its components) has shown that in order to improve the quality of assessment of high voltage transformer's operation and insulation resource it is necessary to determine periodically the moisture content and to observe the tendencies of the moisture content variation.

2. The recovery voltage measuring method of oil-paper insulation by applying the models allow replace the methods as damaging insulation and is enables 4 times more frequently (every 2 years or according requirement) to establish condition of the transformer's solid insulation without its damaging.

3. The developed model of oil-paper insulation's polarization characteristics calculation allow to assess the quality of transformer insulation's (paper layer, barriers and oil channels), moisture content and to collect the measurement data for observation of the water content variation tendency. The deviation of the moisture content establishing (by recovery voltage method) is ± 3,6 %.

4. The method worked out for the evaluation of complex insulation dielectric parameters research enables to investigate variation of the moisture content approximations in power transformers' insulation components based on the experimental data. Approximations deviation R^2 is not less than 0,69.

5. The experimental investigation of the transformers insulation moisture quantity and dielectric parameters assessment has confirmed that the compiled triple-layer model may be used for the assessment of the residual exploitation resource. Exploitation time of the transformers (dependent from age) were investigated in Lithuanian power engineering may be extended from 5 to 15 years.

6. The analysis of experimental research has proved that the use of the developed models of the assessment of polarization characteristics and moisture content will enable to more precisely assess the quality of complex insulation and by regulating the moisture content, to guarantee the reliable operation of power transformers by improving their lifetime by until 30 %.

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REZIUMĖ

DARBO AKTUALUMAS

Kombinuotoji izoliacija yra svarbi, nes elektros energetikos ūkyje naudojama transformatoriuose (galios, matavimo ir įtampos reguliavimo), kondensatoriuose ir įvaduose. Minėtų įrenginių patikimumas ir eksploatacijos trukmė daugiausia priklauso nuo izoliacijos kokybės. Alyvos popieriaus izoliacija pasižymi tuo, kad, laiku pastebėjus defektus, kokybę galima visiškai atnaujinti.

Eksploatuojant įrenginius, kombinuotosios izoliacijos kokybę veikia įvairūs veiksniai. Vienas iš svarbiausių, dielektrines savybes, eksploatacijos trukmę ir senėjimą įtakojančių veiksnių, yra popieriuje, barjeruose bei alyvoje atsirandantis vanduo.

Kombinuotosios izoliacijos kokybės nustatymas yra aktuali problema, kuriai ištirti taikomi įvairūs metodai. Ieškoma naujų metodų, kurie leistų efektyviau nustatyti izoliacijos kokybę.

Vandens kiekio nustatymas ir kitimo analizė leidžia tiksliau įvertinti defektų pobūdį bei vykdyti gedimų prevenciją, kokybiškesnį resurso atnaujinimą ir prailginti įrenginių eksploatacijos trukmę.

Gedimų statistika rodo, kad 1998-2002 metais apie penktadalį visų gedimų įvyko aukštosios įtampos elektros įrenginiuose, kuriuose naudojama kombinuotoji alyvos popieriaus izoliacija. Perdavimo tinklui šie gedimai padarė didelių nuostolių. Neatitaisomas 200 MVA galios transformatoriaus izoliacijos gedimas gali kainuoti iki 10 milijonų litų. Todėl izoliacijos būkle reikia rūpintis nuo pat įrenginių eksploatavimo pradžios. Čia iškyla svarbus uždavinys: nepabloginant savybių nustatyti izoliacijos kokybę ir resursą, kuris daugiausiai priklauso nuo vandens kiekio kombinuotoje izoliacijoje. *Izoliacijos p*opieriaus sluoksnių (barjerų), kuriuose yra 3 % vandens, izoliacijos senėjimo greitis 30 kartų didesnis nei 0,3 %.

1990-2000 m. Lietuvos energetikos ūkyje iki 300 % sumažėjus apkrovoms, pastebėtas vandens kiekio didėjimas kombinuotoje izoliacijoje. Šiam procesui taip pat turėjo įtakos izoliacijos senėjimas.

Perdavimo tinkle eksploatuojama 56 % senesnių kaip 20 metų galios transformatorių, kurių bendroji galia 3159 MVA. 31 % šių įrenginių senesni nei 25 metų. Skirstomuosiuose tinkluose eksploatuojama 37 % senesnių kaip 20 metų galios transformatorių, kurių bendroji galia 1999 MVA.

Išnagrinėjus drėgmės kiekio nustatymo modelius ir parengus naudojimo metodą, galima būtų, nepakenkiant izoliacijai, tiksliau nustatyti transformatorių izoliacijos kokybę ir resursą. Perdavimo ir skirstomuosiuose tinkluose, taikant pasiūlytą drėgmės kiekio nustatymo metodą, galima kokybiškiau eksploatuoti transformatorius ir efektyviau panaudoti remonto ir investicines lėšas.

DARBO TIKSLAS

1. Išanalizuoti kombinuotosios izoliacijos kokybės ir resurso nustatymo metodus.
2. Sudaryti alyvos popieriaus izoliacijos poliarizacijos charakteristikų, drėgmės kiekio ir dielektrinių parametrų tyrimų modelius.
3. Sukurti drėgmės kiekio nustatymo, matuojant poliarizacijos charakteristikas, metodą.
4. Išanalizuoti vandens kiekio įtaką transformatorių izoliacijos dielektriniams parametrams.
5. Sugrupuoti alyvos popieriaus izoliacijos kokybės kriterijus.
6. Nustatyti izoliacijos dielektrinių parametrų ir drėgmės kiekio kitimo tendencijas.
7. Sukurtus modelius ir metodus pritaikyti elektroenergetikoje, transformatorių izoliacijos kokybės ir resurso tyrimams.

MOKSLINIS NAUJUMAS

Išanalizuoti ir sugrupuoti transformatorių izoliacijos defektai, atsirandantys eksploatuojant, dėl komponentų sudrėkimo. Išanalizuoti ir sugrupuoti kombinuotosios izoliacijos kokybės tyrimo metodai, įvertinantys popieriaus sluoksnio, barjerų ir alyvos kanalų sudrėkimo laipsnį.

Sudaryti trijų sluoksnių (du sluoksniai kietosios ir vienas – skystosios būsenų) kombinuotosios izoliacijos modeliai poliarizacijos charakteristikoms ir grįžtančiąjai įtampai apskaičiuoti. Išanalizuota modelių sudarymo metodika. Sukurtas tyrimo metodas, alyvos popieriaus izoliacijos komponentų (popieriaus sluoksnio, barjerų ir alyvos kanalų) sudrėkimo laipsniui nustatyti.

Sukurtas kombinuotosios izoliacijos sluoksnių sudrėkimo laipsnio įvertinimo, tiriant dielektrinius parametrus ir jų kitimą, modelis. Parengtas sudrėkimo laipsnio įvertinimo metodas. Suformuotas transformatorių izoliacijos dielektrinių parametrų tyrimo modelio ir matavimų duomenų bazių sudarymo metodas.

Išanalizuota alyvos popieriaus izoliacijos sluoksnių sudrėkimo įtaka poliarizacijos charakteristikoms bei dielektriniams parametrams. Nustatytos funkcinės priklausomybės tarp kombinuotosios izoliacijos dielektrinių parametrų bei popieriaus sluoksnyje, barjeruose ir alyvos kanaluose susikaupusios drėgmės.

PRAKTINĖ DARBO VERTĖ

Poliarizacijos charakteristikų ir grįžtančiosios įtampos matavimo metodas pritaikytas transformatorių izoliacijos komponentų (popieriaus sluoksnio, barjerų ir alyvos kanalų) sudrėkimo laipsniui ir vandens kiekio kitimui nustatyti.

Poliarizacijos charakteristikų ir grįžtančiosios įtampos analizės modelis ir sukurtas skaičiavimo metodas pritaikytas realaus transformatoriaus izoliacijos parametrams suskaičiuoti.

Sudarytas dielektrinių parametrų įvertinimo modelis ir sukurtas metodas pritaikytas transformatorių izoliacijos sudrėkimo laipsnio kitimo tendencijai tirti. Sugrupuotos alyvos popieriaus izoliacijos komponentų (popieriaus sluoksnio, barjerų ir alyvos kanalų) poliarizacijos charakteristikos ir dielektriniai parametrai pagal sudrėkimo laipsnį.

Minėtųjų modelių ir metodikų pritaikymas leidžia, tiriant vandens kiekio kitimo tendenciją, tiksliau įvertinti transformatorių izoliacijos kokybę ir resursą. Ištirta poliarizacijos laiko pastoviosios funkcinė priklausomybė nuo temperatūros leidžia tiksliau nustatyti drėgmės kiekį transformatorių izoliacijoje.

GYNIMUI PATEIKIAMA

1. Trisluoksniai alyvos popieriaus izoliacijos modeliai (apibendrintas, su netolygiai pasiskirsčiusia drėgme ir kokybiškos izoliacijos) grįžtančiajai įtampai ir poliarizacijos charakteristikoms skaičiuoti bei modelių sudarymo metodika.
2. Kombinuotosios izoliacijos kokybės tyrimo metodai dielektriniams parametrams analizuoti, poliarizacijos charakteristikoms ir drėgmės kiekiui nustatyti.
3. Drėgmės įtakos transformatorių izoliacijai tyrimų taikant sukurtą poliarizacijos charakteristikų ir drėgmės kiekio nustatymo metodą rezultatai bei sugrupuoti ir surūšiuoti kombinuotosios izoliacijos kokybės įvertinimo kriterijai (pagal popieriaus sluoksniuose, barjeruose ir alyvos kanaluose susikaupusį vandens kiekį).
4. Transformatorių izoliacijos dielektrinių parametrų kitimo tendencijos tyrimų rezultatai bei nustatyti dėsningumai taikant sukurtą kombinuotosios izoliacijos dielektrinių parametrų analizės metodą.
5. Alyvos popieriaus izoliacijos kokybės, poliarizacijos charakteristikų ir vandens kiekio nustatymo matuojant grįžtančiąją įtampą eksperimentinių tyrimų rezultatai.

6. Funkcinės dielektrinių parametrų priklausomybės nuo vandens kiekio transformatorių izoliacijoje (popieriaus sluoksnyje, barjeruose ir alyvos kanaluose).

7. Transformatorių izoliacijos resurso kitimo dėsningumai, dielektrinių parametrų kitimo tendencija ir jų funkcinės priklausomybės nuo vandens kiekio.

DARBO APROBAVIMAS

Disertacijos medžiaga pristatyta penkiose tarptautinėse mokslinėse konferencijose, ir penkiose mokslinėse konferencijose Lietuvoje.

Disertacijos tema paskelbta 12 mokslinių publikacijų, iš kurių 5 Lietuvos mokslo tarybos pripažintuose daktaro disertacijai leidiniuose. 5 publikacijos paskelbtos tarptautiniuose moksliniuose leidiniuose, o septynios – Lietuvoje.

IŠVADOS

1. Vandens kiekio įtakos kombinuotosios izoliacijos (bei jos komponentų) dielektrinėms savybėms, senėjimo greičiui ir resursui analizė rodo, kad, siekiant pagerinti 110-330 kV galios transformatorių eksploatacijos bei izoliacijos resurso įvertinimo kokybę, būtina periodiškai nustatyti drėgmės kiekį izoliacijoje ir sekti jo kitimo tendenciją.

2. Grįžtančiosios įtampos matavimo metodas, pritaikius sukurtus skaičiavimo modelius, leidžia pakeisti izoliaciją gadinančius metodus ir iki 4 kartų dažniau (kas 2 metai, arba — esant reikalui), nekenkiant izoliacijai, nustatyti transformatorių kietosios izoliacijos būklę.

3. Sukurtas alyvos popieriaus izoliacijos poliarizacijos charakteristikų skaičiavimo modelis leidžia nustatyti transformatorių izoliacijos popieriaus sluoksnių, barjerų ir alyvos kanalų kokybę, įvertinti sudrėkimo laipsnį bei kaupti matavimų duomenis drėgmės kiekio kitimo tendencijai sekti. Drėgmės kiekio nustatymo (grįžtančiosios įtampos metodu) nuokrypis nuo modeliavimo duomenų yra ne didesnis ±3,6 %.

4. Sukurtas transformatorių izoliacijos dielektrinių parametrų įvertinimo metodas leidžia iš eksperimentų duomenų rasti galios transformatorių izoliacijos komponentų sudrėkimo kitimo aproksimacijas. Jų tikslumas R^2 ne mažesnis už 0,69.

5. Transformatorių izoliacijos drėgmės kiekio ir dielektrinių parametrų nustatymo eksperimentiniai tyrimai patvirtino, kad sudarytą trisluoksnį skaičiavimo modelį galima panaudoti likusiam eksploatacijos resursui nustatyti. Lietuvos elektros energetikoje ištirtų transformatorių eksploatacija (priklausomai nuo amžiaus) gali būti pratęsta nuo 5 iki 15 metų.

6. Eksperimentinių duomenų analizė parodė, kad naudojant sukurtus poliarizacijos charakteristikų ir drėgmės kiekio nustatymo modelius, galima kokybiškiau kontroliuoti kombinuotosios izoliacijos būklę ir iki 30 % prailginti

patikimą galios transformatorių eksploatacijos trukmę, reguliuojant sudrėkimo laipsnį.

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