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DEVELOPMENT OF METHODS OF EVALUATION OF POWER TRANSFORMER INSULATION AGING TAKING INTO ACCOUNT RANDOM EXPLOITATION FACTORS

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At present several approaches are applied to evaluate and control the destruction level, the resource consumption and the residuary resource of the solid insulation in oil-filled power transformers. Among them can be mentioned the following approaches: by the degree of polymerization *(DP)* of paper insulation, by the degree of thermal aging of insulation calculated by means of Montzinger's formula and its modifications, according to the concentration of furan derivatives in the oil of the transformer tank, as well as according to the content of oxides CO and CO_2. To some extent all these methods help to solve the problem of calculating the destruction level of paper insulation, but no exact way to evaluate the consumption resource and the residuary resource has been found yet.

Evaluating the aging level of paper insulation by the degree of its polymerization is considered to be the principle one, as well as the most sound of all. A special place is given to the expert methods of evaluating the current operational state of transformers, including the evaluation of the residuary resource in the whole, and the solid insulation in particular.

The main criteria of applicability of this or that method is their susceptibility to the incompleteness of data and the interference of various factors occurring simultaneously with the operational monitoring of the equipment technical condition. A thorough examination of this aspect shows that taking this fact into consideration makes it necessary to reconsider the approach to resource evaluation itself.

Thus, using the **degree of polymerization** to evaluate the residual resource, we inevitably face imprecision in the value of at least two crucial parameters: the average degree of polymerization *DPo* and the coefficient of aging *K*. According to the results of experiments held in Russia and other countries, the exactitude of evaluating *DP* can be estimated as lying within the range of $\pm$ 10% from its average value. The law of error distribution has not been worked out exactly; therefore in our research we used the uniform *DP* distribution within the interval $[0{,}9 \cdot DP_0,\ 1{,}1 \cdot DP_0]$. The ambiguities in the selection of the coefficient of aging *K*, as recommended, for a example, in [1], even given the optimistic estimation of its variation as $\pm$ 15% , changes within the range of $K \in [2{,}21 \cdot 10^{-8};\ 2{,}99 \cdot 10^{-8}]$.

The histogram demonstrating the distribution of residual life R_{res} (residual life) of transformer insulation where DP_0 = 650 units, and given that there are random changes in the degree of polymerization and the value of the aging coefficient, is shown in Fig.1. The residual life of the insulation was calculated by the method of statistical testing according to the formula $R_{res} = (1/200 - 1/DP_0)\,/8760 \cdot K$.

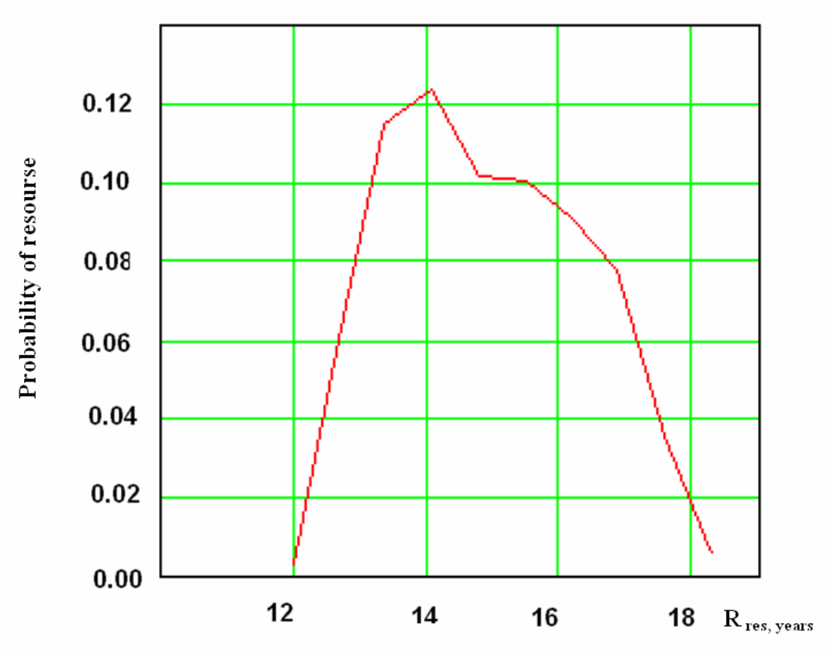

Fig.1. Histogram of the distribution of residual resource with the uniform law of distribution of degree of polymerization within the range 650 ±65 units. (±10%) and the coefficient of aging within the range of $[2,6 \pm 0,49]*10^{-8}$ (±15%).

The histogram (Fig. 1) presents a characteristic case of the uncertainty of the residual life value, obtained as the result of joint variations of DP_0 and K. The degree of imprecision of the residual life value calculations lies within the range from 12,0 to 18,5 years. A reasonable answer to the question concerning further transformer operation, given such a degree of uncertainty, proves to be highly complicated and requires proper evaluation based on the methods of risk analysis.

Thus, the calculations of resources are to be conducted regarding the degree of uncertainty and risk brought about by the solution applied. For this purpose Russia has seen the development of the relevant mathematical apparatus, study guide and software providing for the statistical-probability of control over the resource consumption, based on the determination of the guaranteed risk level: the gamma- percent safety and gamma- percent level of residual life. [2-5].

The dynamics of the resource changing of paper insulation can be estimated by **Montzinger's formula**, according to which, MEK 60075-7 (IEC60075-7) recommends to determine the relative speed of common paper aging by the formula:

$$V(\theta) = 2^{**}(\theta_h - 98)/\Delta = \exp[\ln 2 \cdot (\theta - 98)/\Delta], \qquad (1)$$

where: θ_h – the hottest-spot temperature of the transformer winding (function of time).

Formula (1) with Δ equal to 6 or 7 ℃ is usually used in the systems of monitoring Russian's transformers to evaluate the of resource consumption (reduction the period of service), which in the interval of time (T_1,T_2) is equal to the integral.

$$L = \int_{T_1}^{T_2} V\,dt. \qquad (2)$$

However, the obtained values of the relative wear (aging) of the electrical networks transformer isolation L (T_1-T_2), during a long period of working time (not less than a year) fall within the range of rather small values (about 0,006 - 0,01). It is connected with the fact that electric networks transformers working in normal modes, as a rule, have the load no more than 50 % from the nominal. The level of loads reaches its peak in autumn and winter when the temperature of the air outside is low. For this reason the temperature of the upper layers of oil does not exceed 50-60 °C even in the level of loads.

These features of electrical network transformers operation require the consideration of hydrolysis and oxidation processes in the insulation, leading to considerable acceleration of cellulose depolymerization. Experimental data show that the speed of depolymerization increases in dozens of times with the increased dampening of paper insulation and the oxidation of oil in the tank of transformer with the increased oxygen content dissolved in oil. This cardinally influences an estimation of an admissibility (limit time) of work of the transformer.

In [4,5] is proposed the procedure of calculation of the wear of insulation taking into account the indicated factors, based on the generalization of Montzinger's formula, according to which the relative rate of insulation aging is equal.

$$V = \exp[\ln 2\cdot(\theta_h - 98)/\Delta + \alpha\cdot\ln(w/w_{баз})^i + \beta\cdot \ln (K_{к.ч}/K_{баз})^j + \gamma\cdot\ln(C_{O2}/C_{O2баз})^k], \quad (3)$$

where, w – the dampening of paper insulation, *Ka.n.* – the acid number of oil, C_{O2} – the concentration of oxygen dissolved in oil. The bottom indexes of "bases" indicate the base value of corresponding quantities, for example $w_{баз}$ – the base value of dampening which can be accepted as to equal (0,3-0,5 %). Indexes i, j, k are equal to 0 if the relations in brackets are less than 1 and are equal to 1, if values of parameters w, Ка.n or C_{O2} more than corresponding base values. The coefficients α, also β and $\gamma\cdot$ are selected according to the experimental data.

The monitoring of the aging of paper insulation has no practical value without taking into account the dampening of solid isolation, acid number of oil, and also oxygen content in it.

The quantity of consumption of resource (2) is stable enough to "noise" (filtering action renders integration) therefore it is expedient to introduce the concept of the annual consumption of the insulation resource, i.e. the annual consumption resource. With the increase of the dampening of insulation, the oxidation of oil and the increase of the oxygen content in it, the speed of aging increases in dozens of times, and the relative aging of insulation of network transformers reaches 0, 4–0,8.To prevent the acceleration of the resource consumption it is necessary to carry out the drying of insulation, oil regeneration (for neutralization of acids) and its degasation. After such actions the estimation of the residual resource, as based on the results, of monitoring requires taking into consideration the new initial conditions of dampening, the acid number and the concentration of oxygen, and also the aging of insulation (by the degree of polymerization).

The main objective of the transformer equipment resource conservation is to eliminate the factors which accelerate the aging of insulation in the process of operation of transformers, as well as to maintain the degree of polymerization of paper insulation when drying it.

The Calculation of the Random Process of Insulation Aging

The Problem Formulation

Let γ be the assigned safety guarantee. It is necessary to find the maximum number of years n, so that, with the probability γ during the time interval of n years, the insulation depreciation (aging) would be less than maximum permissible value, or DP> 200 units. This number is called the gamma-percentage resource n (γ).

For example, Figure 2 shows the dependence of probability P (T) of the excess of the maximum permissible value of the polymerization degree of insulation. The probability P is reduced with an increase of the time of operation T. The gamma-percentage resource n of this process corresponds to the intersection point with the curve P (T) of γ level, which in this example is equal to 0, 94.

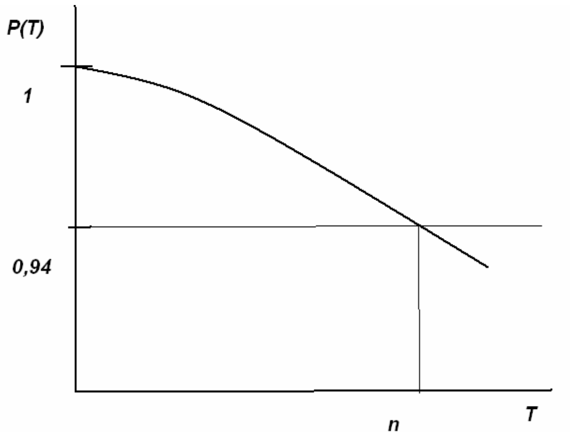

Fig 2. Decrease process of probability *P (T)* and definition of the gamma-percentage residual resource of insulation (γ= 0,94).

Initial data: **m** – the expected value of annual depreciation; **σ-** ASD (the average square deviation) of annual depreciation; ***m_0*** – the expected initial value of depreciation; **σ_0** –the initial ASD of depreciation; ***X_γ*** – the percentile of the normal level distribution γ; ***Dmax*** – the maximum depreciation.

For the Gaussian distribution of probabilities the analytical solution for ***n* (γ)** is reduced to the form [4, 5]:

$$n(\gamma)= [-0{,}5X_\gamma+(0{,}25\ X^2_\gamma+(\sigma_0/\sigma)^2+(D_{max}-m_0)/m)^{0.5}]^2-(\sigma_0/\sigma)^2 . \quad (4)$$

Tabl.1 demonstrates the results of examples of the gamma-percentage resource calculation for the transformer insulation with the expected initial deterioration m_0 =20 years for the safety guarantee γ equal to 0, 95, 0,90 and 0,80, D_{max} =25 years and σ_0= 0,1·m_0 =2 years. The values of annual deterioration *m* vary from 0,1 to 0,5, σ=0,8·*m*.

The calculations of ***n*(γ)** show that the average value of the annual insulation aging is the defining factor which conditions the duration of the transformer insulation residual resource. However, the influence of dispersion cannot be ignored. Provided that ASD increases in 5 times, the permissible service life of insulation is reduced by 1,5 times.

The developed approach makes it possible to consider the real operating conditions, and to obtain the constructive estimations of the gamma- percentage insulation resource on the basis of well-approved methods of the random sequences analysis.

Table 1.

Safety Guarantee γ	Gamma- percentage insulation resource *n* (years) with the expected value of the annual insulation deterioration *m*, years				
	0,1	0,2	0,3	0,4	0,5
0,95	10,5	5,1	3,3	2,4	1,9
0,90	16,8	8,2	5,3	3,9	3,1
0,80	23,9	11,7	7,7	5,7	4,4

Since there is no continuous control over the degree of polymerization, in practice, the method of evaluating the aging of transformer insulation by the **concentration of furan derivatives in oil** is widely used. This estimation is generally conducted according to the furfural concentration 2FAL, which is the steadiest of furan derivatives. Furfural is formed at cellulose disintegration and is mostly absorbed by solid insulation. The correlation between the degree of polymerization of paper insulation and the content of furfural in oil requires additional examination in the directions indicated below. It would more accurate to examine the dependence *DP* and the concentration *2FAL* as a regression curve, thus, raising a question of the distribution of *DP* deviations from the average value. The data analysis shows that the dispersion interval of these parameters is great in the area close to the limiting values of the insulation destruction. Thus, in the area *2FAL* $\in$*[2, 4 ppm*] uncertainty in the values of the degree polymerization in the points, close to those where the heating is maximum, corresponds to the interval from 250 to 500 units.

And if the value of 500 units is quite acceptable for further operating, the value of 250 units makes it compulsory to put the transformer out of operation. The decision as to the further operation can be taken only after the full analysis of all risks. The statistical studies of the transformers' failure and the distribution probabilities of the time of reaching the boundary values by the diagnostic parameters (by the growth of velocity and the dispersion range) on the basis of L.S. Pontriagin´s equations for the processes of reaching the limiting values [7] are required.

Thus, the systems of diagnostic control should provide for the definition of furfural concentrations in oil, taking into account and analyzing all the factors that influence its content (including temperature, dampening, oxidation processes). Furthermore, it is necessary to estimate the furfural diffusion coefficient from paper into oil, taking into account the reduction concentrations of 2FAL caused by the process of oil treatment during the repairs, as well as the furfural adsorptions on the silica gel filters, (which are installed in the transformers operating in Russia, Kazakhstan, Ukraine and other countries).

Some results of examining the furfural concentrations in 500 kV-autotransformers oil with the long service periods are shown in Fig.2. The analysis of results allows formulating some conclusions essential for estimating the insulation resource.

1). The increase process of furfural concentration has oscillatory character. Considerable decrease of furfural concentration is caused by technological reasons, including the replacement of silica gel in the filters. Other oscillations of concentrations are, apparently, caused by the furfural migrations from one zone into another (paper-oil-adsorbent), caused by changes of temperature conditions, by saturation processes and other factors.

2). With the decrease of furfural concentration, according to Chendong´s formula (Chendong I.), [8] we will obtain an increase of the polymerization degree which contradicts the physics of processes. Thus, the correction of the results is necessary.

3). To increase the reliability of the resource consumption estimations according to the concentration of furan derivatives it is compulsory that the migration processes of furfural in the systems *"paper-oil"* and *"paper-oil-adsorbent"* should be mathematically described and experimentally tested.

4). Furfural concentrations close to the limiting condition of paper insulation are located in 5-7 ppm area and confirm Chendong´s data [8]. The maximum levels of 2FAL concentrations, equal to 15 ppm, as indicated in some publications, have never been observed even for the transformers with the operation life of 40-50 years and with deep destruction of insulation.

5). One of the ways to predict the increase of furfural concentrations to the limiting value can be realized by plotting the envelope curve of the 2FAL concentration oscillations. The extrapolation of this curve allows realizing such forecasts even in the condition of furfural concentrations decrease as a result of technological processes.

6). The tendency for growth and the level of furfural concentration were restored practically to their previous level in 1-2 years after the technological operations carried out without any direct action on solid insulation (the addition of oil and its regeneration, sometimes the replacement of silica gel).

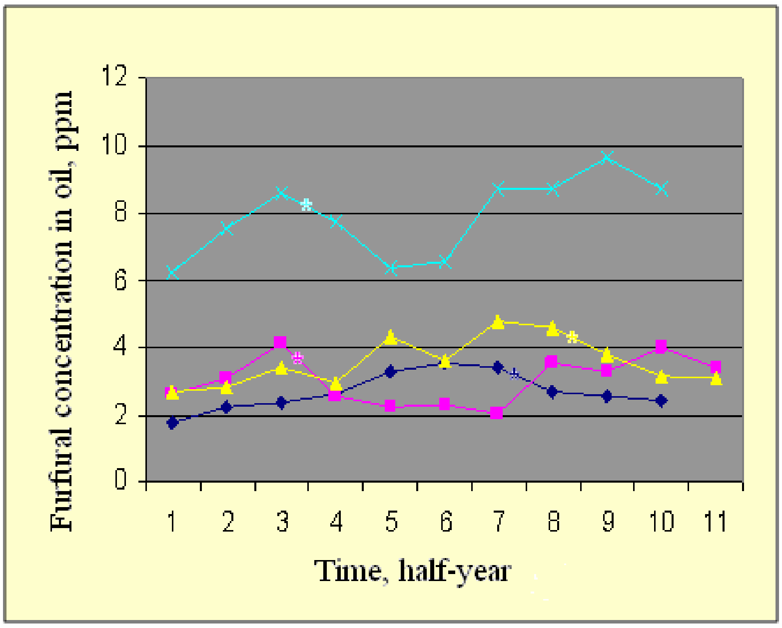

Fig.3. The dynamics of furfural in oil 500 kV-autotransformers with the operation life of more than 35-45 years.

To define the transformers residual resource it is possible to use the **methods of expert estimations (**expert forecasts). The technical documentation on transformers, including the results of diagnostic measurements and analyses, the information concerning the volume and the results of repairs, the operational parameters is presented to a group of engineering specialist, numbering 6-8 people. On getting acquainted with the documentation, each expert indicates the interval in which, in his opinion, lies the transformer residual resource. The function of preference of different resource values is defined by the obtained estimations through methods of the interval analysis.

For instance, Fig. 4 presents the function of transformer preference, the state of which is analyzed by 8 experts. The minimum value of the operation life was indicated by one of the experts as 8 years, and as 20 years by another expert. The maximum point of the function is the preferable estimation resource. The interval estimation of the residual resource is obtained by the cut of the preference function at 0, 70 level. Thus, the expected residual resource ranges from 13, 5 to 17, 0 years.

The expert estimations method proves useful for the development of the operational strategy when the amount of electrical equipment is considerable (e.g., transformers), as well as for electrical networks companies, electric power plants or important industrial enterprises, including the cases when the results of complex diagnostic inspections are not available [9]. In such cases it is expedient to turn to the experience of specialists.

The conditions necessary to make the expert forecast include careful selection of independent experts who would not have any personal interest in the results of the examination, as well as providing the experts with all the necessary technical documentation.

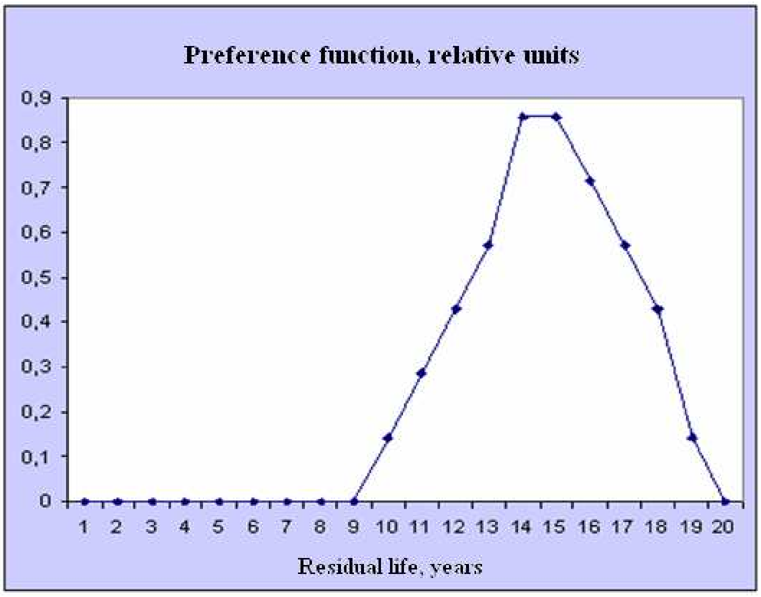

Fig 4. The function of preference as given by a group of experts, based on the interval estimation of the transformer residual resource.

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