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INFLUENCING FACTORS IN INSULATION MODEL TESTING

SUMMARY

The aim of this paper is to examine different factors that influence the quality of insulation models high voltage testing results. These factors are related to model geometry and model testing procedures. Model geometry is visually checked, several influencing factors are detected and their influence on el. field calculation results is evaluated using finite element method (FEM) and cumulative method for oil-barrier insulation design. The procedure for model geometry uncertainty estimation is performed using first-order Taylor series approximation. Also, the influence of previous voltage exposure history of a specimen, so-called “memo effect”, is estimated with a cumulative exposure method.

Key words: oil-barrier insulation, cumulative method, influencing factor, model uncertainty, sensitivity coefficient, step-by-step method

1. INTRODUCTION

Power transformer insulation system is made of two basic materials - paper and mineral oil. These materials can be used in transformer in various forms such as impregnated paper between electrodes (usually between winding turns), oil impregnated paper in combination with oil gap (usually used for leads and many other application) and oil barrier insulation (used for insulation between windings and between windings and earthed parts in all oil immersed HV power transformers).

Transformer insulation design is based on insulation design curves which have been developed as a result of high voltage experiments on insulation models. Experimental curves are used because a well-proven and a widely accepted oil breakdown theory has not yet been found and published. Different types of physical insulation models are reported in literature. In majority of published papers authors use bare electrodes because these electrodes are cheaper and easier to produce. In this work insulation models with paper covered electrodes will be analyzed because of their importance in design curves development – majority of the high voltage isulation systems consist of paper covered electrodes due to better voltage properties. The basic difference between bare and paper covered electrodes, regarding experimental research, is the fact that series of breakdowns can be made between bare electrodes while only one breakdown can be made between paper covered electrodes. Another important difference between these two types of electrodes is related to model geometry – it is more difficult to obtain uniform model parameters in models with paper covered electrodes due to tolerances in manufacturing process. Non-uniformity of model parameters causes discrepancy in comparison to nominal model parameters as well as uncertainty in electric field analysis.

The aim of this paper is to present a model geometry analysis procedure to improve the quality of test results by estimating oil gaps width and paper insulation thickness as precise as possible. This is achieved by calculating mean values of model parameters and their uncertainty. Mean values of actual model parameters are used as input values in minimum safety factor calculation. Measuring uncertainties of these parameters are used to find standard measuring uncertainty of model's minimum safety factor.

Furthermore, the influence of multiple test voltage levels coexistence on insulation system is analyzed as another important factor that influences quality of test results. Insulation models are often tested up to breakdown by using step-by-step method (i.e. ramp in steps) in which voltage is raised every 60 seconds in 3-5% steps of reference voltage level. On the other hand, insulation design curves are usually defined for one-minute constant AC stress. Therefore, it would be useful to analyze the so-called "memo effect" in the insulation system.

2. MODEL GEOMETRY ANALYSIS

2.1. Cumulative method insulation design basics

In this paper safety factors in oil gaps are calculated with cumulative method. El. field values are obtained with FEM. According to cumulative method, oil gaps in transformer main insulation system are designed in a way that the average el. stress along each el. field line is lower than the permissible el. stress which is defined with insulation design curves [1]. Ratio of permissible and average el. stress across a field line is called the safety factor (*σ(x)*) or margine. Minimum safety factor ($\sigma_{\min}$) is defined as:

$$\sigma_{min} = min\{\sigma(x)\} = min\left\{\frac{E_{perm}(x)}{\bar{E}(x)}\right\} \quad (1)$$

where $E_{perm}(x)$ is the permissible el. field and $\bar{E}(x)$ is the average el. field. Average el. field is a function of the el. field along an el. field line (which should be previously transferred to descending function if necessary) and x is the position on the el. field line ($x=0$ represents the starting point of the field line). $\bar{E}(x)$ is calculated as:

$$\bar{E}(x) = \frac{1}{x}\int_{x=0}^{x} E_{desc}(x)dx \quad (2)$$

where $E_{desc}(x)$ is descending el.field.

Cumulative insulation design method is explained in more detail in [2].

2.2. Model parameters influencing factors

As previously mentioned, actual parameters in the insulation models with paper covered electrodes are not uniform due to manufacturing tolerances which leads to discrepancies in comparison to models with nominal parameters. Visual inspection is performed on different types of models and factors that influence the model's minimum safety factor uncertainty (model uncertainty) are determined. For each model parameter the average value and standard measuring uncertainty is found. Also, the comparison of actual and nominal model parameters is made to demonstrate the influence of manufacturing tolerances. Model geometry analysis is performed on models that are used for oil-barrier insulation experiments reported in [3]. Figure 1 shows the cross section of the model and electrodes (oil gap is marked as d_{oil} and paper covering thickness as d_{paper}). In models with barrier, one 2 mm thick barrier is placed horizontally in the middle of the oil gap. In the following, several influencing factors are analyzed and it is shown that average values of all model parameters should be determined as precise as possible due to significant influence on test results.

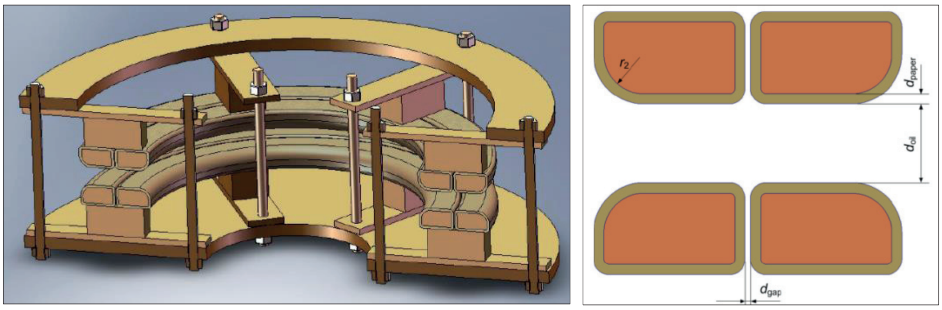

Figure 1 – Model cross section (left); electrodes cross section (right)

2.2.1. Spacer thickness

During the model drying process spacer thickness reduces which leads to reduction in related oil gap width. In order to obtain spacer thickness measures as precise as possible, measurements should be performed immediately after model drying in models with bulk oil gap (models without spacers - in this type of models spacers are used for oil gap width adjustment during the drying process and they are removed before impregnation with oil). In models with spacers in oil gap (for creepage testing) measurement should be performed immediately after the end of HV testing. Table I shows a few examples of nominal and measured values. Measurements are made on 12 samples for each group.

Table I – Spacer thickness measures

Nominal spacer thickness / mm	Average spacer thickness before drying / mm	Average spacer thickness after drying / mm	Relative measurement uncertainty of spacer thickness after drying / %
6	6,1	5,8	1,7
10	10,1	9,4	1,1
22	22,1	20,7	0,5
30	29,8	27,8	0,3

Table II shows σ_{min} values calculated with the cumulative method in the case when spacer thickness differs from nominal. In models with nominal parameters σ_{min} is equal to 1 for reference voltage (which is obtained with cumulative method and insulation design curve reported in [1]).

Table II - σ_{min} values for different spacer thicknesses

	σ_{min}		
Nominal oil gap / mm	Spacer thickness 5% lower than nominal	Spacer thickness equal to nominal	Spacer thickness 5% higher than nominal
3	1,00	1,00	1,00
6	0,99	1,00	1,01
10	0,99	1,00	1,01
18	0,98	1,00	1,02
22	0,98	1,00	1,02
30	0,98	1,00	1,02

From Table I and Table II it can be seen that discrepancies in actual and nominal spacer thickness result in different σ_{min} which means that test results should be recalculated to actual model geometry (average values of model parameters). For example, calculation with nominal parameters in the case of 30 mm oil gap compared to the calculation with measured spacer thickness (Table I) would lead to nearly 3% higher σ_{min}. For 3 mm oil gap spacer thickness change, in the observed range, practically does not affect σ_{min}.

2.2.2. Paper thickness

Electrodes paper covering thickness reduces during the drying process. In majority of cases it is not possible to directly measure paper thickness due to electrode design. Paper thickness is calculated as a difference between paper covered and bare electrode thickness and then an additional factor is applied which simulates the effect of paper drying. This factor depends on paper type and technology. In our experiment it was taken as 0,95 (paper thickness reduces by 5%). Another important fact is that paper thickness is not uniform across the electrode circumference because of manufacturing tolerances and it is advisable to measure these values on several places on each electrode. Table III shows σ_{min} for different nominal oil gaps and depending on paper thickness (σ_{min} is equal to 1 in the case of nominal paper thickness for each nominal oil gap).

Table III - σ_{min} for different paper thicknesses

	σ_{min}		
Nominal oil gap / mm	Paper thick. 5% lower than nominal	Paper thick. equal to nominal	Paper thick. 5% higher than nominal
3 mm	0,97	1,00	1,03
6 mm	0,98	1,00	1,02
10 mm	0,98	1,00	1,02
30 mm	0,99	1,00	1,01

Average values of paper thickness on electrodes reported in [3] are in the range of ±5% of the nominal value (which is 4 mm) and measurement uncertainty is in the range of 2,5-10%. From Table III it can be seen that the influence of these discrepancies is the highest in models with 3 mm oil gaps – errors up to 3% are possible and should be corrected by application of actual instead of nominal values. This component influences the model uncertainty significantly due to high relative measurement uncertainty. Its influence can be reduced only by reducing manufacturing tolerances.

2.2.3. Squeezing of paper insulation on electrodes

Figure 2 shows squeezing of paper insulation under the spacer (spacer is translated from its original position to show the effect of squeezing). The depth of squeezing in models is estimated to be up to 0,5 mm. Estimation is made by comparison with the thickness of an appropriate strip used as a caliber.

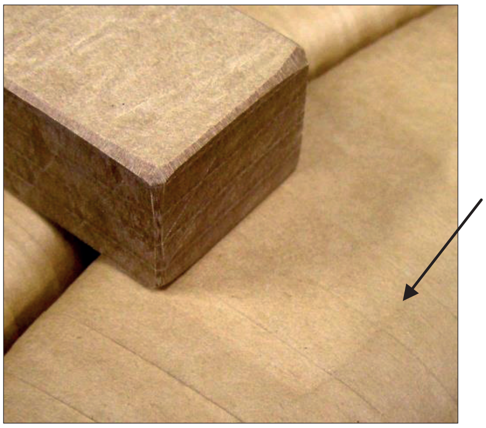

Figure 2 – Paper squeezing under the spacer

El. field calculation (using FEM) is made to analyze the influence of paper squeezing on the experimental results. 10 mm oil gap with squeezing of 0,5 mm on each side of oil gap is modeled in Infolytica ElecNet, as shown in Figure 3.

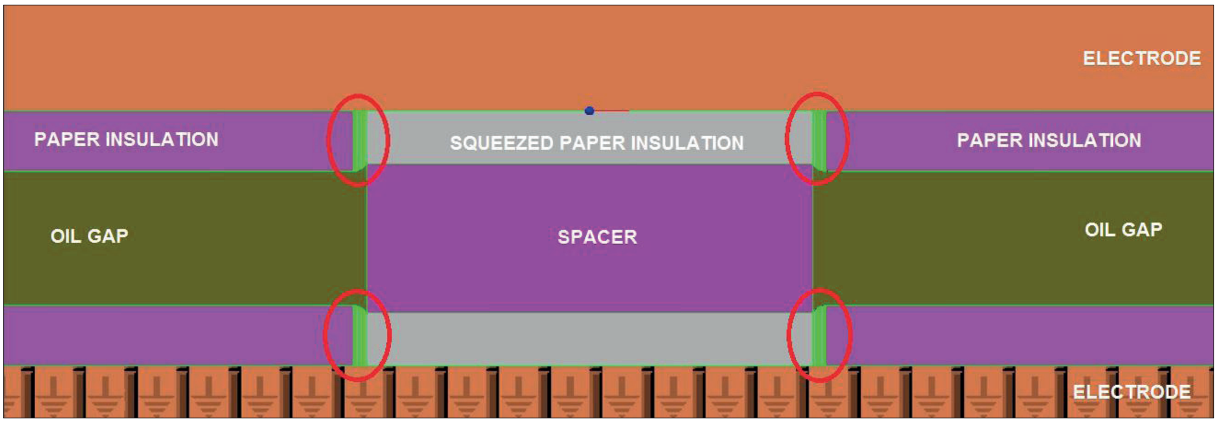

Figure 3 – Paper squeezing model made in Infolytica ElecNet

Paper squeezing has two major effects on model geometry parameters - oil gap width far from the spacer is reduced and paper permittivity is increased in the squeezed region due to paper density increase. Paper permittivity change is modeled in 10 steps (marked with red markers in Figure 3). The influence of paper squeezing is analyzed with cumulative method applied on simulation results, see Figure 4. σ_{min} value in model with nominal parameters is equal to 1.

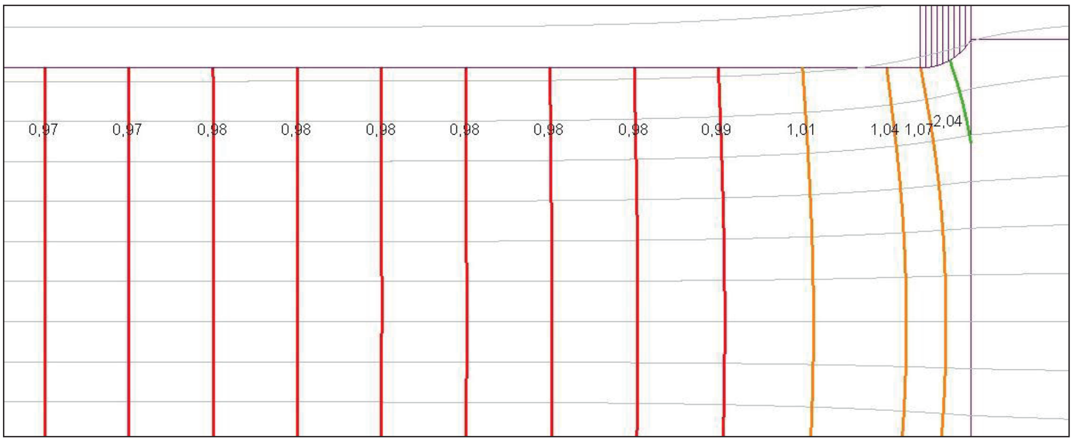

Figure 4 – Safety factors in 10 mm oil gap with 0,5 mm paper squeezing on each side

Figure 4 shows that safety factors in the vicinity of spacer are higher than in the model with nominal parameters which means that paper permittivity change effect can be neglected. On the other hand, oil gap width reduction effect should not be neglected because safety factors far from the spacer are lower than 1. Table IV shows σ_{min} values for different values of paper squeezing.

Table IV - σ_{min} for different values of paper squeezing

	σ_{min}	
Nominal oil gap width / mm	No squeezing	0,5 mm squeezing on each side of oil gap
3	1,00	1,02
10	1,00	0,97
18	1,00	0,98
30	1,00	0,98

Table IV shows that paper squeezing results in lower σ_{min} for models with larger oil gaps and in higher σ_{min} for models with narrow oil gaps. This can be explained by the fact that the slope of the permissible el. field function is higher in the range of narrow oil gaps (permissible el. field in (1) increases in higher amount than the change of the average el. field caused by oil gap width reduction).

2.2.4. Barrier distortion

Figure 5 shows a photo of barrier distortion which was taken during the model disassembling. Barrier distortions are estimated to be between 0 and 1 mm by visual inspection of all models and by using an appropriate spacer as a caliber. Barrier distortion results in different oil gap widths which leads to lower minimum safety factors in actual oil gaps than in nominal models (nominal model consists of two oil gaps of equal width). Barrier distortion of 1 mm changes oil gaps in model from 4+4 mm nominal width to 3+5 mm (as in Figure 5) and lowers minimum safety factor by 8%. Table V shows minimum safety factors for barrier distortions of 0,5 mm and 1 mm in the cases of 4+4 mm, 8+8 mm and 10+10 mm oil gaps (2 mm thick barrier is placed between electrodes nominally in the middle of the oil gap).

Figure 5 - Barrier distortion (the most prominent photo)

Table V - σ_{min} for different values of barrier distortion

	σ_{min}		
Nominal oil gap / mm	0 mm distortion	0,5 mm distortion	1 mm distortion
4+4	1	0,96	0,92
8+8	1	0,97	0,95
10+10	1	0,98	0,96

According to Table V, models with narrower oil gaps are significantly influenced with barrier distortion. Hence, it is necessary to achieve a barrier distortion as small as possible during the model assembling and preparation phase.

2.2.5. Spacer shifting (in models with barrier only)

Oil gaps in model with barrier are formed with spacers placed between each insulated electrode and barrier. In ideal situation spacers are placed at the same positions in both oil gaps (complete overlap is achieved). However, it is not simple to put the spacers exactly on the same position without gluing and they are often displaced from “ideal position” by a few millimeters. Figure 6 shows safety factors in oil gaps for the cases when one spacer is kept in the fixed position and the other is shifted for 0, 2, 4 and 6 mm.

From Figure 6 it can be seen that greater spacer displacement reduces safety factors in oil gaps. In case of 2 mm shifting σ_{min} is still higher than 1, but for 4 and 6 mm shifting σ_{min} reduces to 0,97 and 0,93. According to this, during model assembling spacer displacement should be rigorously controlled and kept below 2 mm if possible. In case this is not possible, the influence of spacer shifting on el. field geometry should be taken into account and additional correction factors should be applied on test results.

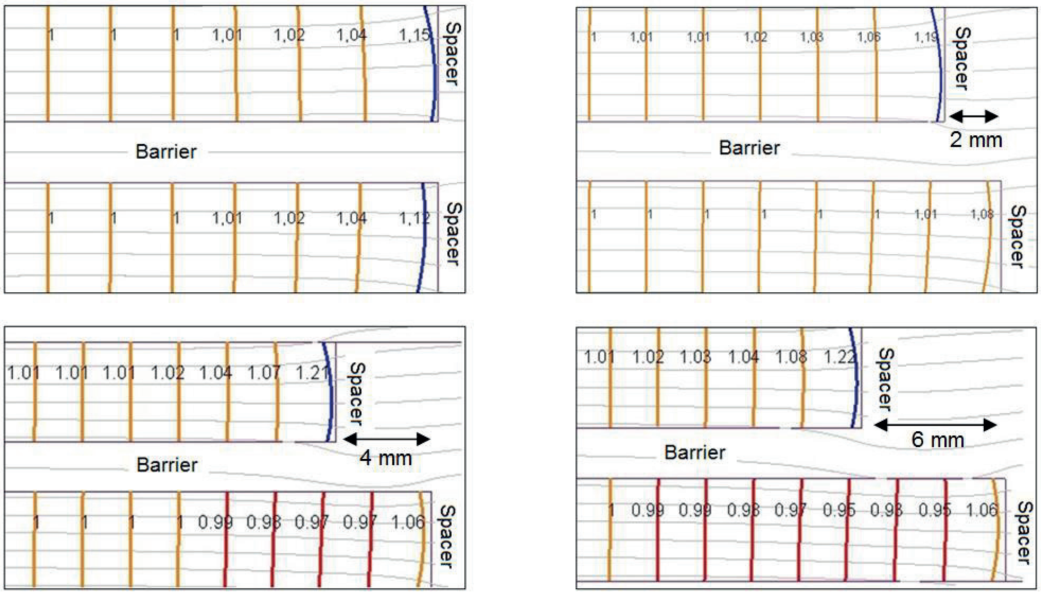

Figure 6 - Safety factors in oil gaps; upper spacer is shifted for 0, 2, 4 and 6 mm to the left side

2.3. Model uncertainty estimation

Relation between model parameters and model minimum safety factor can be expressed as $\sigma_{min} = f(x_1, x_2, \ldots, x_i, \ldots, x_n)$ where x_i is model parameter (influencing factor) defined with average value and measuring uncertainty. Function f is determined with cumulative method and FEM calculations made on model geometry. σ_{min} value should be calculated by using actual (average) values of model parameters as previously demonstrated. Model uncertainty (σ_{min} uncertainty) is estimated with Taylor series approximation because input parameters are independent variables. Input and output variables are considered to be linearly dependent and the first-order Taylor series approximation is used, [4]:

$$u(\sigma_{min}) = \sqrt{\sum_i \left(\frac{\partial f}{\partial x_i}\right)^2 \cdot u^2(x_i)} \quad (3)$$

where $u(\sigma_{min})$ is standard deviation of model minimum safety factor (model uncertainty), $\partial f/\partial x_i$ is sensitivity coefficient of i-th model parameter and $u(x_i)$ is measurement uncertainty of i-th model parameter.

Sensitivity coefficients in (3) are calculated from Tables II-V as:

$$\frac{\partial f}{\partial x_i} = \frac{\sigma_{\min(1)} - \sigma_{\min(2)}}{x_{i(1)} - x_{i(2)}} \quad (4)$$

where $x_{i(2)}$ is 5% higher value than nominal x_i and $x_{i(1)}$ is 5% lower value than nominal x_i. $\sigma_{min(1)}$ and $\sigma_{min(2)}$ are minimum safety factors in case when model parameter x_i is equal to $x_{i(1)}$ and $x_{i(2)}$ while other model parameters are equal to nominal values. For example, sensitivity factor for paper thickness is calculated from Table III and in the case of 6 mm oil gap we have:

$$\frac{\partial f}{\partial d_p} = \frac{0{,}98 - 1{,}02}{0{,}95 \cdot 4 - 1{,}05 \cdot 4} = 0{,}1 \ mm^{-1} \quad (5)$$

Measuring uncertainty of spacer thickness and paper thickness is equal to standard measuring uncertainty based on 12 measurements. Paper squeezing and barrier distortion are modeled using uniform distribution between 0 and maximum estimated value. Average parameter values in these two cases are equal to max estimated value divided by 2, whereas measuring uncertainty is equal to max estimated value divided by $\sqrt{3}$.

For example, Figure 7 shows safety factors for model geometry with spacer thickness of 7,70 ± 0,05 mm, paper thickness of 3,84 ± 0,41 mm, paper squeezing of 0,25 ± 0,14 mm on each side of oil gap and with barrier distortion of 0,5 ± 0,29 mm. Voltage between electrodes is set to reference value which gives minimum safety factor equal to 1 for nominal model parameters. For actual model parameters minimum safety factor is equal to 0,95 ± 0,026 which means that el. field obtained with actual parameters are 5% higher than in model with nominal parameters and model geometry uncertainty is 2,6%. This result confirms necessity to perform geometry analysis in model with paper covered electrodes.

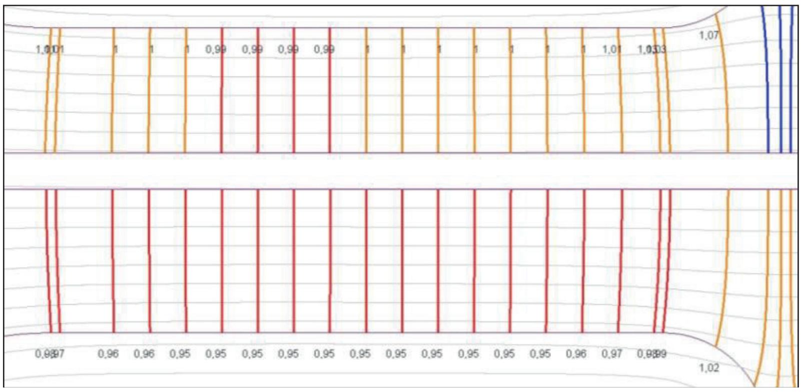

Figure 7 – Safety factors in oil gaps for model parameters as stated in the text

3. INFLUENCE OF THE MULTIPLE TEST VOLTAGE LEVEL

AC design curves for oil-barrier insulation system define permissible el. field strength for different oil gap lengths. Usually these curves are expressed for 1 min AC constant voltage stress (correction factors should be applied for different duration of voltage application). Testing with 1 minute AC constant stress is rarely performed in case of insulation model testing. Step-by-step (ramp in steps) test method is more effective because breakdown or PD inception is reached in a shorter period of time. In this method voltage is raised every 60 seconds in 3-5% steps of reference voltage level. The first voltage level is usually 60-70% of the reference voltage. Figure 8 shows a test voltage shape in step-by-step testing. Different authors reported that permissible el. fields could be underestimated without taking into account the previous exposure history of a specimen, a so-called "memo effect" [5,6].

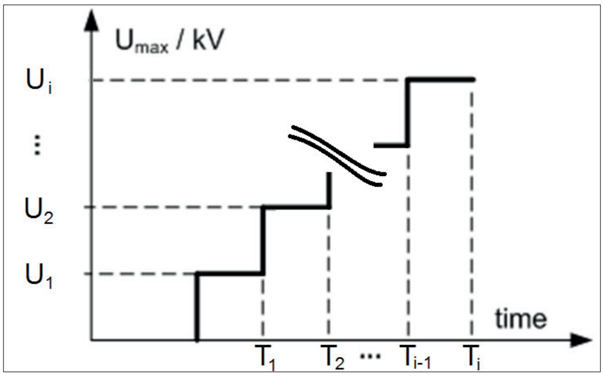

Figure 8 – Step-by-step (ramp in steps) test method

The influence of "memo effect" is analyzed for the V-t characteristics of the oil-filled transformers. V-t characteristics can be approximated by $V^n t=K$, where K is a constant. It is assumed that cumulative fault probability in oil-barrier insulation conforms to the Weibull distribution. Inclination *n* of the V-t characteristics can be expressed as $n=m/a$, where *m* is a Weibull distribution voltage shape parameter and *a* is a Weibull distribution time shape parameter. The Weibull distribution for specimens at constant stress is:

$$P = 1 - \exp(-AV^m t^a) \tag{6}$$

where *A* is a constant. According to [5,6], cumulative fault probability should be retained when voltage changes. This is done by shifting to V-t characteristics with equal $V^n t$. In other words, in step-by-step method step 2 has an equivalent start time s_1 which would produce the same breakdown probability as step 1 within T_1. The equivalent time s_1 at voltage V_2 is calculated from $V_2^n \cdot s_1 = V_1^n \cdot T_1$ and it is equal to

$$s_1 = \left(\frac{V_1}{V_2}\right)^n \cdot T_1 = \left(\frac{V_1}{V_2}\right)^{\frac{m}{a}} \cdot T_1 \tag{7}$$

Cumulative fault probability *P* in the second step (time region $T_1 \le t \le T_2$) is expressed with

$$P = 1 - \exp(-AV_2^m (t - T_1 + s_1)^a) \tag{8}$$

where s_1 is defined in (7).

In the step i ($T_{i-1}<t<T_i$), equivalent time s_{i-1} and cumulative fault probability are:

$$s_{i-1} = \left(\frac{V_{i-1}}{V_i}\right)^{\frac{m}{a}} \cdot (T_{i-1} - T_{i-2} + s_{i-2}) \quad (9)$$

$$P = 1 - \exp(-AV_i^m (t - T_{i-1} + s_{i-1})^a) \quad (10)$$

The influence of the “memo effect” can be estimated with analysis of the case when the one-minute fault probability is equal to cumulative fault probability in the step i. For 60 seconds voltage step intervals we can write:

$$-AV_i^m (60 + s_{i-1})^a = -AV^m 60^a \quad (11)$$

$$V = V_i \cdot \left(\frac{60+s_{i-1}}{60}\right)^{\frac{a}{m}} = V_i \cdot \left(\frac{60+s_{i-1}}{60}\right)^{\frac{1}{n}} \quad (12)$$

where V is corrected voltage value and V_i is measured voltage value.

The “memo effect” influence is analyzed for the case where n = 33,3, m = 10 and a = 0,3 which are typical values for oil-filled transformer reported in literature [5]. Using (9) and (12) it is estimated that for the common test parameters (the first voltage level 60% of reference voltage, voltage step 3% of reference voltage) “memo effect” influence is 1-2% depending on the number of voltage steps before PD inception or breakdown. In case when voltage step is 5% this influence is 0,5-1% (which means that corrected voltage value V is up to 1% greater than measured PD inception or BD voltage V_i).

It is important to state that cumulative exposure model presented in this section has not been adequately verified by experimental research up to now and conclusions are made from theoretical considerations. According to previous, it should be stated that a bit lower permissible values are obtained by using step-by-step test method than in 1 min AC stress testing which means that step-by-step method results are on the safe side.

4. CONCLUSION

In this paper a model geometry analysis procedure is performed to improve the quality of test results by estimating oil gaps width and paper insulation thickness as precise as possible. This is achieved by estimating mean value and measuring uncertainty of model parameters. Sensitivity coefficients of influencing factors are calculated using FEM and cumulative method. It is shown that the difference between results obtained with nominal and actual model parameters can be significant. It is advised to make calculations with actual model parameters in models with paper covered electrodes. Furthermore, the influence of “memo effect” on insulation system is analyzed as another important factor that influences quality of test results. A permissible el. field values obtained with step-by-step test method are a bit lower than in 1 min AC stress testing which means that results are on the safe side.

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