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A CONCEPT FOR EXPERIMENTAL TESTING OF OIL-BARRIER INSULATION SYSTEM

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Original scientific paper
The aim of this paper is to present a concept for experimental testing of transformer oil-barrier insulation system. Design of insulation model is proposed with the purpose to avoid typical problems reported in literature concerning partial discharge testing of paper coated electrodes. Electric field between model electrodes is analyzed with methods commonly used in transformer insulation design - cumulative method and maximum electric field method. Model prototype is produced and tested to confirm functionality of the proposed concept. Also, model uncertainty is estimated to define model geometry influence on the test results.

Keywords: *cumulative method; insulation model; maximum electric field method; measuring uncertainty; oil-barrier insulation; paper coated electrode; partial discharge testing*

Koncept za eksperimentalno istraživanje uljno-barijernog izolacijskog sustava

Izvorni znanstveni članak
Svrha ovog rada je predstavljanje koncepta za eksperimentalno istraživanje uljno-barijernog izolacijskog sustava. Predložen je dizajn modela izolacije s ciljem rješavanja tipičnih problema kod ispitivanja parcijalnih izbijanja papirom izoliranih elektroda. Električno polje u modelima analizirano je metodama koje se uobičajeno koriste za dimenzioniranje izolacije u transformatoru (kumulativna metoda i metoda maksimalnog električnog polja). Prototip modela je izrađen i ispitan kako bi se potvrdila funkcionalnost predloženog modela. Također, procijenjena je nesigurnost geometrije modela kako bi se odredio utjecaj predloženog modela na rezultate istraživanja.

Ključne riječi: *kumulativna metoda; model izolacije; metoda maksimalnog električnog polja; mjerna nesigurnost; uljno-barijerna izolacija; papirom izolirana elektroda; ispitivanje parcijalnih izbijanja*

1 Introduction

Mineral oil and paper are two basic materials that form power transformer insulation system. These two materials have proven their reliability for high voltage transformer insulation for many decades. In spite of a very long and successful usage of oil and paper in oil-immersed transformers, the design of transformer insulation is still sort of an art because a well-proven and widely accepted oil breakdown theory has not yet been found.

Breakdown studies of transformer insulation most often follow two main approaches – research of breakdown mechanism physics and determination of the breakdown process statistical nature. The first approach resulted in several transformer oil breakdown theories. These theories can generally be divided into three categories - ionization theory, weakest-link theory and streamer theory, [1÷4]. Actual transformer insulation design is based mostly on the second approach. Insulation design experts use design curves which have been developed experimentally through high voltage experiments on simplified insulation structures - insulation models. It is not only the models that are simplified but the procedure of research as well. Majority of research projects are performed on a limited range of stressed oil gaps and results are then extrapolated to much larger oil gaps. When doing so it is very important that an adequate distribution of breakdown measurements is determined to avoid huge extrapolation errors.

Many reported research projects are performed on "small-scale" insulation models with bare electrodes. In these projects, experts try to define certain insulation parameter influence on insulation breakdown behaviour. The influence of "size effect" in oil has been widely studied. The basic idea of "size effect" theories is to correlate results of experiments obtained using different geometries (homogeneous, quasi-homogeneous and non-homogeneous). "Size effect" can be interpreted as stressed oil volume (SOV) effect or as a combination of electrode area and oil gap length effect. Weber and Endicott in [5] report that the dielectric strength of transformer oil is a function of the electrode area. SOV theory is introduced by Wilson in [6]. Many other authors tried to explain whether area effect, [7], or volume effect, [8÷12], is dominant. Giao Trinh et al. report that presence of these two effects depends on the quality of mineral oil, [13]. Besides "size effect", coating effect and barrier effect are often investigated as well as creepage strength of transformer insulation [14÷16].

When testing paper coated electrodes, opposed to bare electrodes, the number of produced models should be much higher in order to have sufficient number of test results. This is mainly because paper insulation is always damaged in breakdown event. Also, strong partial discharges (PDs), as well as long lasting PDs, harm paper insulation. Furthermore, paper insulation requires special preparation procedure which is not necessary when using bare electrodes. Hence, experiments with bare electrodes are much cheaper and less time-consuming than experiments made on models with paper insulation coating. Experiments on models with bare electrodes are very useful but they rarely find their way to implementation in actual transformer insulation design because they do not include major part of the influencing factors present in real insulation system. Breakdown data for models with paper insulated electrodes is often treated as industrial secret, so published papers from this field are rare [16÷19].

For transformer insulation design purposes only models with paper coated electrodes, with larger stressed oil volumes and with well controlled oil quality are of interest because such conditions are present in transformers.

In this paper, model concept for transformer oil-barrier insulation research is presented. Oil-barrier insulation system consists of oil-dielectric and barriers made of oil-impregnated paper. Oil-barrier system is used for insulation between windings and between windings and earthed parts in all oil-immersed HV power transformers. The essential for oil-barrier insulation system is that paper barriers divide oil gaps increasing their withstand voltage [20]. The aim of this research is to define an insulation model design for oil gaps testing which would include as much influencing factors from actual insulation system as possible. The model should also avoid usual problems that can occur in partial discharge testing (explained in Section 3).

In the first part common transformer insulation design methods are shortly described, requirements on model geometry are stated and model design is proposed. In the second part, model geometry influence on the test results quality is estimated and, finally, model prototype production and testing is described. Test results are analyzed to verify proposed model concept.

2 Oil-barrier insulation design methods

Prior to model concept proposal, methods used for model geometry analysis are described. These methods are the same as used in transformer main insulation system design (insulation between windings together with insulation between winding and earthed parts). It should be noted that electric stress in each oil gap can be analyzed separately from other oil gaps if barriers are thick enough, [20, 21].

Generally, design of oil-barrier insulation system is relatively simple in homogeneous electric field – actual electric field must be lower than design reference curve divided by a certain margin. The value of margin depends on calculation method, geometry, experience, technology and other parameters. Design reference curve is a result of experimental research on insulation models as roughly described in the introduction. In actual transformer insulation homogeneous electric fields are not common. Electric field in oil barrier insulation is more or less non-homogeneous. Different methods are developed for insulation design in non-homogeneous electric field. The cumulative method [3, 15, 21] and maximum electric field method are generally used for oil-barrier insulation design under AC stress. There are also other methods like streamer [19] and stressed oil volume method [3, 6], but these methods will not be discussed in this paper.

Cumulative method compares cumulative (average) stress along electric field lines to permissible electric field strength defined with design reference curve to find safety factor (σ) which is defined as:

$$\sigma(x) = \frac{E_{\text{ref}}(x)}{\overline{E}(x)} \tag{1}$$

where $E_{\text{ref}}(x) = Ax^{-b}$ is the design reference curve (coefficients A and b are experimentally derived) and $\overline{E}(x)$ is the average electric field value which is calculated as:

$$\overline{E}(x) = \frac{1}{x} \int_{x=0}^{x} E(x)\mathrm{d}x \tag{2}$$

$E(x)$ is a function of electric field along electric field line and x is the position along the electric field line ($x = 0$ represents starting point). Usually, in bulk oil gaps field along field line is descending, but there are some cases where function $E(x)$ should be transformed to a descending function as shown in Fig. 1. In this procedure, exposed lengths of each electric field value should be equal in case of actual $E(x)$ and descending electric field. For example, the exposed length for E_{21}in Fig. 1 is $x_2 - x_1$ and the exposed length for $E_{\max}$ is zero.

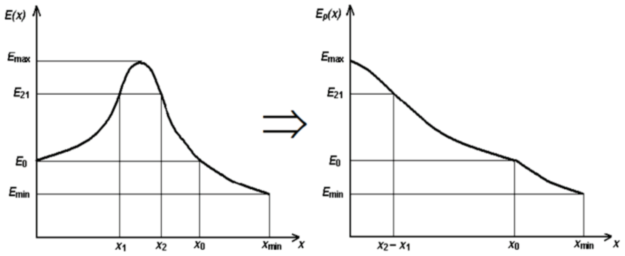

Figure 1 Transformation of $E(x)$ to descending function

According to cumulative method, breakdown probability is related to the electric field line with the smallest minimum safety factor ($\sigma_{\min}$). Minimum safety factor on each electric field line is defined as a minimum value of the function $\sigma(x)$:

$$\sigma_{\text{min, cum}} = min\left[\frac{E_{\text{ref}}(x)}{\overline{E}(x)}\right] \tag{3}$$

Analyzed electric field lines should be dense enough to avoid errors in minimum safety factor determination.

Maximum electric field method ($E_{\max}$ method) compares maximum stress on electric field line to design reference stress. Minimum safety factor is defined as:

$$\sigma_{\text{min}, E_{\max}} = \frac{E_{\text{ref}}(L)}{E_{\max}} \tag{4}$$

where L is the total length of electric field line, $E_{\max}$ is the maximum electric field value on the electric field line and $E_{\text{ref}}(L)$ is permissible stress for field line with total length equal to L. $E_{\text{ref}}(L)$ is calculated from design reference curve (generally it can be the same curve as used in cumulative method). From (3) and (4) it can be seen that for each field line the safety factor is a function for cumulative and a single value for $E_{\max}$ method. Both of these methods have advantages and disadvantages mainly related to electric field inhomogeneity.

3 Model geometry proposal

Several requirements regarding insulation model geometry should be met to ensure application of experimental results in actual oil-barrier insulation system. First of all, this kind of research should be performed in a quasi-homogeneous electric field system and between paper insulated electrodes.

Homogeneous electric field is generally achieved by using plane, Rogowski and Bruce disc electrode profiles [22]. Disc electrodes are appropriate in experiments where no paper insulation is used. It is difficult to apply paper insulation on disc electrodes and different authors report problems with keeping paper insulation tight to the electrode surface [16]. Moulded paper is often used in combination with disc electrodes to simplify model production process. Main problem with application of moulded paper is poor adherence of paper to the electrode surface. As a consequence, PDs may be initiated on relatively low test voltages and obtained PD inception curves could be lower than reference curves that have been proven in transformer insulation design for many years. Gluing of paper insulation is not appropriate for HV electrodes because it also influences early PD inception. To avoid the risk of "early PDs" problem in costly insulation research projects, one of the most important steps in project planning is to define a model design that assures proper adherence of the paper insulation to the electrode surface. In the following, model concept with wrapped paper insulation is proposed.

Insulation model consists of two identical pairs of electrodes designed similar to transformer static end rings. Each electrode is split in two parts with a small gap between them in order to ensure better paper adherence to electrode and better paper thickness accuracy. Other important benefits of the application of static end rings in the insulation models are a widely used production process (transformer manufacturing) and standardized production tolerances. Static end rings electrodes, which are a common part of high voltage (HV) transformer insulation, are placed in an insulating frame that allows changing of oil gap width using insulating screws. Fig. 2 shows the model consisting of electrodes and insulating frame. Upper electrodes are truncated in Fig. 2 to show electrode static ring design. Lower electrodes together with lower insulating parts are exactly the same as in an actual model.

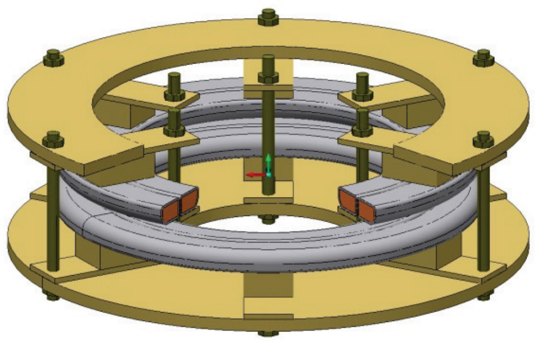

Figure 2 Model drawing (upper electrode and upper part of insulating frame is truncated)

Another requirement regarding model design is related to model size - stressed oil volume should be high enough to achieve better reliability of results. For small stressed oil volumes breakdown voltages are relatively high as well as deviation of results. In case of larger stressed oil volumes breakdown voltages are lower due to "size effect", but deviation is smaller, [6]. In this concept stressed oil volume is roughly 500 ÷ 5000 cm^3 for oil gaps width 3 ÷ 30 mm. This is considered to be sufficient to obtain smaller deviation of test results according to literature [6, 9, 23]. Stressed oil volume is calculated between flat surfaces of electrodes. Oil gap width is selected as a compromise between production tolerances (in case of smaller oil gaps) and the expected highest test voltage level (in case of larger oil gaps). Selected range of oil gap widths (3 ÷ 30 mm) covers major part of oil gap spacing in transformer main insulation.

After defining basic design, model inhomogeneity is evaluated for different combinations of electrode parameters. The goal is to define such electrode geometry that would result in model electric field inhomogeneity factor along paper surface lower than 1,15 which is considered to be acceptable according to experience. Inhomogeneity factor η is in this case defined as a ratio of maximum electric field on the paper surface and mean electric field in homogeneous area:

$$\eta = \frac{E_{\text{max}}}{E_{\text{hom}}} \tag{5}$$

Fig. 3 shows electrodes cross section. Inhomogeneity factors are calculated along paper surface according to (5) and results are shown in Fig. 4. All smaller radii are set to 2 mm, gap between electrodes (d_{gap}) is 2 mm and oil gap width is from 3 to 30 mm. External radius (r) is varied in the range of values that are used in transformer static ring production and paper thickness (d_p) is selected as 2 mm and 4 mm. Paper thickness of 6 mm or more would result in high model uncertainty due to high manufacturing tolerances.

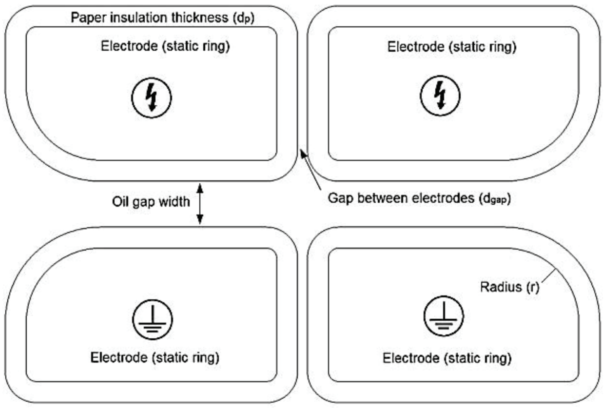

Figure 3 Cross section of electrodes

In case of d_p = 4 mm and radius r above 15 mm, η is acceptable (lower than 1,15) for all analyzed oil gaps. In case of d_p = 2 mm, η is acceptable for oil gaps up to 20 mm. According to previous, it is decided to use d_p = 4 mm to ensure the same geometry for all models. This results in higher uncertainty in models with 3 mm oil gaps, but the manufacturing process is simplified. If uncertainty of 3 mm oil gap model is too high it is advised to check the results by testing several models with paper thickness of 2 mm. From Fig. 4 it is obvious that radius r should be at least 15 mm.

Proposed model can be used for bulk oil gap testing, creepage testing (spacers should be inserted in the oil gap) and barrier effect testing. A pressboard barrier can be easily inserted between upper and lower static ring, supported by appropriate spacers.

After model parameters are defined, more detailed electric field inhomogeneity analysis is made for the desired electrode parameters and oil gaps of 3 mm, 10 mm, 20 mm and 30 mm. Besides inhomogeneity factor of the whole model, η is also calculated for critical electric field lines (with the smallest σ_{min}) in cumulative and E_{max} method. It should be noted that critical electric field lines according to cumulative and E_{max} method do not belong to the same field line. Fig. 5 shows critical electric field lines for cumulative method - 1 and maximum electric field method - 2 in the model with the highest inhomogeneity factor (model with 30 mm oil gap).

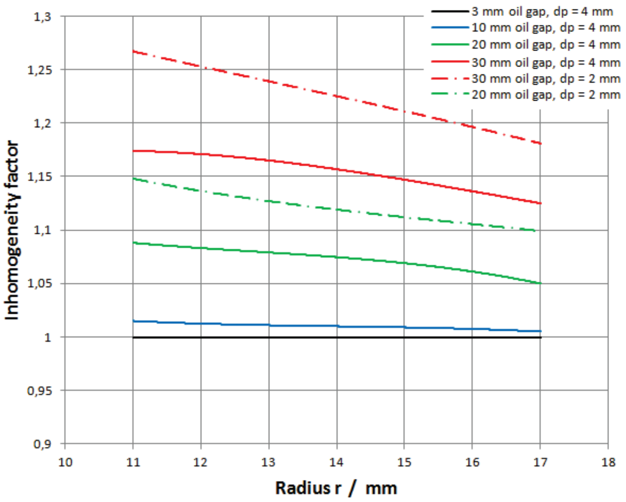

Figure 4 Inhomogeneity factor as a function of external radius r and paper insulation thickness d_p for various oil ducts

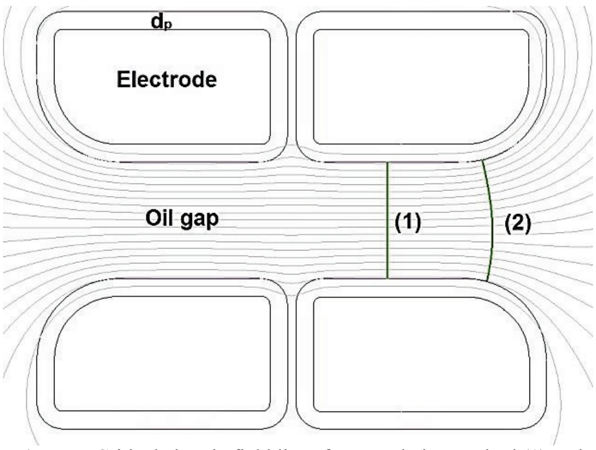

Figure 5 Critical electric field lines for cumulative method (1) and maximum electric field method (2) in model with 30 mm oil gap

Electric field inhomogeneity factors and lengths of electric field lines 1 and 2 are shown in Tab.1.

In the worst case, for 30 mm oil gaps, proposed model has the inhomogeneity factor on the paper surface equal to 1,12. From Tab. 1 it can be seen that the difference between maximum and mean electric field on line 1 is almost negligible, whereas on line 2 this difference is significantly higher (1,23). Also, critical electric field line obtained by E_{max} method is longer than electric field lines in homogeneous area. These results show that proposed model is more suitable for calculation with cumulative method than with E_{max} method. Consequently, the cumulative method will be used for estimation of model uncertainty in the following section.

Table 1 Inhomogeneity analysis results (η_1 – cumulative method; η_2– E_{max} method; η_m – inhomogeneity along paper surface)

Oil gap / mm	η_1 (cum. method) line 1	η_2 (E_{max} method) line 2	Lengths ratio line 2 / line 1	η_m
3	1,00	1,00	1,00	1,00
10	1,00	1,04	1,00	1,01
20	1,01	1,13	1,02	1,07
30	1,02	1,23	1,04	1,12

4 Model uncertainty analysis

In "small-scale" models experts often use nominal values of model parameters in test results evaluation. This approach is acceptable because model parameters do not vary in significant amount and it is easy to maintain parameters close to nominal. In larger size models with paper coated electrodes, actual electrode parameters differ from nominal values because of manufacturing tolerances. Furthermore, these parameters are not constant across the electrode circumference. Mentioned deviation of electrode parameters causes uncertainty in calculated minimum safety factors and in evaluated electric fields as a consequence.

4.1 Influencing factors determination

A pair of electrodes produced for model prototype testing (described in Section 5) is used for model uncertainty estimation. Electrodes are visually checked and parameters are measured. Three dominant influencing factors are detected, quantified and analyzed – spacer thickness, paper insulation thickness (on electrodes) and paper insulation squeezing. For each of the stated influencing factors mean value and standard deviation is found [24].

Spacer thickness defines oil gap width in models. This value reduces during the drying process due to material shrinkage and it should be measured after model drying to get accurate measures. In prototype this value was 9,5 ± 0,1 mm.

Paper thickness is not uniform across the electrode surface because of production tolerances and it should be measured on several different places around circumference of each static ring. Paper thickness of 4,1 ± 0,36 mm is measured in prototype.

Figure 6 Squeezing of paper insulation

Paper squeezing may occur during model assembling and drying process - some parts of paper insulation are squeezed by spacers (see Fig. 6). The depth of each squeezed segment is difficult to measure exactly but it can be estimated using a thin strip as a caliber. In the worst case, paper squeezing is 0,5 mm (on one side of the oil gap).

As a result of paper insulation squeezing oil gap width reduces and paper permittivity of the squeezed segment changes due to paper density change. Fig. 7 shows safety factors in nominal 10 mm oil gap with paper insulation squeezing of 0,5 mm (on each side). Minimum safety factor for nominal model parameters is equal to 1. Green marker in Fig. 7 shows the region where paper permittivity change is modelled in 10 steps. Cumulative method is not significantly influenced by the increase of electric field in the oil wedge inside the green marker in Fig. 7. E_{max} method is much more sensitive to enhancement of local electric field which can lead to significantly lower safety factors. This is an important drawback of E_{max} method in actual transformer insulation design as well.

Safety factors close to the spacer are higher than safety factors far from the spacer. Therefore, the impact of paper permittivity change on minimum safety factor value can be neglected as well as electric field deformation due to spacer permittivity. The second effect of paper insulation squeezing, the oil gap width reduction, cannot be neglected because minimum safety factors for the same voltage are lower than in a nominal oil gap. Consequently, the actual oil gap width should be calculated as a mean value of spacer thickness minus mean value of paper squeezing.

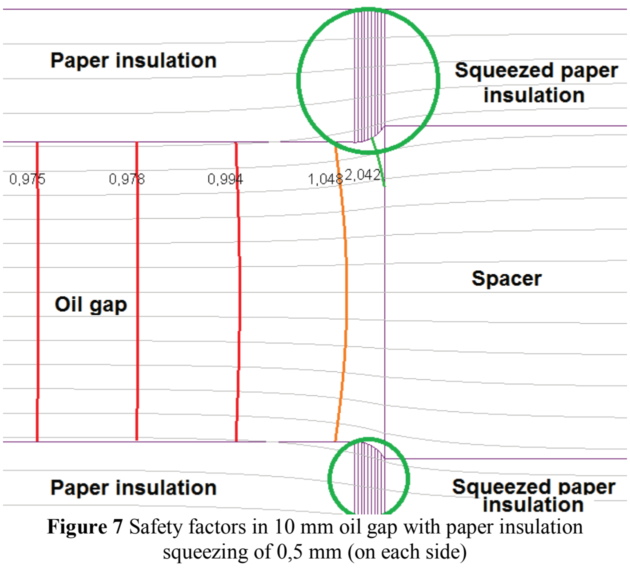

Figure 7 Safety factors in 10 mm oil gap with paper insulation squeezing of 0,5 mm (on each side)

For the purpose of statistical evaluation, paper squeezing effect is modeled with uniform distribution. One-sided paper squeezing mean value is 0,25 mm and standard deviation is 0,25 /$\sqrt{3}$ mm.

4.2 Model uncertainty estimation

Electric field strength in oil gap depends on breakdown or PD inception voltage and model geometry. One of the effects of electrode parameters deviation is a discrepancy between nominal and mean (actual) values up to 10 %. So, during the test results evaluation phase mean values of actual model parameters should be used to get results as precise as possible.

In the produced prototype actual oil gap width is 9,5 − 2·0,25 mm (actual spacer thickness minus the effect of paper squeezing on both sides of oil gap) and paper thickness is 4,1 mm. σ_{min} for this set of parameters is 0,98 which means that the calculation with nominal parameters instead of estimating actual model parameters can lead to a 2 % error. For smaller oil gaps and larger paper thicknesses this error is expected to be up to 5 %.

The second effect of electrode parameter deviation is model geometry uncertainty or σ_{min} uncertainty. This effect cannot be corrected as for mean values of model parameters, but must be analyzed using statistical methods. Model uncertainty is related to uncertainty of a single model parameter and it should be estimated using first-order Taylor series method [25]. If $\sigma_{min} = f(q_1, q_2, \ldots, q_i)$ then we can write:

$$u(\sigma_{\min}) = \sqrt{\sum_i \left(\frac{\partial f}{\partial q_i}\right)^2 \cdot u^2(q_i)} \tag{6}$$

where $u(\sigma_{min})$ is the minimum safety factor uncertainty, $\partial f/\partial q_i$ is the sensitivity coefficient of the i^{th} influencing factor and $u(q_i)$ is the uncertainty (standard deviation) of the i^{th} influencing factor. The procedure for model uncertainty estimation is described in the following.

First, sensitivity coefficients are derived using finite element method (FEM) and cumulative method calculation. These coefficients show the relationship between the individual uncertainty component and the overall uncertainty of the minimum safety factor. Each sensitivity coefficient is calculated from two simulations results. Electrode voltage is set to reference value (U_{ref}) which gives σ_{min} equal to 1 for model with nominal parameters. In analysis of spacer and paper thickness, parameter of interest changes ± 5 % from nominal value while all the other parameters are equal to nominal values. Squeezing of 0 mm and 0,5 mm is used in case of paper squeezing analysis. Minimum safety factor in both cases is calculated with cumulative method and sensitivity coefficient is derived from the change of the minimum safety factor divided by the change of parameter value.

Paper thickness sensitivity coefficient, for example, is calculated as:

$$\frac{\partial f}{\partial d_p} = \frac{\sigma_{\min(2)} - \sigma_{\min(1)}}{d_{p(2)} - d_{p(1)}} \tag{7}$$

where $d_{p(2)}$ is 5 % higher value than nominal d_p and $d_{p(1)}$ is 5 % lower than nominal d_p value. $\sigma_{min(1)}$ and $\sigma_{min(2)}$ are minimum safety factors in case when paper thickness is equal to $d_{p(1)}$ and $d_{p(2)}$ while other influencing factors are equal to nominal values.

Tab. 2 shows measurement uncertainty and sensitivity coefficient for each influencing factor. Model uncertainty is expressed in the last row for models with 3 mm, 10 mm, 20 mm and 30 mm oil gaps. It is important to state that only spacer thickness of 10 mm is measured because these spacers are used in prototype. Spacer thicknesses for 3 mm, 20 mm and 30 mm nominal oil gap width are assumed to behave in the same way as 10 mm thick spacers (5 % shrinkage of material during the drying process). Other model parameters are independent of oil gap width and the prototype measures can be used for uncertainty estimation of all model types.

Table 2 Model uncertainty estimation results

	oil gap / mm			
	3	10	20	30
Spacer thickness sensitivity coefficient / mm^{-1}	−0,007	0,027	0,022	0,016
Paper thickness sensitivity coefficient / mm^{-1}	0,163	0,090	0,060	0,040
Paper squeezing sensitivity coefficient / mm^{-1}	0,052	−0,05 6	−0,04 2	−0,03 2
Spacer thickness standard deviation / mm	0,030	0,100	0,200	0,300
Paper thickness standard deviation / mm	0,360	0,360	0,360	0,360
Paper squeezing standard deviation / mm	0,144	0,144	0,144	0,144
$u(\sigma_{min})$ - according to (6)	0,059	0,033	0,023	0,016

According to results in Tab. 2, uncertainty of models with 20 ÷ 30 mm oil gap is expected to be around 2 %, in models with 10 mm oil gaps uncertainty could be up to 4 % and in 3 mm oil gap models up to 6 %. These values must be taken into account when evaluating test results uncertainty, as well as voltage measurement uncertainty and the influence of voltage application method. From Tab. 2 it can be noticed that the most significant influencing factor is paper thickness due to high values of sensitivity coefficients (especially for models with smaller oil gaps). Model uncertainty can be reduced by obtaining lower manufacturing tolerances (which results in higher costs of manufacturing).

5 Model prototype production and testing

After model analysis has shown that proposed model concept is acceptable from the theoretical point of view, model prototype with oil gap of 10 mm is produced and tested to experimentally confirm this model concept.

The materials used in model prototype are the same materials as in a regular transformer production. In model preparation phase, insulation is vacuum dried on 110 °C for seven days. After drying, model is placed in a testing vessel and impregnated with mineral oil under vacuum of 0,2 mbar. Temperature of oil during the impregnation phase is 60 °C. Finally, oil is processed with an oil processing plant to achieve oil parameters as in actual transformer production practice. Oil parameters before HV testing of prototype are given in Tab. 3.

Table 3 Oil parameters in model prototype

Breakdown voltage (kV; for 2,5 mm gap)	82
Moisture content (mg/kg)	3
Gas content (mL/L)	< 10
Particle content (>5µm in 100 mL)	< 2000

Fig. 8 shows testing setup of a model in a test vessel. Upper electrodes are connected to voltage source through insulated leads and appropriate HV bushing. Test vessel should be large enough to minimize the influence on electric field in model. Volume of oil used in testing vessel is 2 m^3.

Test voltage application method is ramp in steps (step-by-step method). The first voltage step is approx. 60 % of calculated U_{ref}. The increase of voltage per step is roughly 3 % of U_{ref}. Each voltage step lasts for 1 min. PDs are recorded using standard electric method. Figure 9 shows testing setup in high voltage laboratory.

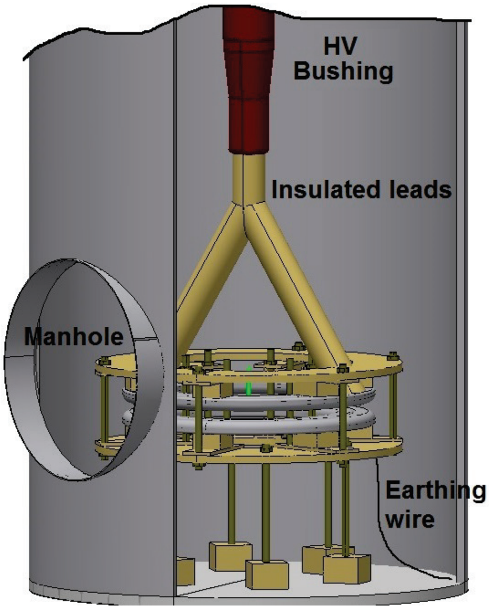

Figure 8 Model in a tank

The intention is to check the occurrence of "early PDs" and not to test oil gap breakdown voltage at this phase. One breakdown voltage result does not give sufficient information about breakdown behavior of an oil gap, but if model shows no "early PDs" problem it can be used in research project for testing different segments of transformer oil-barrier insulation system. So, test voltage is limited to a certain value which should be lower than the expected breakdown voltage, but still high enough to check the "early PD" occurrence.

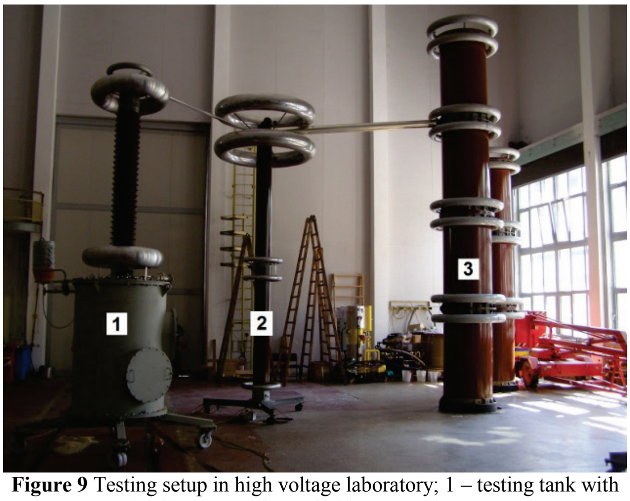

Figure 9 Testing setup in high voltage laboratory; 1 – testing tank with HV bushing, 2 – voltage divider, 3 – voltage source

For the model with 10 mm oil gap reference voltage is derived by using cumulative method in combination with design curve proposed in [14] and it is equal to 142 kV. Design curve in [14] presents low PD inception probability curve. According to results reported in literature [26, 27] it can be expected that the ratio of 50 % probability PD inception voltage and 1 % probability PD inception voltage is between 1,1 and 1,2. Hence, the highest test voltage in the prototype testing should be about 10 % higher than reference voltage to ensure acceptable number of results and to get good information about model characteristics. Test voltages 15 % higher than referent voltage increase breakdown probability and smaller number of test results can be expected. Consequently, it is decided to test prototype with the highest voltage of $1{,}1 \cdot U_{\mathrm{ref}}$.

5.1 Model prototype testing results

Prototype is continuously tested with ramp-in-steps method up to $1{,}1 \cdot U_{\mathrm{ref}}$, with 1 hour break between each test. No permanent PDs higher than 5 pC are recorded in each test and it can be concluded that proposed model concept avoids early PD inception. In our further investigation additional tests up to breakdown or up to PD inception will be performed.

5.2. Test results uncertainty

Besides previously analyzed model geometry uncertainty, there are also two factors related to high voltage testing procedure and equipment that influence test results uncertainty. The first is the influence of ramp in steps testing method. Generally, AC design curves for oil-barrier insulation system 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. Ramp in steps (step-by-step) test method is more effective because breakdown or PD inception is reached in a shorter period of time. Different authors reported that in this case permissible el. fields could be underestimated if previous exposure history had not been taken into account,[28]. Application of ramp in steps testing method is estimated to result in obtaining 1 ÷ 2 % lower permissible stress than in case of 1 min AC test (for ramp in steps method parameters as stated previously in chapter 5), [29]. These theoretical considerations have not been adequately verified by experimental research up to now in oil-barrier insulation system. This topic should be further analyzed in the future. The second influencing factor is high voltage measurement uncertainty which should be estimated for the used high voltage measuring system. Measurement uncertainty estimation for common high voltage measurement systems, as used in our research, is a standard procedure. Details of the procedure are outside of scope of this work but should be included in actual test results uncertainty estimation.

6 Conclusion

Presented model concept for testing oil-barrier insulation system is appropriate for testing of oil gaps up to 30 mm in low inhomogeneity electric field configuration. Model uncertainties are acceptable from practical point of view and model geometry influence on test results is not significant. Model prototype is tested and the obtained results show that the paper coating insulation used in this model concept avoids "early PDs" problem. Proposed model concept can be used for testing of different segments of transformer oil-barrier insulation system so as bulk oil gap, creepage strength and barrier effect. High costs cannot be avoided in this type of research but with good test plans and model concept costs can be reduced.

7 Acknowledgment

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