Journal of Energy

VOLUME 61 | 2012

journal homepage: http://journalofenergy.com/

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RESEARCH OF TRANSFORMER MAIN INSULATION DESIGN RULES

SUMMARY

Kappeler research performed more than 50 years ago is widely used for HV transformers insulation design. Even though the original experiment was done for oil ducts width from 0.5 to 6 mm, the results have been extrapolated to ducts up to 100 and more mm without detailed publication that would confirm the validity of this extrapolation.

This paper presents the experiment that aims to expand Kappeler research to oil duct width up to 30 mm. Model setup also allows creepage and barriers effect testing up to 30 mm.

Key words: power transformer, insulation, electric field, partial discharges, insulation design

1. INTRODUCTION

Power transformer insulation consists of two main materials: paper and oil. These two materials have proven their reliability for HV transformer insulation for many decades. They can be used in transformer in various forms – from oil impregnated paper between electrodes (usually between winding turns) to oil impregnated paper in combination with oil gap (usually used for leads and many other application). A special combination of the least is a so called oil barrier insulation and it is used for insulation between windings and between windings and earthed parts in all oil immersed HV power transformers.

The essential fact for oil barrier insulation is that oil channels are divided with paper barriers with the aim of increasing their withstand voltage. Insulation should be designed in such manner that the ratio of permissible stress and obtained (calculated) stress in all channels is greater than a certain value. This ratio is well known as the safety factor or margin.

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 a widely accepted breakdown theory has not yet been found. Permissible dielectric strength of oil ducts is increased when oil duct width decreases. The following formula for permissible electric field is widely used:

$$E_p = Ax^{-b} \quad (1)$$

where:

A and *b* are factors obtained by experiments
x is the oil duct width along electric field line.

One of the widely used researches regarding the above-mentioned is [1], in transformer society well known as Kappeler research. This research was performed more than 50 years ago, and published in 1958. It deals with observation of gas bubbles in an oil gap between paper insulated electrodes that form nearly homogeneous AC electric field. Voltage exposure time was 3 min and the experiment was performed for degassed and gas (air) saturated oil. Oil distance range between electrodes was from 0.5 to 6 mm (Figure 1).

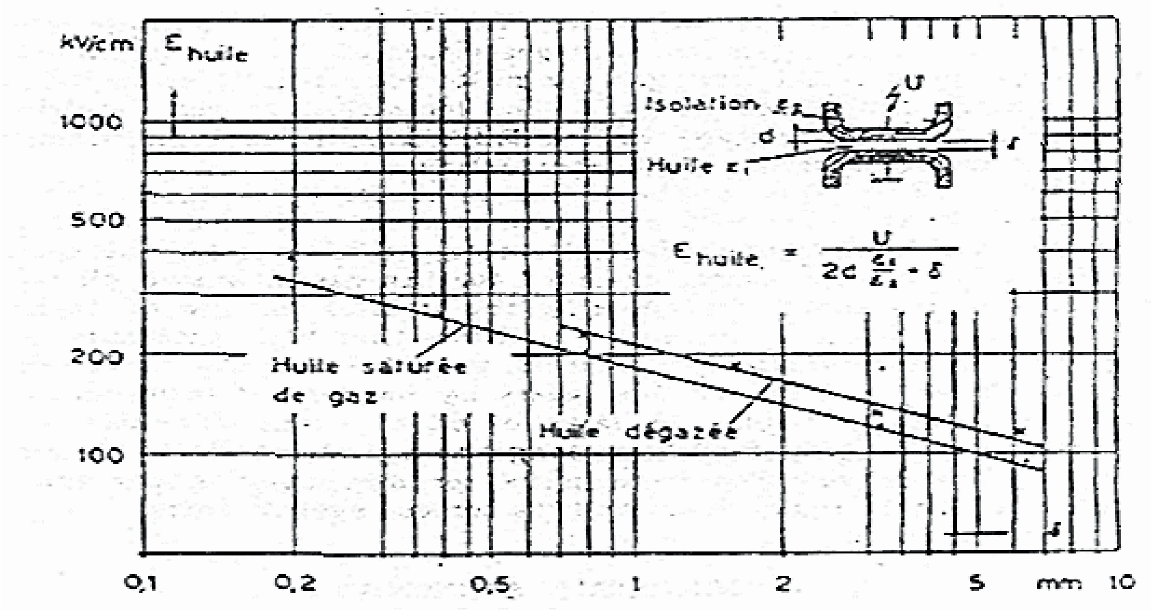

Figure 1. Kappeler research results

It is important to note that Kappeler research is extrapolated up to 100 and more mm and is used for oil ducts design in HV transformers. According to the authors' knowledge, validity of that extrapolation was not well published in literature. Also, Kappeler (or similar) results are used for paper - oil creepage design and some other very specific purposes in HV power transformer insulation [2].

Regarding the above mentioned, it has been decided to perform one of the most intriguing research in oil immersed transformer insulation design: estimation of oil ducts dielectric strength. This paper presents the experiment that will test Kappeler research but with enlarged oil ducts width up to 30 mm. Such oil distances need pretty complicated and large model setup arrangement that is PD free up to aprox. 325 kV. Because of that electric field around electrodes is extensively studied.

Configuration of electrodes used in this research differs from the configuration that Kappeler used in his investigations. Voltage shape and PD measurement method are also not the same since Kappeler observed gas bubble appearance as a PD indication and in this research electric and acoustic methods are used. All the mentioned differences may result in certain discrepancies between the results of these two experiments. Besides testing Kappeler results the aim is to research barrier effect and spacers creepage strength as well. For this purpose several dozen of models will be manufactured in 16 different arrangements. Possible variations of models are:

- models without barrier and spacers
- models with spacers (without barrier)
- models with barrier and spacers (one and two barriers per model)

2. MODEL CONCEPT

Specially designed static end rings (similar to that widely used on HV transformer windings) are used as electrodes and placed in an insulating frame that allows changing of oil gap width using insulating screws. Inner diameter of electrodes used in model is about 450 mm and outer about 700 mm. Figure 2 shows the arrangement of electrodes in the model and Figure 3 shows the cross section of the model. Static rings were chosen for model electrodes because of various reasons: they are easy to produce in transformer factory, it is not difficult to obtain low tolerances, it is relatively easy to obtain near homogeneous el. field and what is perhaps the most important they are used in the area of a transformer exposed to the highest electric stresses. Because of their simple cylindrical geometry it is easy to calculate el. field and to solve possible crepage stresses problems.

Model consists of two identical pair of electrodes, upper and lower static end rings. Each static end ring is split in two parts with a small gap between them. Such arrangement is used because it is easier to achieve better tolerances. This gap is also used for fastening of the rings to other insulating parts. Each static end ring is connected in two points with paper insulated copper rope which is used for grounding or voltage appliance (not shown on fig 2 and 3). Ring electrode is produced in a similar way as for transformer end rings with an exception – electrode overlap is not used.

Three groups of models will be produced as stated in the introduction. In models with barriers, spacers are used to assure the distance between both electrodes and between one or two barriers. Barriers will be placed horizontally between electrodes in the middle of oil gap, so tangential el field on the barrier will be negligible.

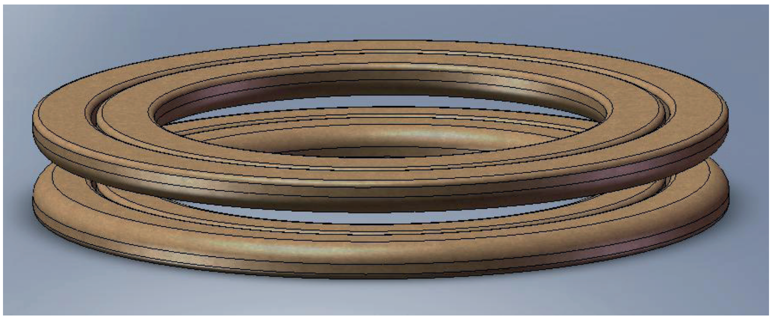

Figure 2. Arrangement of electrodes in the model

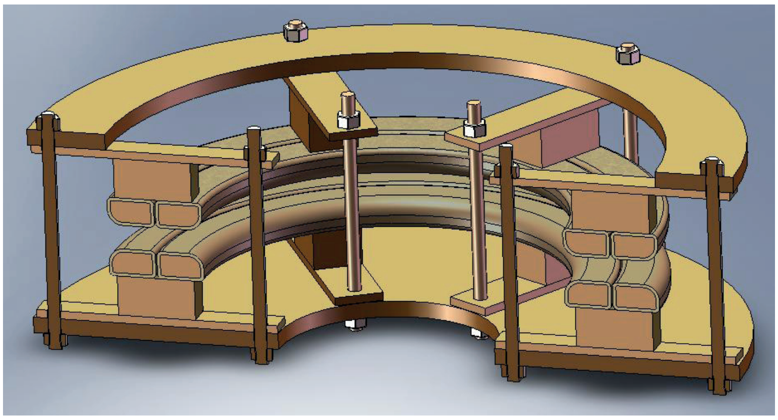

Figure 3. Model cross section

3. ELECTRIC FIELD CALCULATION

In order to achieve the lowest possible inhomogeneity factor, several electrode parameters have been analysed - paper insulation (d_{paper}), radius of the ring body (r_2) and the gap between the rings (d_{gap}). Cross section of electrodes configuration is given in Figure 4.

Electric field inhomogeneity factor is calculated according to expression:

$$f_{in} = \frac{E_{\max}}{E_{\text{hom}}} \quad (2)$$

where:

E_{max} is maximal electric field in oil on oil-paper bound,

E_{hom} is average magnitude of electric field in oil on oil- paper bound in the area where field is homogenous.

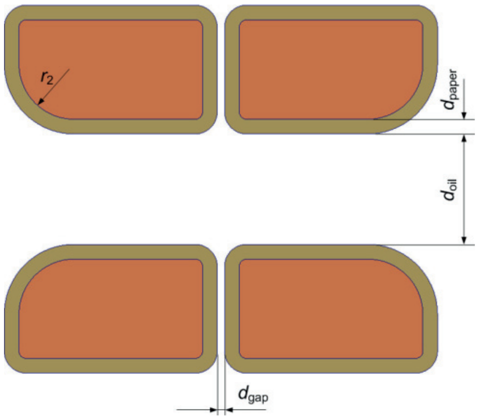

Figure 4. Cross section of electrodes configuration

Size of electrodes and paper thickness which result in the lowest inhomogeneity factor have been chosen. Procedure was based on several calculations of electric field (using FEM based software) for different electrode parameters and analysis of field inhomogeneity in oil. Obtained inhomogeneity is about 1,1 for oil distance of 30 mm. It decreases to 1 rapidly with the decrease of oil distance, so that for 15 mm inhomogeneity is about 1,02. Chosen insulation thickness, ring radiuses and the gap between the inner and outer ring remain the same for all the models. Models mutually differ in the gap between the upper and the lower rings, barriers and spacers (weather they have them or not). Electrical field has been calculated as cylindrical.

Field distribution for model without barriers and with a 30 mm gap between the rings is given in Figure 5. Shaded plot displays field magnitude and contour plot equipotential lines.

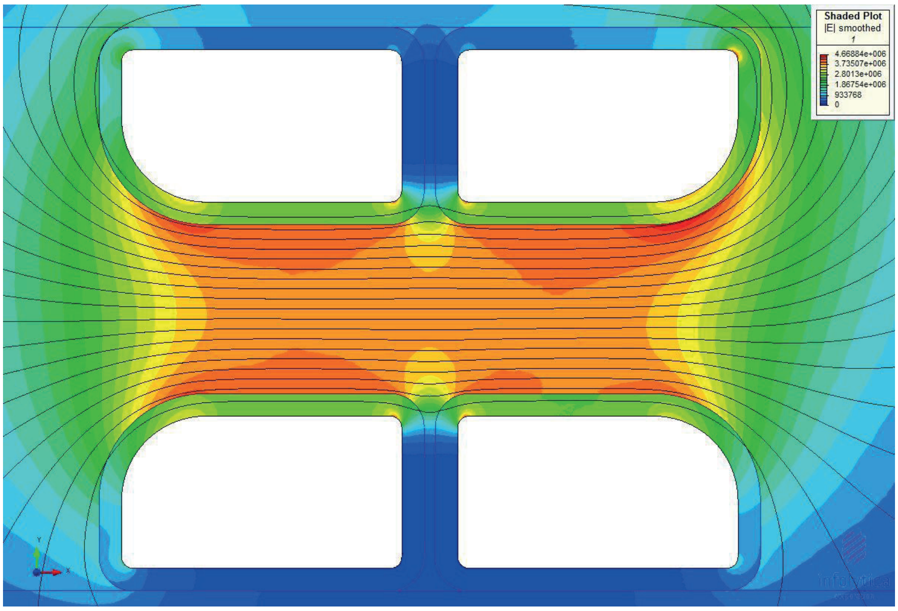

Figure 5. Electric field distribution

Figure 6 shows field lines in the gap between two outer rings along which safety margins have been calculated. Although they were calculated along 17 field lines, only few of them are shown in the figure. Safety margins have been obtained using cumulative method, [2], which means that they are defined as a ratio of permissible stress $E_p(x)$ and actual average field $\bar{E}(x)$ along the same field line. $E_p(x)$ has been calculated according to (1). Minimum safety margin σ_{min} is the minimum value of the function $\sigma(x)$.

$$\sigma(x) = \frac{E_p(x)}{\bar{E}(x)} \tag{3}$$

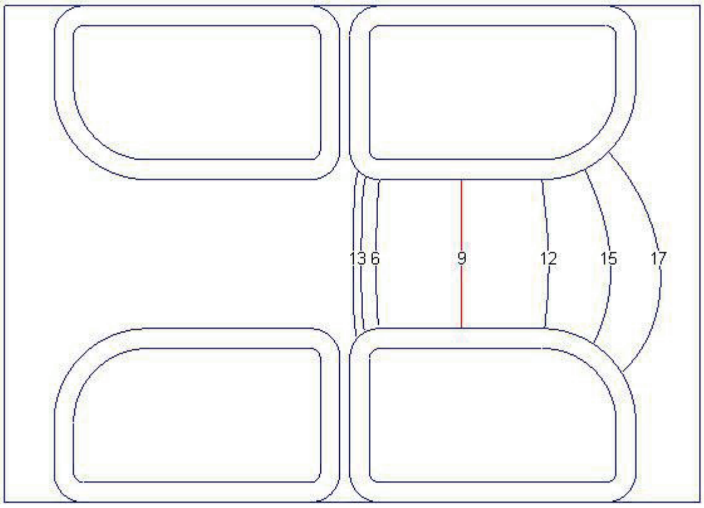

Figure 6. Field lines along which safety margins were calculated

Calculated safety margins for U = 213 216 kV are given in Figure 7.Permissible stress is according to Kappeler research for degassed oil. Minimum safety margin has been obtained for field line no.9 and it's equal to minimum allowable value σ_{min}= 1. It is worth wile to notice that minimum safety margin does not lie on the field line which starts at the point of maximum el. field (E_{max}). This is a consequence of the applied cumulative method for safety factor calculation and it happens often in complex el. fields.

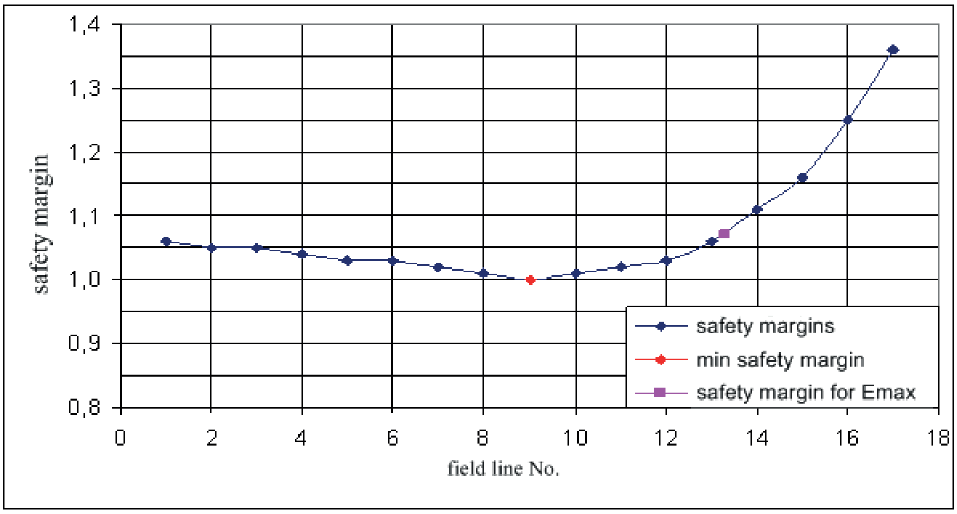

Figure 7. Safety margins along field lines 1-17 (Figure 6), calculated for U = 216 kV

4. MODEL TESTING ARRANGEMENT AND PROCEDURE

Assembled models are vacuum dried in a drying oven at the temperature of about 110 °C for seven days. Duration of drying process depends on moisture content and is usually seven days. After the completion of the drying process, pressure in the oven should be below aprox. 0,5 mbar. Dried models are finally checked, tightened, assembled with leads and placed in a testing vessel (volume cca 2 m^3), and assembled with appropriate bushing, figure 8. In the next step, models are vacuum treated and impregnated with processed mineral oil. The final value of vacuum in a testing vessel after impregnation should be less than aprox. 0,2 mbar. After impregnation, oil is processed once again with an oil processing plant to decrease the particle content. Before testing starts oil samples are taken for DGA, air content, humidity content, particle content measurements and BDV.

Figure 8. Model in a testing vessel, side view

Model is connected to AC voltage source using insulated leads and 245 kV bushing (Figure 9). Test voltage shape is a ramp in steps as shown in a Figure 10. Expected test voltages of all models are lower than 325 kV. The first voltage step should be approx. 60% of calculated withstand voltage. The increase of voltage per step should be about 3% of calculated withstand voltage. Each voltage step (T1) should last for 1 min.

Figure 9. Test arrangement

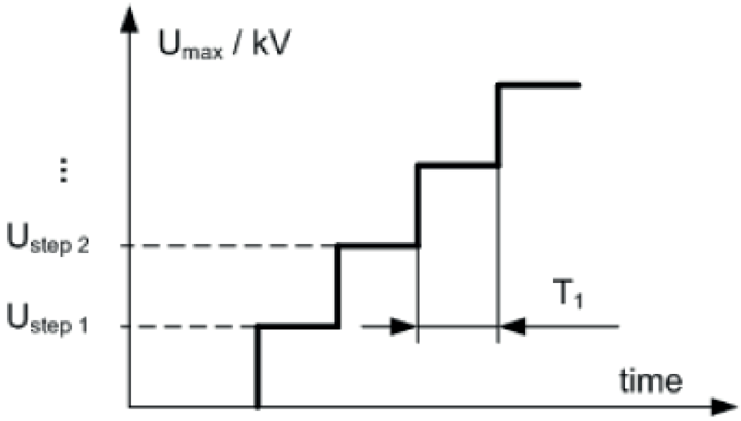

Figure 10. Test voltage shape

Voltage will be applied until PD starts and after that the model will be deenergized. Voltage must be decreased and switched off at the moment PDs are detected. If possible, each model should be tested 10 times. Time between subsequent tests of the same model should be at least 1 hour. PDs are measured using standard electric method and acoustic method. Sensitivity of the acoustic method might be a problem. In case of PD level which is too low, this method cannot be used. A serious problem could be in case of breakdown without PD inception. If this happens the number of models will be increased.

5. CONCLUSION

Paper explains some basic principles of HV transformer insulation design. Those principles originate from Kappeler research performed more than 50 years ago. Kappeler's results have been extrapolated and widely used in transformer society all over the world even though the validity of that extrapolation has not been properly published in literature. This paper presents the research that is meant to test the validity of Kappeler results and the validity of the extrapolation to larger oil ducts. Besides Kappeler results testing, the aim is to research barrier effect and crepage strength as well. The paper describes model arrangement and construction, electric field calculation as well as laboratory testing procedure.

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