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OIL DUCTS AND SOLID INSULATION IN BARRIER SYSTEMS AT HVDC STRESSES

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ABSTRACT

HVDC-transmission is getting more and more important in the global development of remote hydro plants and other energy sources. Yet still there are engineering challenges in terms of specific characteristics of the HVDC insulation. These challenges arise from the fact that the electric AC field distributions are determined by permittivities, DC fields predominantly by conductivities which are inaccurately known and difficult to control. The paper reports on polarity reversal measurements, measurements of conductivities and polarization processes related to materials (Transformerboard, RIP and oil) and HVDC insulation test models consisting of two or three materials. Advanced material models for solid and liquid insulation are derived. Simulations with the new models give good agreement with measurements. Results also show how charge carriers move in oil and influence currents and field strengths. Calculations of transient field strengths require the application of advanced material models, traditional permittivity/conductivity models are not sufficient.

Index Terms - HVDC, PDC, insulation, conductivity, polarity reversal, barrier system, transformer oil, pressboard, measurement, modeling

1. INTRODUCTION

High voltage direct current (HVDC) transmission is increasingly getting important, as AC transmission is faced with technical and economic limits. Large projects with power ratings up to several GW require voltages up to 800 kV [1]. Consequently there is a strong need for improved knowledge about the specific properties and behavior of HVDC insulation which is totally different from the behavior of AC insulation systems. Even transformer windings, feeding the HVDC valves, are exposed both to AC and DC stresses. Therefore internal transformer insulation is very complex and it is expected to have a high potential for optimization, especially for oil-pressboard barrier systems and barrier-bushing interfaces.

1.1. HVDC stresses and aim of investigation

When the voltage is switched on, HVDC stresses consist initially of displacement fields, which are determined by permittivities. After a long time a steady state condition is reached, which is determined by conductivities.

During the transition from the initial field towards the steady state field complex charging, discharging and polarization processes among the insulation system components occur. They are determined by permittivities, conductivities and polarization properties.

Unfortunately, these properties are difficult to measure and to control. Furthermore, polarity reversals (PR) superimpose strong displacement fields to the actual transient or steady state conditions and a new transient process is started [2], [3]. Therefore, HVDC insulation systems are not as simple as AC insulations which are determined by well known permittivities only.

The aim of the investigation described here, was the measurement of dielectric material properties in order to get physical models. These models were used to simulate polarization currents and field strengths during polarity reversal experiments in simple insulation systems with two or three materials.

Measured and calculated polarization currents were compared; in order to see how precisely HVDC field stresses can be assessed by simulation models. Furthermore, the interaction between liquid and solid insulation was studied, in order to develop physical explanations.

1.2. Dielectric behavior

After polarity reversal, complex field conditions with very high field strengths can occur, especially in barrier systems. Therefore the different materials in transformer barrier systems and their interactions are of special interest, mainly for solid insulation (Transformerboard, resin impregnated paper RIP) and for liquids (transformer oil).

First of all, a precise knowledge of the dielectric material properties (permittivities, conductivities and polarization properties) is required.

A dielectric material can be described by an equivalent circuit, fig. 1. Different physical properties are represented by circuit elements, i.e. the permittivity (at power frequency) by a capacitance C_{Geo}, the relevant polarization processes by a number of R_iC_i-elements (corresponding to the relaxation time constants of the polarization mechanisms) and the so called DC-conductivity by a resistance R_∞.

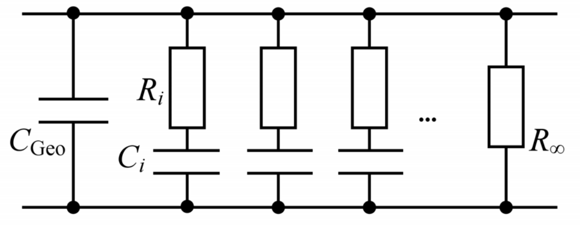

Figure 1: Dielectric material equivalent circuit derived from extended RC-model.

Especially DC-conductivity is of high importance for HVDC insulation design it determines steady state field distributions. DC-conductivities can be calculated from end values of polarization current measurements. If an end value is not yet reached, conductivity must not be calculated from the actual current value. Nevertheless, this is often done, but for clarity it should be called “apparent conductivity”, as the corresponding currents are caused by polarization of the material and not by conduction only. Standard conductivity measurements (IEC 60093; 60167; 60247; 61620) are not applicable to HVDC insulations, they do not give a sufficient picture of the relevant dielectric properties.

2. MEASUREMENTS

2.1. Test cell

Flat dielectric material samples and flat insulation models were measured between stainless steel guard ring electrodes in a glass vessel filled with transformer oil [4], [5], [6], fig. 2.

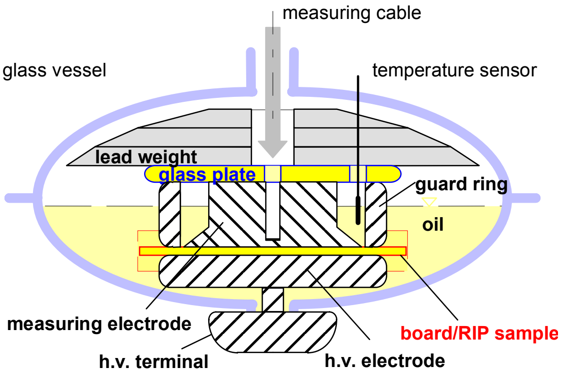

Figure 2: Experimental setup for the polarity reversal measurement. The insulation model (oil, board, RIP) is measured between stainless steel guard ring electrodes.

The treatment of solid samples, high-density pressboard B.3.1 according to IEC 60641 (Transformerboard T IV) and resin impregnated paper RIP, consisted of drying under hot temperature and vacuum, mounting in the thoroughly cleaned test cell, drying and impregnation under vacuum. Insulating oil (Shell Diala GX or Shell Diala G) was filtered, dried and degassed. Water contents $< 0.3\,\%$ (solids) and < 5 ppm (oil) were achieved.

2.2. PDC analysis

The first aim is to identify dielectric properties of materials from polarization and depolarization currents. PDC measurements are basically step response measurements containing all the information about the dielectric system. Analysis can be performed by curve fitting with a number of exponentially decreasing currents which are related to a number of parallel RC series elements [7]. PDC analysis is a powerful tool for the evaluation of dielectric properties. It was used to determine dielectric models for all materials, used during the polarity reversal measurements described below.

The long term (end) value U/R_∞, which is determined by the DC-conductivity is time-consuming to determine because of very long lasting polarization processes. In the case of solid insulation the term “conductivity” is always used to describe DC-conductivity, determined from long term PDC measurements converging towards theoretical end values. A new method for the estimation of DC-conductivities from polarization and depolarization charges was developed, the so called Charge Difference Method (CDM) [5]. I.e. a better convergence to U/R_∞ is achieved, if the sum of polarization and depolarization charges (i.e. the difference of the charge amounts) is regarded.

2.3. PR measurements

The second aim was to understand the behavior of materials during PR. For this purpose a special PR test and control setup was developed. A PR measurement consists of four intervals: (1) The PDC analyzer starts the measurement of currents, no voltage is applied for 8 s. (2) Then a stabilized DC source is switched on for some 1,000 s. (3) After this polarization interval the voltage is switched off for 8 s, in order to allow the DC source to reverse polarity automatically. (4) Finally the reversed polarity is switched on. During interval (1) and (2) the current is displayed in a double-logarithmic diagram. During interval (3) and (4) the current is shifted and displayed in the former diagram, in order to compare the currents at both polarities directly.

The DC voltage source can deliver a highly stabilized voltage up to +/- 65 kV. The resolution of current measurements is 1 pA. Temperatures and partial discharges are monitored.

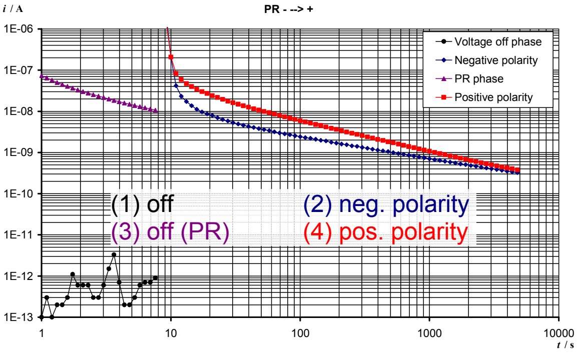

Figure 3: Absolute values of the current before and after the polarity reversal. (Weidmann T IV, d = 1 mm, 30 kV/mm, 20 °C)

The four intervals of a PR measurement are explained by means of oil impregnated Transformerboard sample (T IV, with a thickness and an electrode distance *d* of 1 mm), fig. 3: During interval (1) there is no voltage applied. The current is a small depolarization current of a few pA which can be neglected. Interval (2) shows the negative polarization current during application of negative voltage for 5,400 s. During a few seconds the test voltage is not yet stable and displacement currents are superimposed for approx. 5 s. In interval (3) the voltage is switched off and the sample is short circuited. There is a high depolarization current which is typical for solid materials. It is superimposed to the former diagram for comparison purposes. In interval (4) the sample is connected to the (reversed) positive voltage and a positive polarization current is superimposed to the (positive) depolarization current. Therefore the measured current value is bigger than in interval (2).

3. SOLID MATERIALS

3.1. Measurements

Measurements on Transformerboard were already explained above, fig. 3. Measurements on resin impregnated paper RIP show very similar behavior, but the current increase after PR is a little bit lower. This may be explained by the fact that the cellulose in oil impregnated board is more polarizable than the resin impregnated material.

3.2. Physical explanation

The intervals of the PR measurement can be explained by the linear equivalent circuit, fig. 1: In interval (2) the applied field polarizes molecules, molecule groups, fibers etc. Movement of charges and orientation of dipoles result in decreasing polarization currents with different time constants. They are superimposed to the measured decreasing current.

Only after complete polarization, conduction current is remaining, exclusively caused by the DC-conductivity. In fig. 3 this situation is not reached.

In interval (3) the relaxation of the polarized material delivers a current, the so-called depolarization current. In solids it is nearly as high as the polarization current in interval (2). This shows that the current is mainly caused by polarization effects and that conduction current is negligible. After polarity reversal the new polarization current i_{Pol}’ has the same direction as the former depolarization current i_{Depol}. I.e. in interval (4) the discharging of the material and the re-charging in opposite direction cause currents in the same direction. Therefore the current after PR $i’= i_{\mathrm{Pol}}’+i_{\mathrm{Depol}}$ is higher than the current during the initial polarization.

This can be observed for long times, fig. 3. It should be mentioned that these effects can enhance field stresses in HVDC insulation systems: Polarization/depolarization currents in solid materials can cause additional field stresses in oil ducts.

3.3. Modeling

The measurements clearly show that it is not sufficient to describe solid materials just by conventional circuits consisting of a capacitance and a resistance, representing a permittivity and conductivity respectively. Polarization processes require an extended model according to fig. 1.

Analysis shows that for RIP and board linear circuits can be used. Only for very high field strengths in the order of 30 kV/mm board shows a slight nonlinearity. The elements of the material models are determined by PDC analyses and Schering bridge measurements.

4. TRANSFORMER OIL

4.1. Measurements

PDC and PR measurements with transformer oil were performed in the arrangement according to fig. 2. The distance between the electrodes was determined by placing oil impregnated Transformerboard spacers with a thickness *d* = 2 mm between guard and HV electrode.

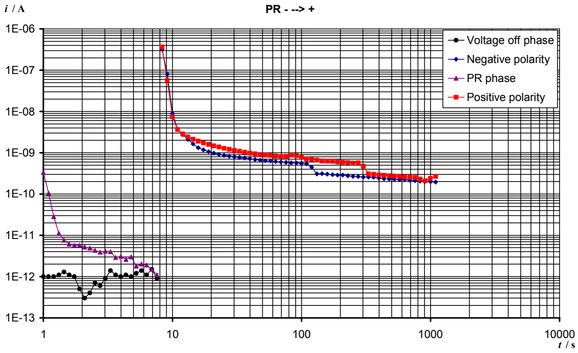

Figure 4: PR measurement on transformer oil (Shell Diala G, d = 2 mm, 2 kV/mm, 20 °C) with a distinct transit time τ at 120 s in interval (2) and at 300 s in interval (4).

In contrast to solid materials the decreasing current in interval (2) is a conduction current and not a polarization current, fig. 4. This can be proven by the negligible depolarization current in interval (3), it shows that the material was not polarized to a significant extent. After PR the current in interval (4) is not influenced by any remaining depolarization current, it is not very different from the initial current in interval (2).

4.2. Physical explanation

After DC voltage application, charge carriers drift towards the electrodes within a transit time τ and disappear from the bulk oil volume [8]. A new equilibrium at a lower level of conductivity is achieved. Therefore it was expected that the current after PR would start at the low level which was reached already during the first voltage application.

Interestingly this is not the case; both currents are not so different, fig. 4. This means that the charge carriers were not neutralized at the electrodes; probably they were accumulated in a space charge zone and were available again for current transport after PR.

After PR almost all charge carriers start drifting from the proximity of the electrodes towards the opposite electrodes. Therefore, the average transit time is prolonged, i.e. the current curve is slightly shifted to longer times, fig. 4.

This explanation is described in fig. 6. In interval (1), the charge carriers are equally distributed in the oil. In interval (2), the charge carriers drift towards the electrodes (2a) and form a space charge zone in the end (2b). The average drift distance is approx. half the gap width.

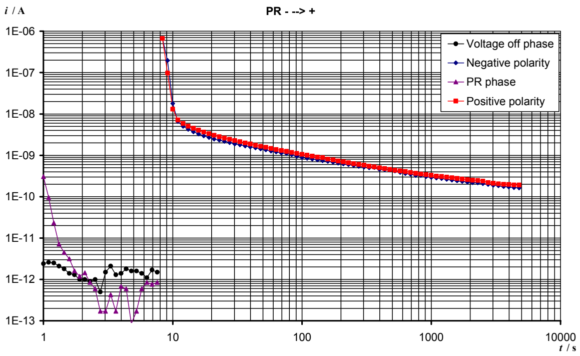

Figure 5: Repeated PR measurement on oil (Shell Diala GX, d = 2 mm, 5 kV/mm, 20 °C)

After PR in interval (4) the charge carriers drift in the opposite direction (4a) and form a space charge zone with reversed polarity (4b). The average drift distance is approx. the full gap width [10].

If the polarity is reversed several times, a so-called "conditioning" takes place and the difference between the currents in interval (2) and (4) disappears completely, fig. 5. I.e. both for the negative and for the positive voltage the charge carriers are accumulated in space charge zones close to the electrodes and drift distances are equal in both cases.

This effect is of interest for voltage tests on HVDC equipment: The behavior of the insulation system depends on the history of preceding tests (memory effect).

For very high field strengths (above 3-6 kV/mm), new charge carriers are generated, conductivity increases nonlinearly and movement of charge carriers and charged particles gets an erratic nature, fig. 7. Thereby the effects described above are masked completely.

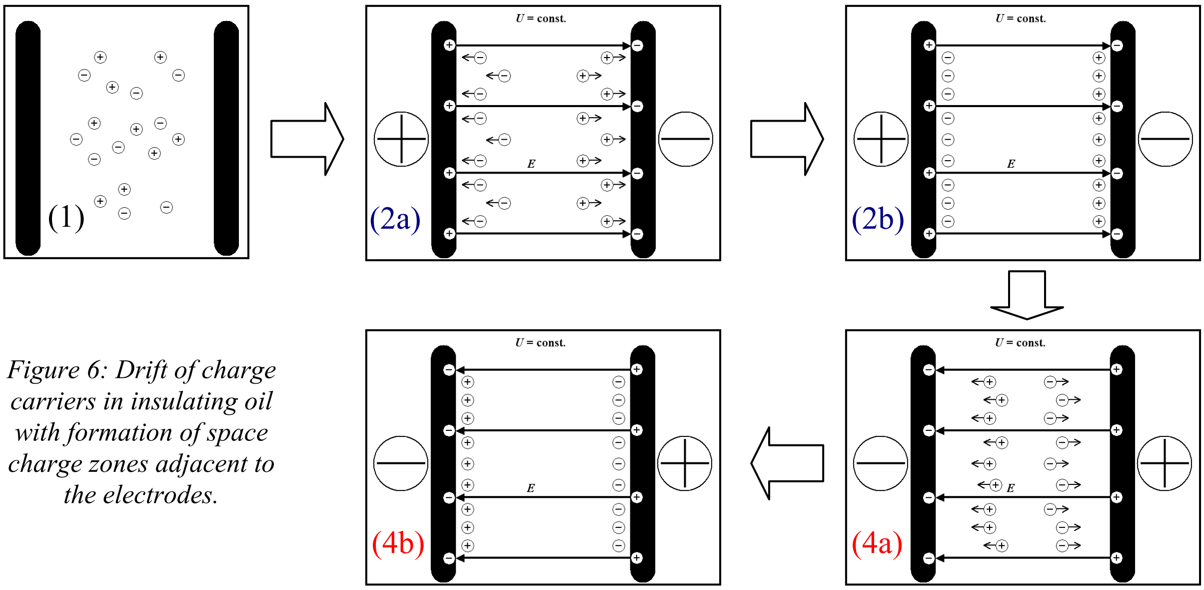

Figure 6: Drift of charge carriers in insulating oil with formation of space charge zones adjacent to the electrodes.

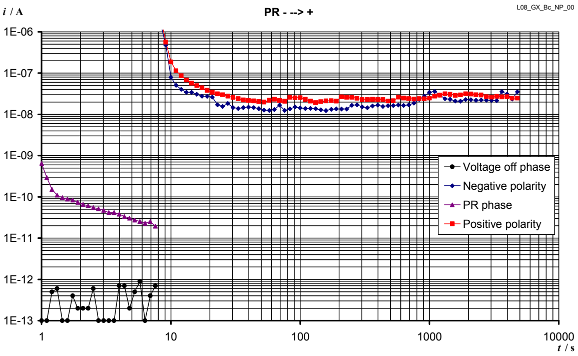

Figure 7: PR measurement on transformer oil (Shell Diala GX, d = 2 mm, 10 kV/mm, 20 °C)

4.3. Modeling

The voltage-step response of oil shows a decreasing current, but depolarization currents are negligible. The dielectric circuit is reduced mainly to a capacitance and a nonlinear conductivity depending on several parameters. Linear circuits are not applicable any more. A physical description of the oil has to include the nonlinear behavior and the drift of charge carriers. Therefore the so-called “oil model” [11] was further developed: It is assumed that the initial amount of charge $Q(0)$ is diminished by the already transported amount charge $q(t) = \int i_{\mathrm{Pol}}(t)\mathrm{d}t$:

$$Q(t) = Q(0) - \left|\int i_{\mathrm{Pol}}(t)\mathrm{d}t\right| \qquad (1)$$

The actual amount of charge $Q(t)$ in the oil gap is used to calculate the actual current $i_{\mathrm{Pol}}(t)$. The width of the oil gap is d and the charge carrier mobility is μ:

$$i_{\mathrm{Pol}}(t) = Q(t)\cdot\mu\cdot E(t)/d + I_{\mathrm{End}}(E) \qquad (2)$$

It should be noted that oil conductivity measurements were performed between stainless steel electrodes which is not the situation in a transformer, but the results (next chapter) could successfully be used to simulate the behavior of barrier systems with oil ducts not being in contact with a metal electrode.

5. BARRIER SYSTEMS

5.1. Measured and simulated currents

Insulation models with two barriers (Weidmann Transformerboard T IV) and an oil duct in-between were measured and analyzed, e.g. fig. 8. As expected, the comparison of the two polarities shows a current increase after PR. The depolarization current from the previous polarization is added to the polarization current after PR. This effect is caused by the solid material components.

The oil duct plays a role in the charging of the board capacitance via the resistance of the oil duct, fig. 8 (arrow).

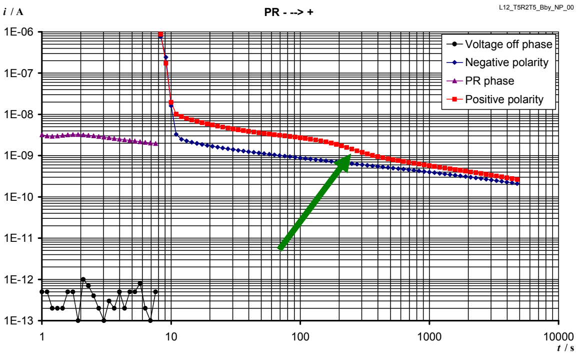

Figure 8: PR measurements on a board-oil-board system (0.5 mm - 2 mm - 0.5 mm, 15 kV, 20 °C).

This should not be mixed up with the transit time for the charge carrier drift in an oil duct. The charging effect can not be identified in the negative polarity, since the oil is non-linear. In the negative polarity there is a significantly lower field strength in the oil duct than in the positive polarity after PR.

Fig. 9 shows the comparison of the measurement with a simulation. The simulation is based on linear extended circuits for the solid insulation and the charge carrier model eq. (1) and (2) for the oil.

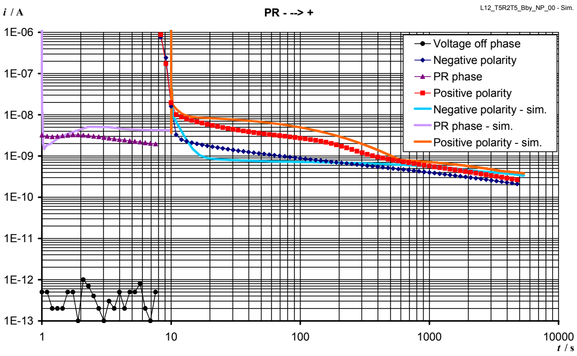

Figure 9: Comparison of measurement from fig. 8 with advanced simulations (“sim.”).

There is a good match of the simulated currents with the measured currents at all times during the measuring cycle. It is concluded that the physical explanations, on which the models are based on, are accurate. This enables a much better description of HVDC insulation systems than with simple conventional circuits. Therefore, these models were used to calculate transient field strengths in barrier systems.

5.2. Simulation of transient field strengths

Transient stresses after DC voltage application and PR were calculated for a three layer insulation system (50 mm Transformerboard - 100 mm oil - 50 mm RIP) at 800 kV with the simple classic simulation model, fig. 10, and with the advanced simulation model, fig. 11. These three layers represent a higher number of thinner layers in real insulation systems. Fig. 10 shows a calculation with simple RC-circuits representing permittivities and conductivities only.

I.e. only interfacial polarization effects are described: The oil is discharged, RIP and board are charged.

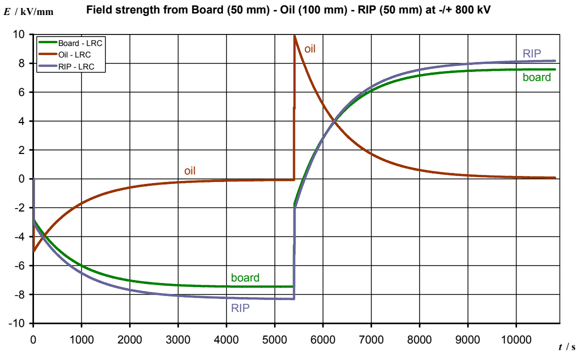

Figure 10: Simulation of field strengths in a three layer dielectric system after DC voltage application and PR with simple classic linear RC-circuits.

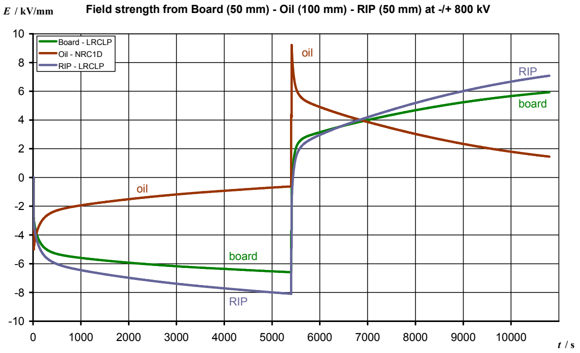

Figure 11: Simulation of dielectric strengths in a three layer dielectric system after DC voltage application and PR with advanced material models. Linear models for board and RIP include material polarization. The model for oil includes non-linear conductivity and charge carrier drift.

Fig. 11 shows the calculation of the same model with an advanced material model. It includes extended linear models for both board and RIP and an oil model with charge carrier drift and non-linear conductivity.

It is interesting to see that transient field strengths differ significantly from fig. 10 which is based on far-reaching simplifications. These differences can both be seen in maximum field amplitude and in duration of longer lasting stress profiles.

6. CONCLUSIONS

HVDC stresses can be calculated from permittivities for changing voltages and from conductivities for long term steady state conditions. Step response measurements at realistic field strengths can be used for the measurement of polarization and depolarization currents (PDC) containing the complete dielectric system information about the insulations under realistic conditions. Furthermore, PDC analysis can be used to investigate the behavior of materials and systems under polarity reversal conditions. Therefore PDC analysis is a powerful tool for a sophisticated evaluation of physical dielectric properties, i.e. polarization processes, long term conductivity values and nonlinear behavior.

The behavior of solid materials is largely influenced by polarization processes, it can be well described by extended linear equivalent circuits. In contrast, mineral oil is not polarized, but its conductivity is strongly nonlinear (i.e. field dependent), and it is influenced by charge carrier drift processes. The physical behavior of oil has to be described by a mathematical “oil model”.

PR measurements on solid materials (Transformerboard, resin impregnated paper RIP) show that currents after PR are enhanced because of long lasting depolarization currents from the preceding polarization interval.

PR measurements on oils show that charge carriers drift towards the electrodes during DC voltage application. They remain as space charge zones in the proximity of the electrodes, and they are not neutralized. After PR these charge carriers contribute to the current again. Their average transit time is increased because of increased drift lengths.

If polarity is reversed several times, there is no difference between the subsequent currents of opposite polarity. This “conditioning effect” can be explained by the theory of charge carrier drift.

The new findings from the measurements show that classical equivalent circuits are not sufficient to describe the materials. Therefore, new models for simulation are being iteratively developed and validated by measurements. The newly developed model for solid insulation takes into account the material polarization in addition to the capacitive dielectric properties and conductivities. The newly developed model for insulating oil takes into account (in addition to the capacitive dielectric properties) a nonlinear field-dependent conductivity and the drift of charge carriers in the electric field.

Another important finding is that the material properties from the PDC analysis between stainless steel electrodes also apply for barrier systems.

Advanced simulation models were developed during the investigations reported here. They are accurate enough to describe polarization and depolarization current in HVDC insulations precisely. Therefore these models are used for the calculation of transient field strengths. They differ significantly from simulations which are performed with the simple RC-(conductivity/permittivity-) models. The field strength curves clearly show the potential of the new models. The polarization processes of solid materials lead to an increase in the transient load of the oil ducts in a barrier system. The charge carrier drift and the nonlinearity of the insulating oil have the effect of stress reduction, particularly after the polarity reversal. The load is temporarily reduced, however, due to the solid polarization time it lasts longer.

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