DETERMINATION OF THE CONDITION OF TRANSFORMER OIL USING DIELECTRIC RESPONSE ANALYSIS

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Abstract: This contribution describes the laboratory and on-site determination of oil conductivity as a sensitive quality and ageing marker for insulation liquids utilizing dielectric response analysis. For laboratory application, measurement instruments determined the oil conductivity in the time range of 1-10'000 s and in the frequency range of 1000-0,001 Hz as a function of measurement time, field strength, temperature, moisture and ageing condition. Oil conductivity was found to be extremely sensitive to contaminations such as residues after refinery and ageing by-products, resulting in a values range of 0,01-2000 pS/m. Beside this, oil conductivity greatly influences the dielectric response of impregnated pressboard. For on-site diagnostics, dielectric response analysis (PDC, FDS) was successfully applied to calculate oil conductivity without the need to take an oil sample and at the same time providing information about the pressboard material. The close interaction between oil conductivity, ageing and field distribution should be considered when operating transformers by utilizing appropriate diagnostics.

1 INTRODUCTION

Insulation liquids like mineral oil show a very low conductivity, which reacts very sensitively to contaminations of polar nature and ageing by-products and is therefore an excellent quality measure for new liquids and an ageing indicator for elder insulation systems. Moreover, for HVDC transformers, the ratio between the conductivities of oil and cellulose material determines the field distribution between oil and paper/pressboard and is thus of highest interest for insulation design. During application of an AC voltage, the permittivities of the materials determine the field distribution, whereas for the DC case the electrical stress follows the conductivities.

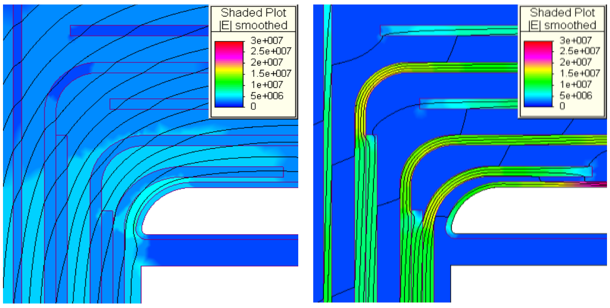

Figure 1: Electric field distribution in an oil-barrier insulation under AC and DC stress (l.t.r., [1])

Though oil conductivity and particularly its ratio to cellulose conductivity is such important parameter, for transformers in operation today:

- The conductivity ratio between oil and cellulose remains unknown,
- Even oil conductivity in samples is not determined on a regular basis,
- Various testing methods exist, which are partly inconsistent,
- During actual operation often different oil is used than for factory testing.

The complains above were partially stated by the Cigré JWG A2/B4.28, [2], and also motivated for the present paper.

The present publication briefly describes the physical background of oil conductivity, measurements in the laboratory, the influence of oil conductivity on paper/pressboard and focuses on the on-site determination of oil conductivity using dielectric response analysis.

2 IONIC CONDUCTION IN MINERAL OIL

Impurities give rise to the volume conductivity of mineral insulation oil, similar to solid dielectrics. Pure insulation oil, as saturated hydrocarbons, shows neither ions nor free electrons. After refinery, some pollutants, moisture and acids remain providing ions as the dominating charge carrier in liquids.

Ions may arise from spontaneous dissociation of ionisable substances. The separation into ions under the influence of water is called electrolytic dissociation. Water of course exists in mineral oils only in traces of some µg/g. Thus, conductivity is intensified by other ionisable substances as for example carbon and carboxylic acids. Mineral oil also contains acids after refinery and especially because of oil and paper aging. These acids dissociate as follows:

$$H\text{-}COOH + H_2O \rightarrow H\text{-}COO^- + H_3O^+ \qquad (1)$$

H-CO is the aldehyde group of a carboxylic acid, which is for example CH_3CO as acetic acid.

Beside organic acids, carbon as a product of cellulose deterioration, bases, salts and macro molecules from polymerisation and polycondensation of hydrocarbons also contribute to electric conductivity.

2.1 Influence of Measurement Time

Ions differ in the velocity of their movement and space charges lower the conductivity after some time. Therefore current and conductivity depend on time or frequency. According to [3], fast polarization processes determine the short times in Figure 2. Later, fast ions dominate conductivity. After a time of 10-1000 s, space charges increase the volume resistance. An equilibrium between continually dissociating ions and recombinations then cause the conductivity at very long times. From the figure it becomes obvious that the application of an electric field results in an "electrical cleaning" effect.

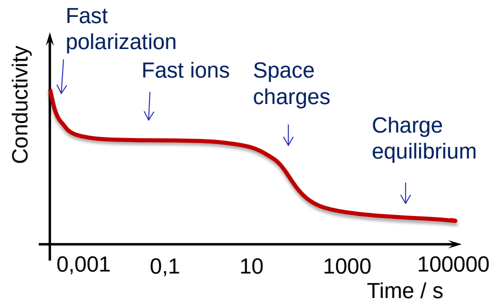

Figure 2: Time-dependent conductivity in an insulating liquid

2.2 Influence of Electric Field Strength

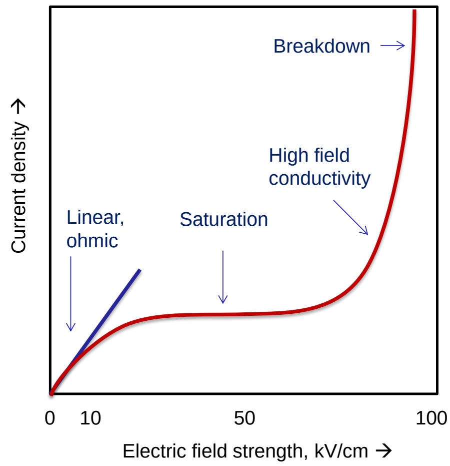

Figure 3: Current density as a function of electric field strength with values for transformer oil and 6 mm gap, [4]

If an electric field is applied to parallel plates, three regions of conduction can be characterized:

1) First, a low field region where the current density is proportional to the electric field strength (ohmic region)
2) Second, a region, where the current density seems to saturate
3) Third, a region the the current density increases strongly with applied electric field strength, finally leading to breakdown, [4].

2.3 Influence of Temperature

Temperature influences intensely the dielectric properties as it changes the polarisation processes and the conductivity of a material. If depicted in frequency domain, the influence results in a shift of the measured spectral function along the frequency axis. The logarithmic shift of the spectral function from temperature T_1 to T_2 expresses an Arrhenius equation, actually a formula for the temperature dependence of a chemical reaction rate. So the shift from one frequency ω_1 to another ω_2 can be calculated by:

$$\log(\omega_1) - \log(\omega_2) = \frac{E_a}{k}\left(\frac{1}{T_2} - \frac{1}{T_1}\right) \qquad (2)$$

E_a is the activation energy of the material, which can be determined by two measurements at different temperatures. k is the Boltzmann constant with $k = 8{,}617385 \cdot 10^{-5}$ eV / K. The following equation compensates the conductivity for a temperature change from T_1 to T_2.

$$\sigma_2 = \sigma_1 e^{\frac{E_a}{k}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)} \qquad (3)$$

3 LABORATORY MEASUREMENTS

In the laboratory, the dielectric properties of mineral oil were measured in time and frequency domain using a guarded measurement cell, [6]. The following equation calculates oil conductivity from results in time domain.

$$\sigma(t) = \frac{\varepsilon_0}{U_C C_0} i(t) \qquad (4)$$

U_C is the applied DC voltage, C_0 the empty capacitance of the measurement cell. The equations validity is restricted to materials with negligible polarizability.

For dissipation factor measurements in frequency domain, oil conductivity can be calculated with the following equation. A negligible polarizability and a real part of the permittivity of 2,2 are supposed.

$$\sigma(\omega) = 2{,}2\varepsilon_0 \omega \tan\delta(\omega) \qquad (5)$$

3.1 Influence of Field Strength and Aging

Figure 4 displays the conductivity of insulation oil as a function of measurement time and field strength. New Nynas Nytro 3000 shows the impact of a cloud of charged ions as described in Figure 2. At the low voltage of 5 V/mm this happens at times longer than 30 s. For the service-aged Shell K6SX this effect is nearly invisible. Here the fast ions dominate the ionic conduction up to 1000 s. In general, the charge cloud effect appeared especially in dry and new oils. With increasing moisture, aging and temperature the effect is hidden by the high volume conductivity.

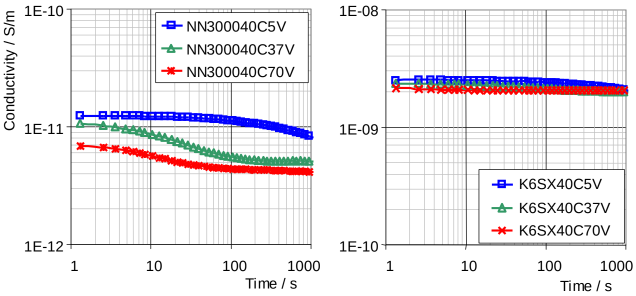

Figure 4: Oil conductivity as a function of time and field strength for new Nynas Nytro 3000 (left) and service-aged Shell K6SX (right), measured at 40°C and moisture saturation of 35 %

3.2 Influence of Temperature

Information about temperature dependence is needed for the correction of temperature induced effects. To compare the temperature influence on the different oils single points of oil conductivity were used instead of the whole time range. These points are 10 s in time domain and 0,1 Hz in frequency domain. The time domain data agree well with that from frequency domain, however in most cases the frequency domain conductivity somewhat undercuts that of time domain. Figure 5 shows the results for new Shell Diala D, new Nynas Nytro 3000, service aged for 25 years and service aged Shell K6SX, measured at a field strength of 5 V_{DC} and 5 V_{RMS}

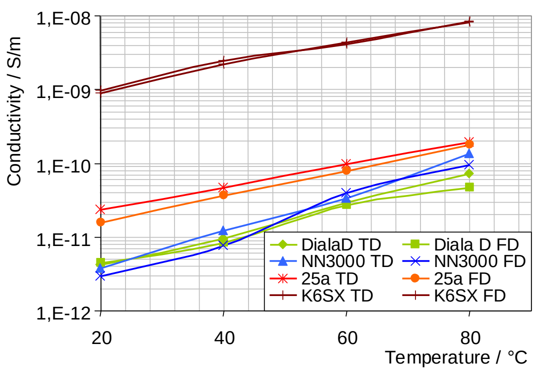

Figure 5: Influence of temperature on oil conductivity for new and aged insulation oils

The activation energy of the specific oil causes the different gradients in Figure 5. Activation energy characterizes the temperature dependence of a material property, usually for chemical reactions, but here for conductivity. The following table shows the activation energy for the investigated oils, calculated from the measurements using (3).

Table 1: Activation energy of the investigated oils

Oil	E_a from time domain	E_a from frequency domain
Diala D	0,43	0,35
Nytro 3000	0,54	0,52
25a aged	0,32	0,37
Aged K6SX	0,32	0,33

3.3 Oil and Pressboard Conductivity

Figure 6 depicts the influence of the conductivity of the oil used for impregnation of new pressboard samples on dissipation factor. Although the moisture content of all samples was identical with 2,6 %, the losses increased with the conductivity of the oil used for impregnation, which were 0,05; 3,5; 21 and 148 pS/m.

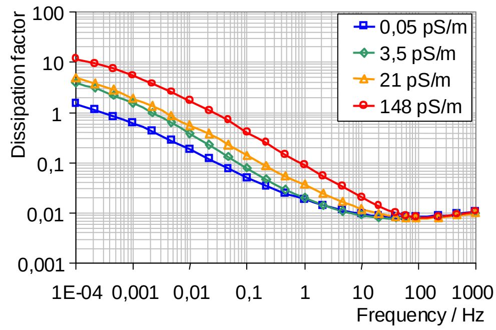

Figure 6: Dissipation factor of pressboard impregnated with oils of different conductivity

4 ON-SITE DETERMINATION OF OIL CONDUCTIVITY BY DIELECTRIC RESPONSE ANALYSIS

4.1 Introduction

This section describes the on-site determination of oil conductivity by dielectric response analysis. Dielectric response analysis measures dielectric properties of insulation systems over a very wide frequency or time range and calculates condition variables like oil conductivity and insulation wetness by use of mathematical modelling, [5]. It is applied as a non-intrusive on-site test for periodical assessments of the aging condition of insulation systems, particularly power transformers.

4.2 Measurement Setup

A dielectric response measurement is a three terminal measurement that includes the output voltage, the sensed current and a guard. The guarding technique insures for an undisturbed measurement even at onsite conditions with dirty insulations and electromagnetic interferences. For two winding transformers, after disconnection from the network, the voltage output is connected to the HV winding, the current input to the LV winding and the guard to the tank. Figure 7 depicts the typical capacitances of a two winding power transformer as well as a connected instrument for measuring C_{HL}.

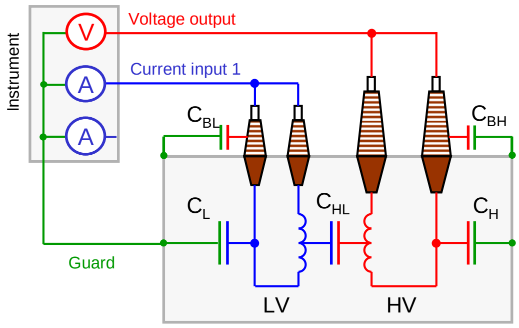

Figure 7: Capacitances and measurement circuit for a two winding transformer

The abbreviations of the capacitances stand for: C_{HL} – HV to LV winding; C_H – HV to tank, C_L – LV to tank, C_{BH} – all HV bushings to tank and C_{BL} – all LV bushings to tank.

The test can be performed in

- Time domain while applying a DC voltage. The corresponding technique is called Polarization and Depolarization Currents PDC.
- Frequency Domain while applying an AC voltage leading to Frequency Domain Spectroscopy FDS or Dielectric Frequency Response DFR.

Both test techniques reflect the same fundamental polarization and conduction mechanisms and can be combined.

4.3 Interpretation of Results

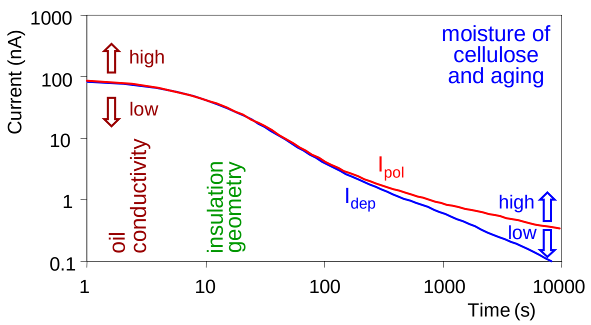

Figure 8: Main features of PDC response in an oil-paper barrier system

For a time domain test (PDC), most interesting information is obtained for longer times up to a few thousands seconds. The barriers are charged via the oil ducts immediately after voltage step application. Therefore the initial current values and the main time constant of the current curves are directly related to the conductivity of oil in the main ducts. The polarisation and depolarisation current and the difference between polarisation and depolarisation curves at longer times are directly related to the conductivity of the paper/pressboard part and its water content, Figure 9.

In frequency domain (FDS, DFR), the dissipation factor plotted via frequency shows a typical s-shaped curve. With increasing oil conductivity, moisture content, temperature or aging the curve shifts towards higher frequencies. The middle part of the curve with the steep gradient reflects oil conductivity. Insulation geometry conditions determine the "hump" left of the steep gradient. Moisture influences the low and the high frequency parts, Figure 9.

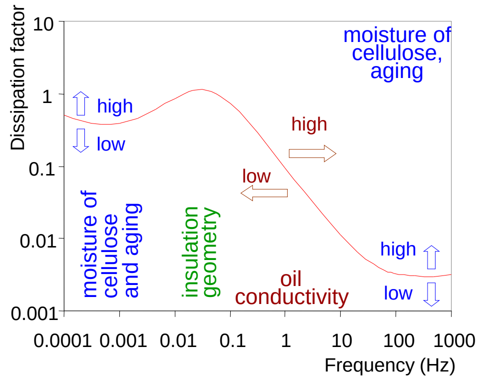

Figure 9: Interpretation scheme for frequency domain data providing discrimination between the properties of oil and the solid insulation

4.4 Calculation of Oil Conductivity

Oil conductivity strongly influences the dielectric response and thus can be calculated by means of mathematical modelling. Today the so-called XY-model, as proposed by various Cigré working groups, is commonly accepted, [5].

The XY-model represents the volumetric fraction of two materials in one insulation system. In the cylinder-shaped transformer insulation all pressboard barriers and insulation paper are made into one single barrier with relative thickness X. All spacers of the cylindrical insulation form one with width Y. All the oil ducts form one oil duct of relative thickness 1-X and width 1-Y, Figure 10.

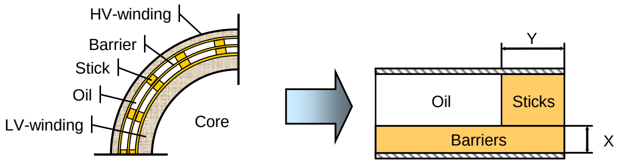

Figure 10: Representation of a cylindrical transformer insulation by the XY-model

Based on this model, the total permittivity $\varepsilon_{tot}(\omega)$ of a multilayer insulation can be calculated by the following equation.

$$\varepsilon_{tot}(\omega) = Y \cdot \varepsilon_{PB}(\omega) + \frac{1-Y}{\frac{1-X}{\varepsilon_{Oil}(\omega)} + \frac{X}{\varepsilon_{PB}(\omega)}} \quad (6)$$

Suppositions of this model are that the dielectric properties of pressboard in barriers and in spacers are identical and linear. $\varepsilon_{PB}(\omega)$ is a complex, frequency dependent vector. $\varepsilon_{Oil}(\omega)$ is the permittivity of oil. Since oil has only a small polarizability, the following equation covers its dielectric properties. The real part of $\varepsilon_{Oil}(\omega)$ as 2.2 is similar for all mineral oils, but much higher for vegetable oils.

$$\varepsilon_{Oil}(\omega) = 2{,}2 - j\frac{\sigma_{Oil}}{\varepsilon_0 \omega} \quad (7)$$

Using (6) and (7), the oil conductivity can be calculated from the dielectric response by automatic curve fitting, [6].

Figure 11 compares the dielectric response of a complete oil-paper insulated power transformer to that of an oil sample taken from the same transformer. The dissipation factor curve of the oil is nearly parallel to that of the oil area of the total response. Differences come from the superposition with cellulose and will be regarded by the XY-model.

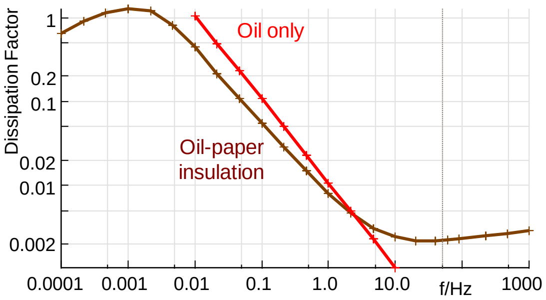

Figure 11: Dielectric response of the whole power transformer insulation and of the corresponding oil only

4.5 Case Study: Assessment of New Transformers in the Factory

With the awareness of the hazardous effects of moisture the demand to receive new transformers in dry condition increases. Therefore the moisture content in the solid insulation of two new transformers was evaluated with dielectric response measurements in the factory. In Figure 12, transformer A shows much lower losses than transformer B, so from a first glance at the dissipation factor trace one may conclude that the transformer with higher losses is in worse condition. However, a closer look at the dielectric response of transformer B reveals low losses at the very low frequencies below 1 mHz. This is important, since that region is very sensitive to moisture (Figure 9). Moisture analysis software actually calculated the moisture content in the cellulosic insulation of both transformers to be 0.6 %, which is a very low value. The difference in the dissipation factor curve comes not from moisture but from different conductivities of the insulation oils (0.05 pS/m for transformer A, 0.94 pS/m for transformer B).

The example illustrates that particularly for new transformers the very low frequencies, which reflect the condition of the solid insulation, are important for moisture analysis using dielectric response methods. Limiting the frequency range would make the discrimination between the different condition of oil and cellulose impossible.

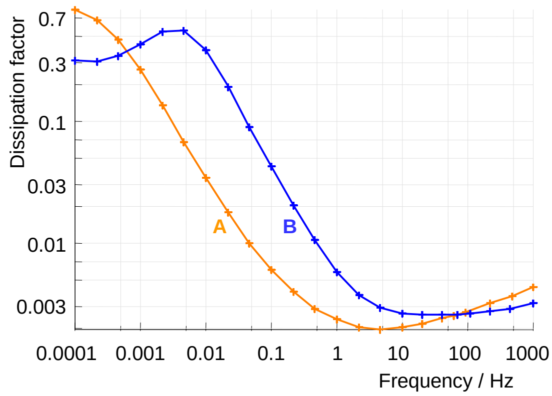

Figure 12: Dissipation factor over frequency for two new transformers with similar water content, but different oil conductivities (0,05 and 0,94 pS/m)

4.6 Case Study: Effect of Oil Processing

For a 480 MVA, 230 kV GSU transformer the oil was processed with heat (50°C) and vacuum. Figure 13 depicts the dissipation factor versus frequency before and, seven months later, after oil processing, in both conditions for similar temperatures. From mathematical moisture analysis [6] it appeared that the oil conductivity decreased from 11 to 2.7 pS/m. However the moisture content remained the same with 1.8 % before and 1.7 % after oil processing. Because of the hydrophilic nature of cellulose, the solid insulation stores 200 times more water than the liquid insulation. Thus oil drying or replacement will not improve the overall moisture condition.

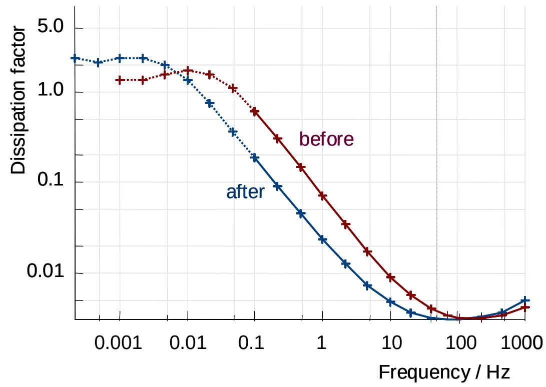

Figure 13: Dielectric response of a GSU transformer before and after oil processing

4.7 Comparison between Oil Sampling and Modelling of the Dielectric Response

Figure 14 compares the oil conductivities as obtained from direct measurements at oil samples (measured) to these calculated from the dielectric response of the whole insulation system (modeled). The agreement is very good, considering the fact that oil conductivity varies over 5 decades under real conditions.

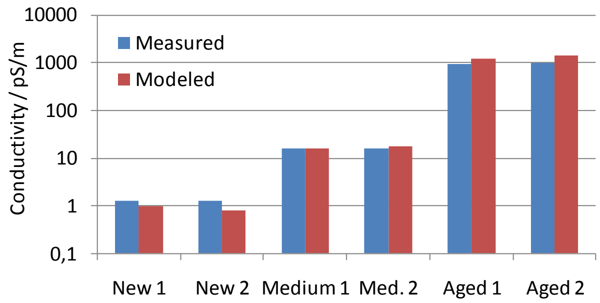

Figure 14: Comparison between oil conductivities as measured directly in oil samples and calculated from the dielectric responses of 8 different transformers

4.8 Comparison to Limits of IEC 60422

Figure 15 compares oil conductivity results of real oil samples to the classification given in IEC 60422; i.e. very good, good and satisfying, [7]. While for real transformer oils the conductivity varies from 0,01 to 2000 pS/m, the standard addresses only a range from 3 to 60 pS/m. The authors of this publication would appreciate a revision of the limits.

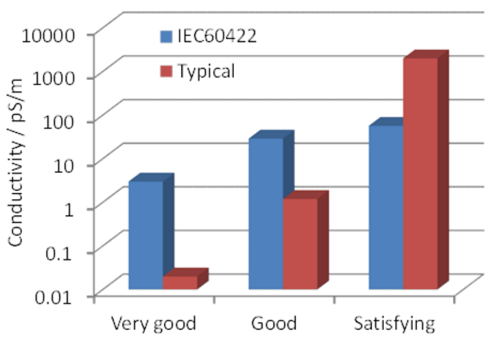

Figure 15: Comparison of limits according to IEC 60422 to measurement at real power transformers

5 CONCLUSIONS

Calculating the oil conductivity of power transformers from the dielectric response provides the following advantages:

- Dielectric response analysis provides the conductivity ratio between the insulting liquid and the cellulose material.

- The test result (oil conductivity) is representative for the oil gap of the main insulation duct, a very important design parameter of HVDC transformers.

- The test can be performed on-site without the need for taking an oil sample, interferences due to sampling are excluded (contamination, transportation, sample handling).

- The test result is repeatable with different diagnostic equipment.

The method implies the following disadvantages:

- The field strength in the oil is only a few volts per millimeter; therefore voltage-dependent characteristics cannot be investigated

The calculation of oil conductivity by dielectric response analysis can be used as an appropriate tool for on-site assessments of HVDC transformers, particularly in combination with the determination of other ageing indicators like water concentration in the solid insulation.

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