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ELECTRICAL CONDUCTIVITY OF PRESSBOARD AND THE INFLUENCE OF MOISTURE CONTENT

SUMMARY

The electrical conductivity σ is an important parameter for material condition evaluation at AC applications and is responsible for electrical field distribution in DC equipment. With a focus on HVDC equipment design, the influence of moisture content in oil-impregnated pressboard is determined in this preliminary investigation. The electrical conductivity of pressboard samples, which have been wetted artificially in the laboratory, is investigated within this work. Moisture contents between <0,3% and 5,5% could be achieved artificially through increasing pressboard moisture content levels in a climate chamber. The electrical conductivity was determined by voltage-current measurements at 20°C in the style of IEC 60093 with measurement times up to and longer than 24 hours. For these investigations, the pressboard samples with a thickness of 1 mm have been placed in an (mineral) oil-filled test vessel and stressed by a DC field with E = 3 kV/mm.

It could be demonstrated that the moisture content of pressboard has a strong influence onto the electrical conductivity: An increase of electrical conductivity by a factor of around 10 for each percentage point of moisture increase up to moisture levels of around 3,5% was observed. At higher moisture contents (>5%), other mechanisms seem to govern the electrical current and the conductivity respectively, which is also discussed within the work.

Key words: Electrical conductivity, pressboard, moisture content, artificial moistening, HVDC equipment

1. INTRODUCTION

Electrical conductivity is an important parameter for insulating materials, especially at HVDC applications. At (steady-state) DC stress, the electrical field within an insulation system distributes according to the geometry and the different electrical conductivities of the materials used. Therefore, the electrical conductivities play an important role in terms of dielectric behavior of an insulation system.

At oil-cellulose insulation systems, which are commonly used at HVDC converter transformers, the electrical conductivities of oil and board can vary strongly. For example, at 20°C the electrical conductivity of pressboard can be around 10 to 100 times lower than the conductivity of typical mineral oils. During HVDC network operation, the insulation system of e.g. a converter transformer is severely stressed by AC and also through superimposed DC stress. In case of such a mixed electrical stress, the electrical field distribution is different from the one at pure AC stress, which is governed by the (relative) permittivities only. Several factors are influencing the electrical conductivity. For example, there is a strong effect of temperature as well as moisture content, which is investigated here.

2. ELECTRICAL CONDUCTIVITY

The determination of electrical stress in HVDC equipment is more complex than at AC stress, as the electrical conductivity is the governing parameter in terms of field stress. The conductivity of typical high-voltage insulation materials can differ easily by one or even several orders of magnitude. Further, electrical conductivity depends on temperature, moisture content and field strength, as indicated by Figure 1 and 2. Currently, in measurement and simulation processes, electrical conductivity is often considered as a single value only; at best a field and temperature dependence will be considered. This could lead to the misjudgment of the real situation in an insulation system, which is also discussed in [1, 2] in detail. The main influencing parameters of the electrical conductivity of oil-impregnated paper (OIP) are described for example in [3].

Due to polarization and charging processes, Ohm's law cannot be applied directly at insulation oils and pressboard, as the resistivity varies with (measurement) time. In detail, knowledge about charge carrier density and mobility is needed for a theoretical approach [4].

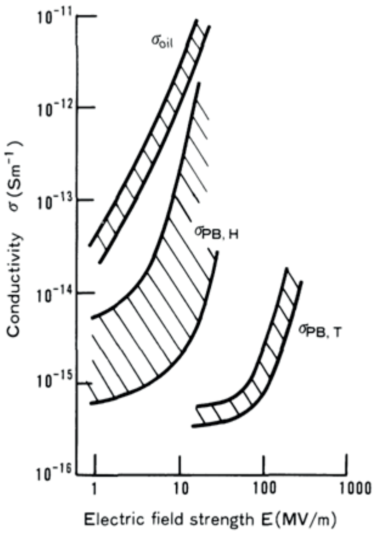

Figure 1 - Electrical conductivity of oil and pressboard (Index $_T$ – Conductivity through and $_H$ – Conductivity along laminated layers) [5]

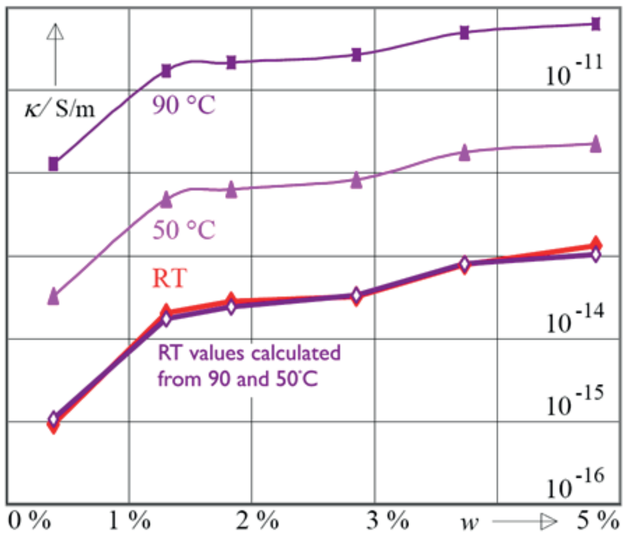

Figure 2 - Electrical conductivity of oil-impregnated paper (OIP) in variation of temperature and moisture content at E = 0,1 kV/mm (from [6])

2.1. Determination of the electrical conductivity of solids

Guidelines for the determination of electrical conductivity determination of solid insulating materials can be found in the standard IEC 60093 [7]. A typical set-up consisting of three electrodes is pictured in Figure 3. A guard electrode is used for the elemination of surface currents. However, standards like this one are criticized (see exemplary [2, 8]) when it comes to HVDC applications. Basically, this is due to two reasons: First, present standards only determine a single conductivity value without considering polarisation and charging processes. Furthermore, this single value is determined already 1 minute after voltage application. Secondly, the field strength used for measurement purposes is generally much less than the actual operational field strength. Both drawbacks may lead to strong discrepancy between material measurement data and actual behaviour. Possible remedies are the determination of the time trend at higher field strengths and even the usage of a different method, e.g. charge-difference method (CDM) [8].

When using the voltage-current method, the specific resistivity can be determined from measuring the time trend of the current when applying a (constant) direct voltage:

$$\rho = R_x \cdot \frac{A}{h} \quad (1)$$

where:

ρ	Specific Resistivity [Ωm]
R_x	Measured Resistivity [Ω]
A	Area of measurement electrode [m²]
h	(averaged) Sample thickness [m]

For the determination of the (effective) measurement electrode surface area, the method described in [7] is used. In literature, different approaches are documented, which take e.g. flux fringing into account [9]. However, at comperable thin samples (in reference to the diameter), the influence of such methods and processes respectively is low [10]. Resistivity was determined for every data sample (sampling rate of around 1 Hz) through voltage-current measurements. The electrical conductivity σ is then determined as the inverse of the specific resistivity ρ.

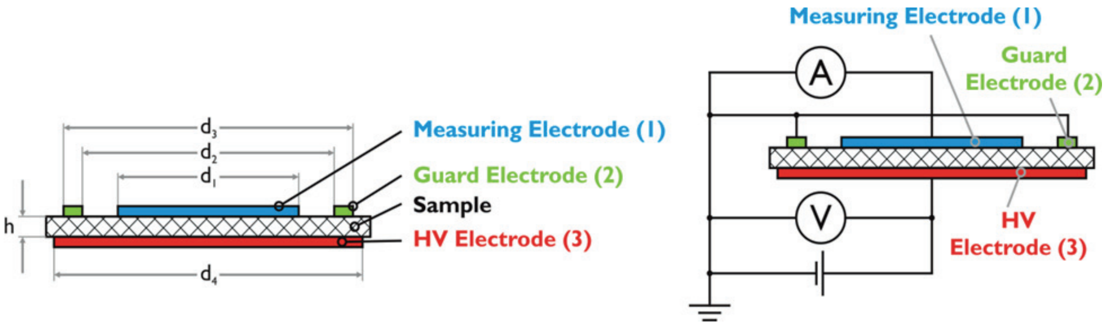

Figure 3 - Schematic set-up for the determination of electrical conductivity according to IEC 60093

3. PARAMETERS INFLUENCING THE ELECTRICAL CONDUCTIVITY OF PRESSBOARD

Selected parameters (besides moisture content) for pressboard are discussed briefly below. More details can be found, for example, in [10].

3.1. Temperature

Temperature constitutes one of the strongest influences onto the electrical conductivity. With rising temperature, conductivity increases and time constants decrease. A conversion of measurement data to temperatures, which differ from the temperature during measurements, is possible with the Arrhenius equation. In [6] this is conducted exemplary for steady-state conductivity values of 50 and 90°C to estimate the conductivity values at 20°C (see also Figure 2).

3.2. Electrical field strength

As indicated in Figure 1, there is a strong nonlinear behavior of the electrical conductivity of pressboard at higher field strengths somewhere in the region of E = 100 MV/m (when measured through the bulk of the material). At lower field strengths, the influence is negligible (e.g. see [10]). However, if the conductivity along laminated layers is studied, a nonlinear behavior can be observed also at much lower field strengths [5]. There, interfacial effects dominate the conduction process which leads to an increased conductivity when compared to bulk conductivity, as seen in Figure 1. For thin samples, the electrical conductivity through the bulk is quite independent of electrical field strength [8, 10].

3.3. Other parameters

Other parameters, like material ageing, acid content or impregnation oil type may also influence the electrical conductivity. An increase of electrical conductivity with ageing is very plausible, as with progressive ageing the moisture content of both oil and cellulose rises due to degradation processes. Furthermore, ageing by-products like acids might be generated, which also influence (rise) the electrical conductivity respectively. The influence of ageing and impregnation oil type for pressboard is discussed in [10] and for OIP in [3].

4. MEASUREMENT SET-UP AND PROCEDURE

High density pressboard samples (Type B3.1 [11], with sieve structure) with a diameter of 190 mm and a thickness of 1 mm have been used for this investigation.

4.1. Sample preparation and artificial moistening

Pressboard samples have been dried and impregnated with a mineral oil (σ_{Oil} around 10^{-14} S/m at 20°C, E = 1 kV/mm) prior usage. The pressboard discs have been dried in a thermal oven at 105°C for more than 48 hours. Afterwards, they have been transferred into a vacuum oven. There they have been dried further (at a pressure <1 mbar) at 105°C for at least 24 hours. Then the temperature was reduced to 90°C for the following impregnation process (in the style of [12]). Samples have been kept oil-immersed under vacuum for another 24 hours. This leads to good impregnated and dried samples with moisture contents of <0,3% and a degree of polymerization (DP) of around 1.200 [10].

Samples prepared in such a manner have been artificially wetted in a climate chamber subsequently. They were kept in a controlled environment with 40°C and at 70% relative humidity. A residence time of around 1 hour was necessary for each percentage point increase of moisture content. This was controlled regularly with Karl-Fischer-Titration (oven method) through the whole process.

However, most of the moisture is assumed to be at or very near the pressboard surface. This can be observed also visually, as pictured in Figure 4: The left picture shows a new and processed sample series (with a moisture content <0,3%) directly after removing them from aluminum compound foil. After around 1 h residence time within the climate chamber, a thin moisture film and a slight change in color was noticed, as seen in the figure below.

Figure 4 - Samples before insertion into climate chamber and after wetting process right before removal

4.2. Test set-up

Within this work, a customized set-up in the style of IEC 60093 [7] (see Figure 3 and Figure 5) was utilized to determine the electrical conductivity of pressboard. A stabilized voltage source with a very low ripple was used to supply a constant voltage of U = 3 kV. At the investigated samples (h = 1 mm), this leads to a field strength of E = 3 kV/mm. Stainless steel electrodes ($\varnothing_{HV}$ = 170 mm, $\varnothing_{Meas.}$ = 147 mm,

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gap of 1,5 mm) have been used, as well as an additional weight (stainless steel, 1,4 kg). This totals with the electrodes and the spacer in a weight of 7,8 kg and a pressure on the sample of >0,2 N/cm², which is recommended in [13].

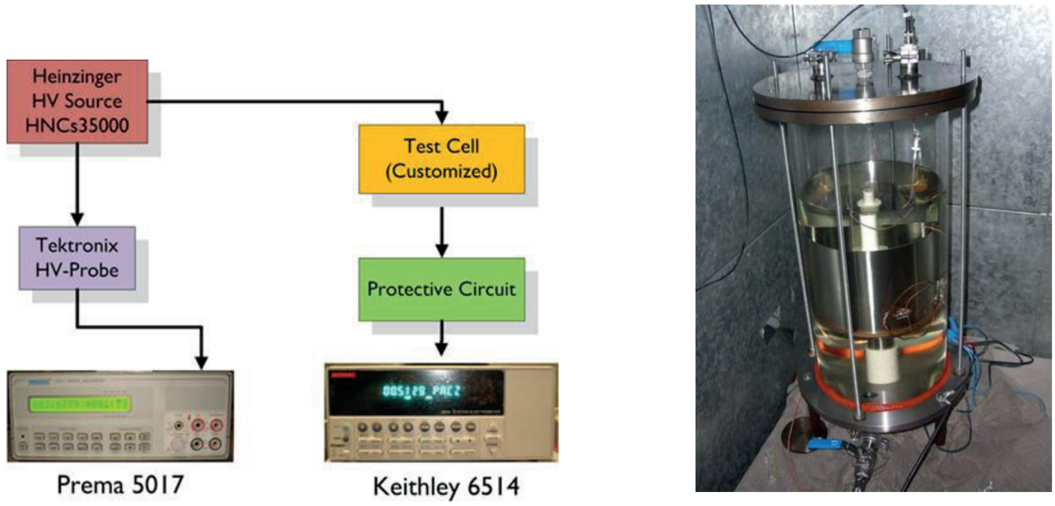

Figure 5 - Measurement schematic and actual set-up

4.3. Data processing

The determination of electrical conductivity of artificially wetted samples was conducted - with one exception (only one sample at 2,3%) – for at least 3 independent samples. The herin presented results are averaged values of these single measurements. The raw current (and voltage) measurement data has been checked for outlieres, e.g. due to measurement range changes of the electrometer or caused by external disturbances, before applying a moving average filter. Especially due to long measurement times and when operating at such low currents (pA range), averaging is an elegant possibility to reconstruct the (average) time trend.

5. RESULTS

The influence of moisture content onto electrical conductivity of pressboard is clearly shown in Figure 6. With the exception of the very wet samples (5,5%), the electrical conductivity decreases steadily during the measurement time interval. The slope of the current (di/dt) and conductivity (dσ/dt) respectively is decreasing with increasing moisture content. This implicates that polarization processes proceed faster and the steady state value is reached sooner.

The results are summarized in Table I. There, the values in the column “n” denote the number of single measurements made on individual samples to determine electrical conductivity. It can be seen, that the increase of electrical conductivity during the measurement time range is between a factor of 3,7 and around 13 for each increase in moisture content by 1 percentage point. Basically, these results are in good agreement with results reported in literature, for example in [3], which have been gained at OIP and pressboard samples.

An unexpected behavior was observed at the samples with very high moisture content (5,5%): The current and the electrical conductivity actually increased after voltage application. This indicates that no charge carrier depletion is taking place but instead conductive paths in the bulk (or more probably near the surface) are formed. Dielectric heating as the source for the increase of current and conductivity respectively can be ruled out, as the converted power is very low (around 1 mW, [10]).

Generally, the reproducibility of the conductivity measurements is good, as Figure 7 indicates. The differences in electrical conductivity between the investigated moisture contents are large enough to allow the secure determination at each level.

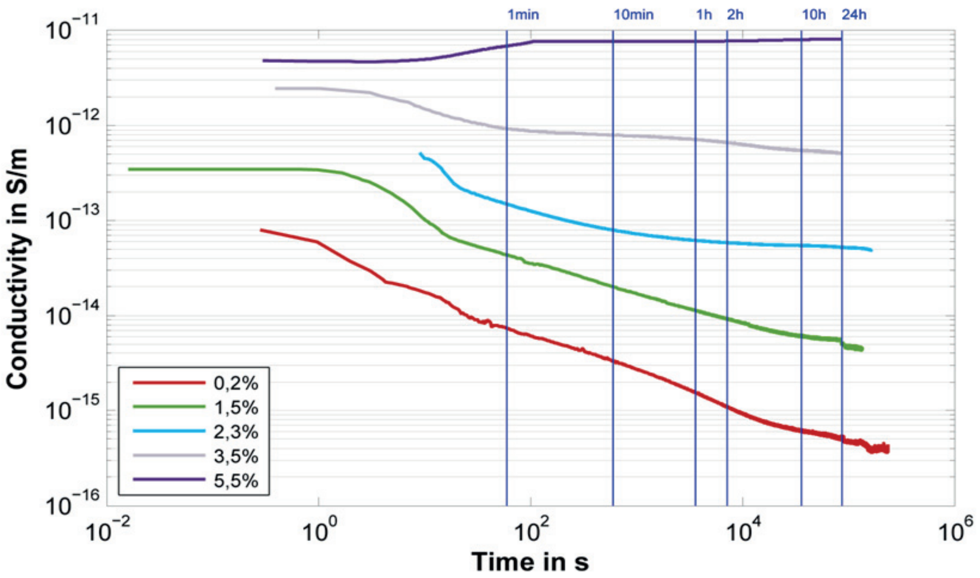

Figure 6 - Electrical conductivity of investigated pressboard samples with varied moisture content (artificially wetted), determined in the style of IEC 60093 with E = 3 kV/mm

Table I - Average electrical conductivity σ of n pressboard samples with varied moisture content in S/m

Moisture	n	1 min	10 min	1 h	2 h	10 h	24 h
0,2%	3	7,31E-15	3,33E-15	1,53E-15	1,10E-15	6,04E-16	5,23E-16
1,5%	7	4,37E-14	2,01E-14	1,14E-14	9,22E-15	6,12E-15	4,96E-15
2,3%	1	1,49E-13	7,90E-14	6,19E-14	5,84E-14	5,45E-14	5,20E-14
3,5%	3	9,31E-13	7,92E-13	7,11E-13	6,57E-13	5,45E-13	5,09E-13
5,5%	3	6,85E-12	7,69E-12	7,67E-12	7,71E-12	7,98E-12	8,08E-12

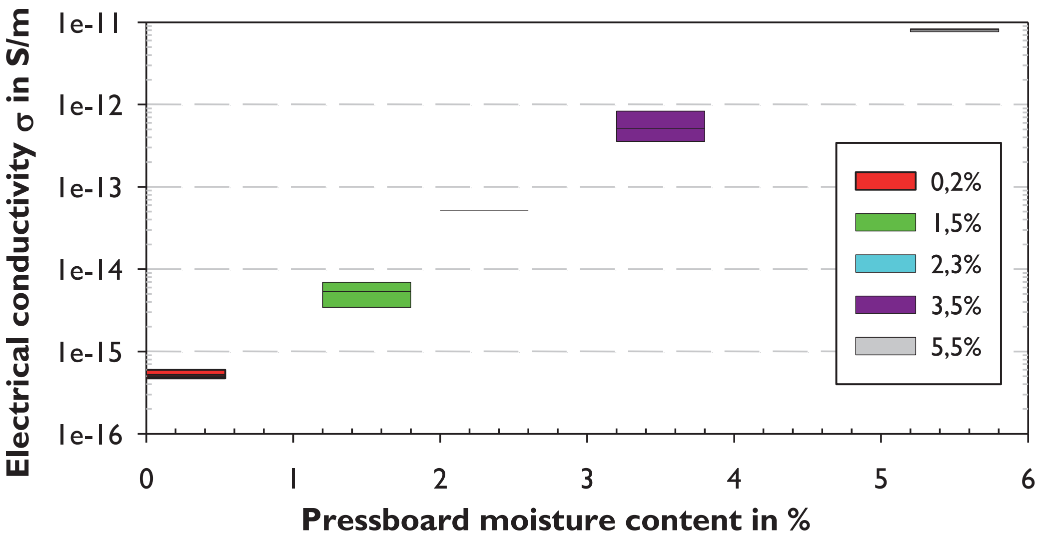

Figure 7 - End values of determined electrical conductivity of pressboard with varied moisture content

6. CONCLUSION

Moisture content of pressboard has significant influence on the electrical conductivity as demonstrated at the investigated samples. However, these results may only serve as a basis for further research: Due to the comparable short residence times of the pressboard samples within the climate chamber, most of the moisture is concentrated onto or near the surfaces. Diffusion processes have much larger time constants - therefore it is very likely that a moisture gradient inside the samples existed with reduced local moisture content with increasing sample thickness/depth. A different procedure with an improved set-up with a stabilized supply of air, which has a defined moisture content, over several hours or even days is necessary to achieve a homogeneous moisture penetration.

For moisture determination however no difference is expected, as the Karl-Fischer-Titration (oven method) is always an integrative method and therefore an averaged moisture content of a volume is determined. In terms of electrical conductivity an inhomogeneous moisture distribution might have an influence though.

The large spread of electrical conductivity of oil and pressboard and insulation paper respectively is troublesome in terms of electrical field distribution at HVDC equipment. With typical ratios of around 10 to 100 between pressboard and oil, the former gets stressed much more severe by the same factor. Now, if the moisture content of pressboard is slightly increased, say in the range between 1 to <2% and when using a very low conducting oil, the electrical field distribution is homogenized between oil and board/paper. In that sense, some kind of field grading is possible if moisture levels can be controlled. However, the long-term stability of such a distribution is questionable, as it might change with ageing processes.

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