# Conductivity of Pressboard for HVDC Insulation Systems

Original Scientific Paper

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***Abstract*** – *The cellulosic material pressboard is a key component in insulation systems for HVDC (high-voltage direct current) equipment. Pressboard compounds are considered from a chemical point of view in order to link it in a subsequent study with electric conduction processes in pressboard. For a better understanding of pressboard, its manufacturing is described and fiber geometry is evaluated by SEM (scanning electron microscopy) analyses. Especially for HVDC insulation, pressboard conductivity is the most important property. For an air-impregnated pressboard sample, the dependence of conductivity on time, temperature and water content is presented. For this purpose, step response measurements in time domain are performed with a sensitive current device. Furthermore, the influence of oil-impregnation on pressboard conductivity is evaluated. The conductivity of oil-impregnated pressboard is up to 13 times higher than the conductivity of unimpregnated pressboard for the given conditions.*

***Keywords*** – *cellulose, conductivity, HVDC transmission, insulation, pressboard*

## 1. INTRODUCTION

The growing demand of energy all over the world gives rise to the development of alternative ways of power generation. Therefore, the use of renewable energy sources such as hydro power and solar power has to be improved and increased. Most of the renewable energy sources are located in remote areas and the power has to be transported over long distances. HVDC (high-voltage direct current) transmission is a good and efficient choice.

In an HVDC converter substation, the alternating current (AC) from grid 1 is transformed to a higher voltage level in a converter transformer and it is rectified. It can be necessary to use two or more stages in series. In that case, the secondary winding of the second transformer is stressed with AC voltage and with a superimposed DC (direct current) voltage. After rectification, the current is smoothed by reactors and transferred over long distances to the second converter substation. After the inverted rectifier, the AC is transformed to the required voltage level and supplied in AC grid 2.

HVDC transmission has many advantages compared to AC transmission. DC power transmission losses are much lower than AC power transmission losses. Only active power is transmitted and the whole conductor cross-section is used. Offshore wind farms for example require grid connection via DC cables as cable capacitances make it problematic to use AC for long-distance transmission.

In HVDC converter transformers, which are one of the key components of HVDC transmission, the windings and other current-carrying components are on different potentials and therefore have to be insulated against each other and against the transformer tank. The major insulating materials used in converter transformers are oil and pressboard in barrier systems. In order to understand the behavior of the material, knowledge about the material pressboard is necessary, see Chapter 2

Insulation design of these barrier systems requires the understanding of field distributions in the insulating materials used in AC, DC and transient cases. The type of voltage stress significantly influences the electric field distribution [1]. On the one hand, insulating oil has good material properties concerning insulation and convective heat dissipation. On the other hand, the mechanical stability of insulation components made out of pressboard allows the construction of cooling ducts which in turn permit design of higher power ratings for the given size and weight of the transformer. Moreover, pressboard has good electrical properties such as breakdown voltage and arc resistance.

AC field distribution is determined by the displacement currents and therefore by dielectric permittivities $\varepsilon$ of insulation materials. For DC fields, conduction currents and therefore conductivities $\sigma$ of insulation materials are the determinative parameters.

Permittivities are comparatively well known material properties, but conductivities of insulation materials are inaccurately known [2], still today [1], [3]. In the present paper, focus is set to the insulating material pressboard. The fact that the conductivity of pressboard depends on various parameters (temperature, electrical field strength, water content, impregnation and geometry of the arrangement) sets multiple engineering challenges when designing insulation systems. Moreover, polarization plays an important role.

In the following chapters, the compounds of pressboard as well as pressboard manufacturing are explained in order to get an impression of the material properties. The geometry of pulp fibers is examined by SEM (scanning electron microscope). Afterwards, the setup for a step response measurement to determine pressboard conductivity is described and parameter dependences are evaluated in order to improve the physical understanding of the behavior of insulating materials. With this knowledge, insulation design of transformers can be optimized to ensure efficient and safe transformer performance and therefore a reliable energy supply

## 2. PRESSBOARD STRUCTURE AND MANUFACTURING

Pressboard is manufactured out of pulp, which is derived from wood. To achieve insulating pressboard with high mechanical strength, softwood with long fibers is preferred [4].

The aim of pulp manufacturing is to extract resin and other impurities, thus enhancing the relative amount of cellulose

Pulp Manufacturing:

At first, the bark is cut off the trees and the stripped logs are mechanically chipped into small pieces. The surface is enlarged. During the chemical pulping process, the pulp is chemically opened in a digester by a sulfate process. This enables extracting of resins completely and reduces the amount of hemicellulose, lignin and inorganic compounds substantially. The unbleached pulp shows a higher lignin content compared to bleached pulp. Further cooking or even bleaching would lead to a degradation of the degree of polymerization, so unbleached pulp is preferred for electrical applications. After a refining and cleaning process, pulp is dried under temperature and pressure.

Board Manufacturing:

The pressboard manufacturer disperses pulp in water and produces pressboard in a discontinuous high-tech paper layer wrapping process. This involves wet laminating of many thin layers without a bonding agent on a board-making machine to form the required thickness by continuous winding of the paper layer onto the making roll. Then, dehydration by compression and drying is performed in special presses [4]. Depending on the desired quality and the requirements, drying and (hot or cold) pressing is done at the same time or subsequently [5].

Fig. 1 visualizes a SEM image of a pressboard layer. A single fiber can be seen in the foreground. The fibers seem to have an elliptic cross section. The fiber width $a$ and the fiber thickness $b$ are detected to be 30 µm and 8 µm, respectively. This information is necessary for modelling the conduction mechanism and for simulations ongoing in our laboratory.

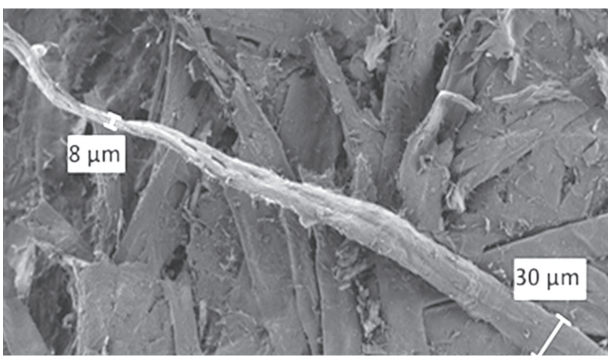


**Fig. 1.** SEM image of cellulose fibers in a pressboard layer, platinum sputtered

To gain insight into conduction processes in pressboard, the components in pressboard have to be considered from a chemical point of view.

The major component of wood is cellulose. Cellulose is a biopolymer consisting of β-D-glucose monomers linked by a 1-4 glycosidic bond.

Hemicelluloses are polysaccharides, which contain a β-1-4 coupled sugar backbone and different sugar side-groups. As the side groups reduce the intermolecular interactions between the polymer chains, hemicelluloses are usually amorphous solids [6].

Lignin has a complex molecular structure [6], which varies between different wood types. In contrast to cellulose and hemicellulose, lignin consists of aromatic groups resulting in a higher electrical conductivity. It is partly removed during the kraft-pulping-process [7] and responsible for the brown color in pressboard [8].

## 3. SAMPLE PREPARATION AND HANDLING FOR CONDUCTIVITY MEASUREMENTS

Samples for conductivity measurements are cut from flat pressboard sheets (pressboard according to IEC 60641-3-1 B 2.1 and B 3.1). They are larger than the outer diameter of measuring and high voltage electrodes in order to ensure sufficient creepage distance and to allow for cutting off some pressboard pieces for water content measurements [9].

The ingress of water and other foreign substances that might affect the measurements have to be avoided. Therefore, the samples are touched with gloves instead of bare hands on the measuring area. The samples are stored and transported in a dry environment without major changes in temperature to protect them against dust and dirt.

In order to get reproducible results of conductivity measurements, the condition of the pressboard sample has to be adjusted carefully. The pressboard sample is dried under vacuum for at least 24 hrs at 105°C according to IEC 60641-2, then vacuum is released and dry air is lead to the sample slowly.

Next, the pressboard sample is installed quickly into the measuring test cell in order to keep air contact short and a second drying process is started to dry again both pressboard and the test cell with the electrodes at approximately 75°C under vacuum. With this procedure, it is ensured that the pressboard samples are dry and thus measurements of dry pressboard (water content lower than 0.5 %) are possible.

A few pressboard samples are measured without oil impregnation in order to get closer to a physical concept of pressboard conductivity. For this, pressboard is impregnated with dry air.

To examine pressboard conductivity impregnated with oil, the test cell with the pressboard sample in it is slowly filled with dry and degassed mineral oil (water content lower than 5 ppm) under vacuum and at elevated temperature. Impregnation of the pressboard sample under vacuum is necessary to avoid moisture access and gas bubbles formation. Then, vacuum is released, heating is switched off and conductivity measurements are performed after a waiting and relaxation time of at least 15 minutes or even longer depending on the desired measuring temperature.

Moreover, pressboard conductivity is examined in undried condition to study the impact of humidity.

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## 4. PDC METHOD

The measuring procedure used for conductivity determination of pressboard is a step response measurement in time domain [10], [11] called the "PDC method". PDC means polarization and depolarization current.

For PDC tests, a glass vessel was made of two desiccator covers. It contains the high voltage electrode, the measuring electrode and the guard ring electrode [1]. The pressboard sample is situated between the plane electrodes, Fig. 2. Moreover, a sensor for temperature control and lead weights are added to the test cell in order to ensure plane pressboard samples and to avoid gaps.

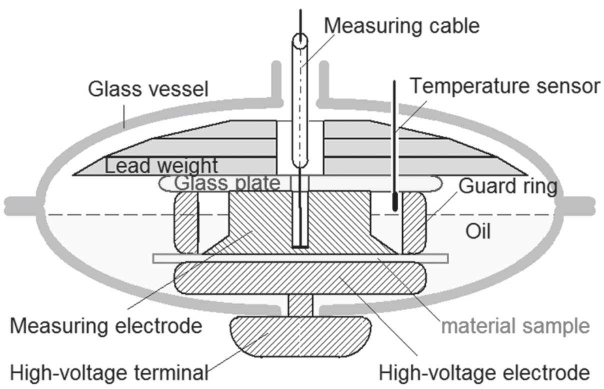


**Fig. 2.** High-voltage test cell for PDC measurements (schematic)

Voltage is applied to the arrangement and the current through the pressboard sample is recorded. The dielectric system response of pressboard contains all necessary dielectric system information. In detail, this PDC method consists of three phases, Fig. 3.

1. relaxation phase without an applied electric field in order to discharge all remaining polarization,
2. polarization phase with the DC test voltage applied,
3. depolarization phase without applied voltage (terminals short-circuited).

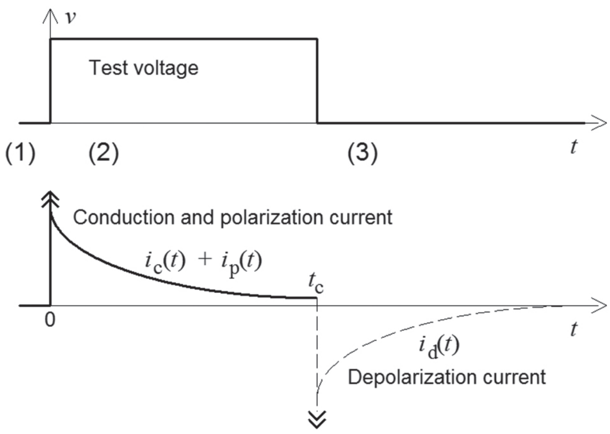


**Fig. 3.** SEM image of cellulose fibers in a pressboard layer, platinum sputtered

$i_c$

The current measured in phase (2) is the sum of the conduction current $i_c$(t) and the currents caused by polarization processes $i_p$(t). This total current is often just called "polarization current", because polarization processes dominate the measured current remarkably long after voltage application. In phase (3), the depolarization current $i_d$(t) is measured. In order to discuss the polarization current and the depolarization current, both currents are depicted in the same diagram. It is recommended to use a log-log plot to visualize short, medium and long-term processes in the pressboard sample. For direct comparison of the measured currents during phase (2) and (3), the absolute value of the depolarization current has to be calculated and the current has to be time shifted, see Fig. 4.

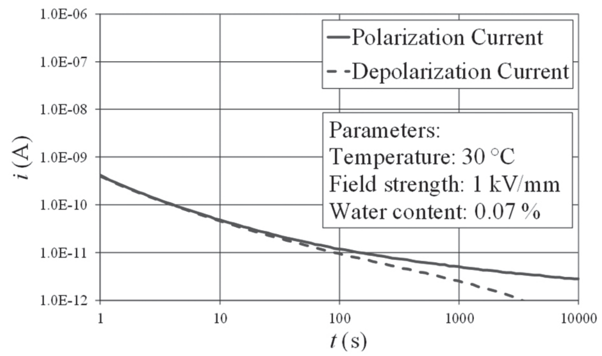


**Fig. 4.** Example of a current measurement of an air-impregnated pressboard sample at 30°C and at a field strength of 1 kV/mm (polarization phase); polarization current with continuous line, depolarization current (absolute value, time shifted, without voltage) with dashed line

The DC conductivity $\sigma_{DC}$ is calculated from current $i_{DC}$, voltage $V$, sample thickness $d$ and electrode area $A$ at steady-state condition:

$$\sigma_{DC} = \frac{i_{DC}}{V} \cdot \frac{d}{A} \quad (1)$$

Alternatively, $\sigma_{DC}$ can be calculated from the difference between the sum of charges in the polarization phase $q_p$(t) and the sum of charges in the depolarization phase $q_d$(t) (Charge Difference Method CDM [12]), both at the same time $t$:

$$i_{DC} \approx i_p(t) - i_d(t) \quad (2)$$

Alternatively, $\sigma_{DC}$ can be calculated from the difference between the sum of charges in the polarization phase $q_p$(t) and the sum of charges in the depolarization phase $q_d$(t) (Charge Difference Method CDM [12]), both at the same time t:

$$q_{diff}(t) = q_p(t) - q_d(t) \quad (3)$$

The gradient of the charge-difference curve is an estimation for the steady-state current:

$$\frac{\partial q_{diff}}{\partial t} \approx i_{DC} \quad (4)$$

The Charge Difference Method requires the same measuring duration as the Current Difference Method, but it is less sensitive to noise because of the integration procedures [12].

## 5. RESULTS AND DISCUSSION

### 5.1. CONDUCTIVITY OF DRY PRESSBOARD

Fig. 5 shows the polarization and the depolarization currents of dried pressboard impregnated with dry air vs. time at 1 kV/mm and at different temperatures. The water content of pressboard is 0.07 %.

The measured currents are obviously very small. The used current device allows for determining the currents through the insulating system from $10^{-12}$ A to $10^{-3}$ A. Polarization currents measured after voltage application are displayed with continuous lines, depolarization currents measured after voltage release and short-circuiting are displayed with dashed lines. The time of energization and the recording time of both currents is set to three hours.

It can be seen that all six currents have a significant current-time characteristic and decrease with time. Both currents at the same temperature (polarization and depolarization currents) are similar for many seconds and differ for longer times of energization. This is due to charge accumulation in pressboard and orientation of dipoles during the polarization phase and due to discharge of pressboard during the depolarization phase. Many charge carriers are stored during the polarization phase. This can be significantly different for other insulating materials such as mineral oils [13].

At 30°C and 50°C, a steady state current can only be estimated or calculated by means of the Current Difference Method or the Charge Difference Method. At 90°C, however, the approximate steady state current can directly be read from the diagram. After decaying of the polarization processes, a steady state current remains, which is a conduction current. The conduction current is proportional to the conductivity, which can be calculated according to eq. (1).

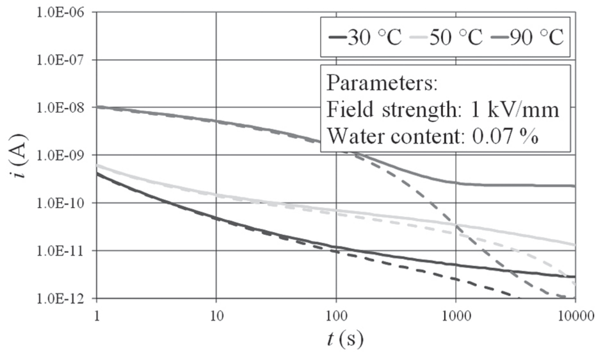


**Fig. 5.** Currents through an air-impregnated pressboard sample at a field strength of 1 kV/mm and at different temperatures; polarization currents with continuous line, depolarization currents (without voltage) with dashed line

In consequence, before reaching the steady-state condition, the calculated conductivities are named "apparent conductivities". The time-varying apparent conductivity is visualized in Fig. 6.

It can be seen from the figure that the conductivity of air-impregnated dry pressboard is very low and ranging between $10^{-16}$ S/m and $10^{-13}$ S/m at a field strength of 1 kV/mm and at different temperatures from 30°C to 90°C, see Table 1.

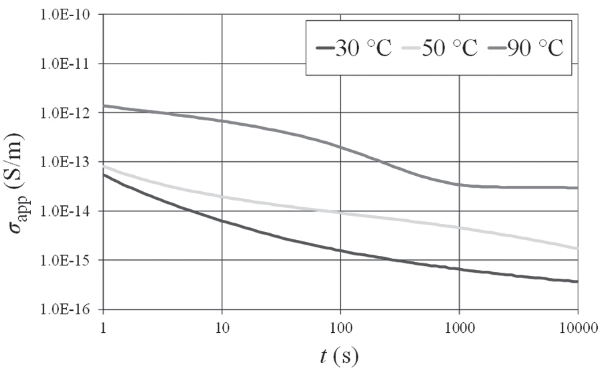


**Fig. 6.** Apparent conductivity of an air-impregnated pressboard sample at a field strength of 1 kV/mm and at different temperatures calculated out of measured currents of Fig. 5

There is a strong temperature dependence of the conductivity of air-impregnated pressboard. The conductivity increases by two orders of magnitude by increasing the temperature from 30°C to 90°C (temperature difference 60 K). This temperature-dependence has to be kept in mind.

### 5.2. CONDUCTIVITY OF UNDRIED PRESSBOARD

Fig. 7 shows a current measurement of air-impregnated pressboard with a water content of 6.1 % (determined by coulometric Karl-Fischer-Titration after the PDC measurement). The measurement was performed at a field strength of 1 kV/mm at 20°C.

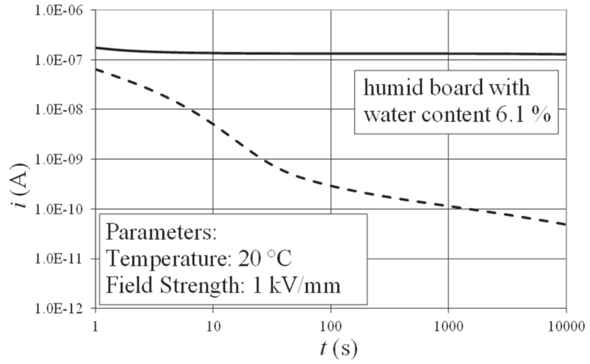


**Fig. 7.** Current through an air-impregnated pressboard sample (water content 6.1 %) at a field strength of 1 kV/mm and at 20°C; polarization current with continuous line, depolarization current (without voltage) with dashed line

The polarization current is much higher than for dry board (compare with Fig. 4 and note that the temperature is 20°C in Fig. 7 and 30°C in Fig. 4). Moreover, there is a significantly reduced time dependence of the polarization current. Additionally, the (time-dependent) depolarization current is remarkably smaller than the polarization current, even immediately after voltage release. High water content leads to additional polarization phenomena and to significantly enhanced conduction currents [5], [9]. Both polarization and conduction currents are dependent on water content [5], [9]. In summary, water content has a significant influence on both polarization and conduction processes in pressboard.

### 5.3. INFLUENCE OF IMPREGNATING FLUIDS ON PRESSBOARD CONDUCTIVITY

The apparent conductivity of dried pressboard samples is measured under vacuum in order to eliminate the possible influence of any impregnating fluid. It has been found out that the breakdown voltage (vacuum breakdown) limits the measurement of pressboard conductivity under vacuum and therefore only very low field strength can be applied. The results of conductivity measurements under vacuum are similar to conductivity measurements of air-impregnated pressboard in the examined range of field strengths (< 0.5 kV/mm) [9]. That is why measurements of pressboard under dry air can be performed instead of measurements of pressboard without an impregnating medium (that means in vacuum).

After the conductivity measurement of the dried pressboard sample in dried air (see Section 5.1), the test cell was evacuated again, filled with oil and aerated with dry air. Thereby, the pressboard sample is impregnated carefully. Oil is a commonly used mineral oil for transformer insulation. It has been previously dried, degassed and filtered. Water content of oil is 1.6 ppm. Fig. 8 shows the apparent conductivity derived from measurements according to the PDC method at a field strength of 1 kV/mm and at different temperatures. The pressboard sample is the same as in Figs. 4-6.

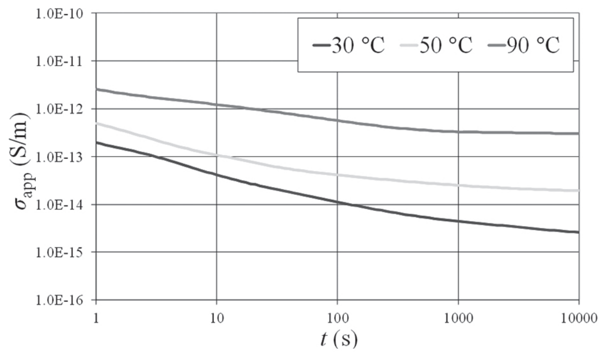


**Fig. 8.** Apparent conductivity of an oil-impregnated pressboard sample at a field strength of 1 kV/mm and at different temperatures

The apparent conductivity of oil-impregnated dry pressboard exhibits a similar dependence on time as the conductivity of air-impregnated pressboard. It decreases with time at every measured temperature. In contrast to air-impregnated pressboard (Fig. 8), the conductivity of oil-impregnated pressboard is much higher. The factors between conductivity values are calculated in Table 1 for the three temperatures. The significant factors are obviously caused by oil. The steady-state conductivity of the used oil, measured at 30 °C and 1 kV/mm using the same electrodes arrangement, is $10^{-14}$ S/m. Insulating oil exhibits a much higher conductivity than unimpregnated pressboard. Moreover, there is a temperature dependence of the conductivity of oil-impregnated board similar to air-impregnated board.

**Table 1.** Steady state conductivity of air-impregnated and oil-impregnated pressboard at 1 kV/mm

| Temp. | $\sigma_{air\text{-}impregnation}$ | $\sigma_{oil\text{-}impregnation}$ | Factor between conductivities |
|---|---|---|---|
| 30°C | 3.5 · 10-16 S/m | $2.4 \cdot 10^{-15}$ S/m | 6.8 |
| 50°C | $1.5 \cdot 10^{-15}$ S/m | $1.9 \cdot 10^{-14}$ S/m | 13.0 |
| 90°C | $2.9 \cdot 10^{-14}$ S/m | $3.0 \cdot 10^{-13}$ S/m | 10.3 |

The factors between the steady-state conductivity of air-impregnated and oil-impregnated pressboard range between 6 and 13 in the considered cases. The conductivity of oil-impregnated pressboard is much higher than the conductivity of air-impregnated pressboard. Therefore, the oil conductivity has a significant influence on the dielectric behavior of the whole HVDC insulating system. No trend of temperature-dependence on the calculated factor can been seen, but the interaction of the pressboard material with the impregnating fluid has to be kept in mind.

Conductivity of pressboard has been studied and a few parameter influences such as time, temperature, water content and impregnation are better known. Further investigations on the conductivity behavior of pressboard are intended to find a link between the pressboard structure and compounds and the measured polarization and conduction behavior.

## 6. CONCLUSION

Pressboard is one of the key components in HVDC converter transformer insulation. By broadening knowledge of conduction processes in pressboard it will be possible to improve cellulosic insulation materials and insulation designs.

In order to come closer to a physical understanding of conduction processes in pressboard, its main compounds, cellulose, hemicellulose and lignin are considered from a chemical and physical point of view. Moreover, pressboard manufacturing is explained and fiber geometry quantified via SEM images.

Pressboard conductivity is an important quantity for HVDC field distributions and dependent on various parameters. In the present paper, pressboard conductivity is evaluated with air impregnation and with oil impregnation by applying a step response measurement technique called the PDC method.

The step-response current of insulating pressboard (proportional to a so-called apparent conductivity) is time-dependent. After a voltage step, it decreases with time and the measured currents of dry pressboard become very small, which makes it difficult to measure. Moreover, the steady-state conductivity of air-impregnated pressboard increases by two orders of magnitude when the temperature is increased from 30°C to 90°C.

Besides time dependence and temperature dependence of pressboard conductivity in dry condition, an undried pressboard sample was measured in order to quantify the influence of water. Moisture is one of the biggest issues for high-voltage insulation materials. Ideally, it has to be as low as possible since pressboard conductivity increases by several orders of magnitude with a few percent of water. High water content leads to additional polarization phenomena, too, which was shown in the experiment. Both conduction and polarization are therefore dependent on water content.

Measurements on oil-impregnated pressboard revealed a much higher conductivity than measurements on air-impregnated samples within the considered temperature range. The conductivity of oil-impregnated pressboard is up to 13 times higher by impregnation with this particular oil than the conductivity of air-impregnated pressboard or unimpregnated pressboard under vacuum. Therefore, oil conductivity has a significant influence on the dielectric behavior of the whole HVDC insulating system.

Further analyses are going on in order to determine other influences on pressboard conductivity and in order to search for a model of charge carrier transport along cellulose fibers or through oil-filled pores in pressboard.

## 7. ACKNOWLEDGMENT

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