Parameter Influences on HVDC Transformer Insulation and Its Link to Conduction Processes

Case Study

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Abstract – *HVDC (high voltage direct current) transmission is an effective way to transport electrical power over long distances by using direct current. The insulation system of HVDC components has to be designed for both AC and DC field distributions. It consists of mineral oil and pressboard. The used insulation material behavior has not been completely understood under DC stress. In this paper, electrical conductivity of pressboard is evaluated and conduction processes are considered. Therefore, conductivity measurements are linked to a number of RC network elements in order to achieve a network model representative for the insulation material behavior under DC stress. Time-constants are determined under different temperatures and different electric field strengths. In addition, the performed simulations provide evaluation of parameters affecting the dielectric behavior of the insulation system oil and pressboard, which are not measured or even cannot be determined by measurements.*

Keywords – *HVDC insulation, pressboard, RC network, step-response measurement.*

1. INTRODUCTION

HVDC (high voltage direct current) transmission plays an increasing role in supplying urban areas with electric power. This type of power transmission requires reliable operating high-voltage converter-transformers and therefore, the insulating material used must ensure safe operation of transformers. Mineral oil impregnated pressboard is widely used as an insulation material, e.g., for converter transformers. The insulation system is stressed with AC and superimposed DC stresses.

To ensure safe operation of these insulation systems under service conditions, the knowledge about the behavior of the materials under service stresses has to be improved. For DC stresses, conductivities are relevant and field distributions are determined by the conductivity ratios of different materials interacting in the insulation system.

On the one hand, polarization mechanisms for example due to the orientation of dipoles in pressboard have to be regarded; and on the other hand, pressboard conductivity is determined by conduction processes when polarization mechanisms are over. Moreover, the conductivity of pressboard is affected by a variety of parameters such as temperature, electric field strength and water content. All of these parameters have to be borne in mind when designing or diagnosing impregnated pressboard for DC applications.

A physical understanding of the processes in pressboard can significantly reduce measurement duration and parameter variations. That is why simulation of pressboard insulation is of interest in current research. Therefore, the second chapter presents an experimental technique for determining the dielectric properties of pressboard. Afterwards, the way to model the measured current by the RC network is described. In Chapter 4, the measured currents when using different voltage sources are compared and a method to get comparable currents even in the first few seconds after voltage application is discussed. Chapter 5 shows the dielectric behavior of pressboard under different impregnating fluids. To understand the influence of impregnation, in Chapter 6, the time-constants of the measured currents are evaluated. Finally, conclusions are drawn and an outlook into further research is given.

2. STEP RESPONSE MEASUREMENT

Step response measurements in time-domain are performed by using a PDC (polarization-depolarization current) analyzer [1], [2] in order to determine the dielectric properties of pressboard insulation.

A voltage step is applied to the material sample between guard-ring electrodes in a special test cell [3] and the time-dependent current is measured (polarization current). Afterwards, the sample is short-circuited and a depolarization current having the opposite direction is now recorded. For detailed information regarding the test cell and measuring equipment, see e.g. [4], [5].

Measurements of dried pressboard samples with different impregnating fluids have been performed under different temperatures (30° C, 50° C, 90° C) and field strengths (0.1 kV/mm up to 10 kV/mm) and apparent conductivities are calculated from the measured currents by using the effective electrode area of the configuration, sample thickness and applied voltage. For detailed information on sample preparation and measurement, see [6].

In the next chapter, the measured currents are linked to polarization mechanisms and conduction processes and a simulation model is presented.

3. TIME-CONSTANTS AND RC NETWORK

Currents through oil-impregnated pressboard measured according to the aforementioned step-response measurement seem to decrease exponentially with the energization time. Fig. 1 shows the results in a log-log scale.

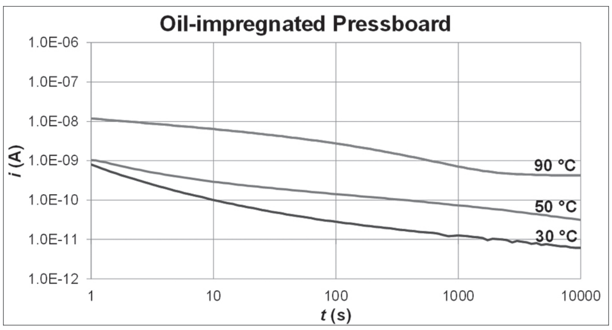

Fig. 1. Currents through oil-impregnated pressboard at 1 kV/mm and different temperatures

The initial current is relatively high and it decreases with the energization time until a steady state is reached. When due to orientation polarization and interfacial polarization all polarization mechanisms are negligible, conduction phenomena dominate the steady-state value of the current. Since polarization mechanisms may be relevant for a very long time, measurement duration to achieve the steady-state conditions and a steady-state current is often very long. Therefore, pressboard modelling and simulation provide a powerful tool to determine material behavior under different conditions.

The measured current can be fitted using a mathematical fitting algorithm. Unfortunately, using only one exponential function is not sufficient because there is not only one polarization mechanism. Moreover, because of mathematical fitting, it is not possible to directly link the determined time-constants with the physical behavior of polarization mechanisms.

The current-time characteristic of pressboard can be modelled by a superposition of many exponential functions with fitted time-constants or RC network elements, respectively [4], [7].

The current can be expressed mathematically by implementing the applied voltage U, the steady-state resistance R_∞ (representing conduction processes) and many decreasing exponential functions with different time-constants $\tau_i = Ri \cdot Ci$ (representing different polarization mechanisms):

$$i(t) = \frac{U}{R_\infty} + \sum_i \frac{U}{R_i} \cdot e^{-\frac{t}{\tau_i}} \qquad (1)$$

In Equation 1, it is assumed that due to the geometric capacity C_{Geo} the current can be neglected after one second. The number and values of network elements may vary between different measurements depending on the measured current shape. A direct link between physics and the determined values is not possible since mathematical fitting is used.

The network element values were determined by means of the evaluation software provided by the PDC analyzer. This means that the evaluation software calculates RC network element values for a measured current-time characteristic. The amount of RC values and time-constants leads to an adequate shape of the polarization current. A scheme of this network is presented in Fig. 2.

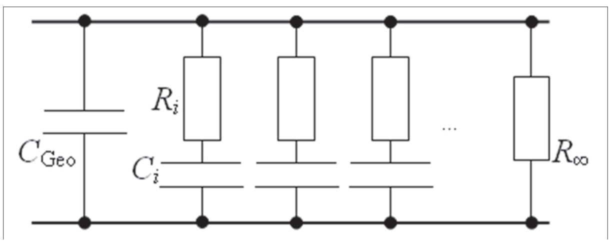

Fig. 2. Network model with RC elements [5]

4. COMPARABILITY OF POLARIZATION CURRENTS UNDER DIFFERENT VOLTAGE SOURCES

In order to evaluate the dependence of pressboard conductivities on the electrical field strength, different field strengths are applied on air-impregnated pressboard and oil-impregnated pressboard (1 mm thick). Therefore, different voltage sources are used, since the voltage-stabilized internal source of the PDC analyzer provides voltage of only up to 2 kV. To achieve higher field strengths, an external power supply has to be used. This external voltage source needs a certain time for stabilization and meanwhile, displacement currents are recorded in addition to the polarization and conduction currents caused by the material. Displacement currents are superimposed to polarization currents within the first few seconds after energization, until the voltage source is stabilized. These displacement currents have to be eliminated in order to achieve comparability of measurements with internal and external voltage sources.

In fact, the depolarization current recorded after short-circuiting the material sample contains the physical information to modify the polarization current in the first few seconds and the influence of the displacement current on the recorded current is no longer obvious.

Fig. 3 shows a PDC measurement (log-log scale) with an internal (field strength of 1 kV/mm) and an external (field strength of 6 kV/mm) voltage source. The recorded current from the external source is influenced by a superimposed displacement current within the first few seconds until a certain time t_m.

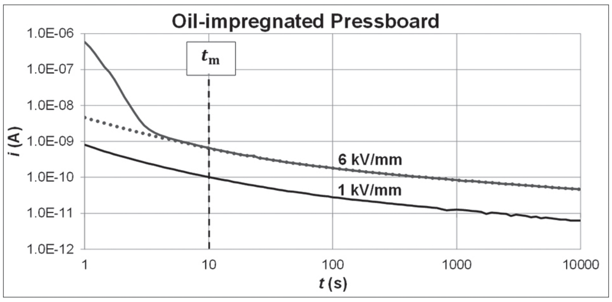

Fig. 3. Currents through oil-impregnated pressboard at different field strengths, at 30° C and with a modified current (a dotted line)

In this time range (generally, $t_m \leq 10$ s), the measured current can be replaced by an extrapolation: The difference of the measured current at t_m and the amount of the depolarization current at this time t_m can be calculated. In the next step, this difference can be added to the amount of the depolarization current for energization times of up to t_m. This modified current at 6 kV/mm is plotted by a dotted line in Fig. 3.

Neglecting the conduction current, it seems that after voltage application and after short-circuiting currents are in the same range for the first few seconds. Therefore, after voltage application the measured current has to be modified near the value of the depolarization current after short-circuiting of the material (dotted line in Fig. 3).

Note: There are more possibilities to modify the polarization current in the first few seconds in order to neglect the displacement current caused by the power supply. In this paper, only one method is described and verified. Other methods have to be evaluated in further research. With the presented modification method it is not possible to completely represent the physics behind the processes in the material and therefore the results cannot be evaluated in respect to physical processes.

A direct comparison of the currents through pressboard at different field strengths (representative of different stresses in HVDC equipment) is now possible for the first time. Table 1 lists RC element values as well as the calculated time-constants $\tau_i = Ri \cdot Ci$ exemplarily for oil-impregnated pressboard at 90° C and at the field strength of 6 kV/mm.

Table 1. *RC* element values and calculated time-constants for pressboard measured at 90° C and 6 kV/mm

	Ri in GΩ	Ci in pF	τ_i in s
i = 1	332.5	5.4	1.8
i = 2	334.2	16.8	5.6
i = 3	556.0	32.0	17.8
i = 4	418.1	134.5	56.2
i = 5	971.9	183.0	177.9

As can be seen from Table 1, resistivity values increase and capacity values decrease with time.

It seems that the current-time characteristic in Fig. 4 (nearly exponentially decreasing currents via time) is similar for all applied field strengths. The higher the field strength, the higher the currents of oil-impregnated pressboard.

As can be seen from Fig. 4, modification of the currents through oil-impregnated pressboard leads to similar shapes of the curves for field strength both with the internal and the external voltage source.

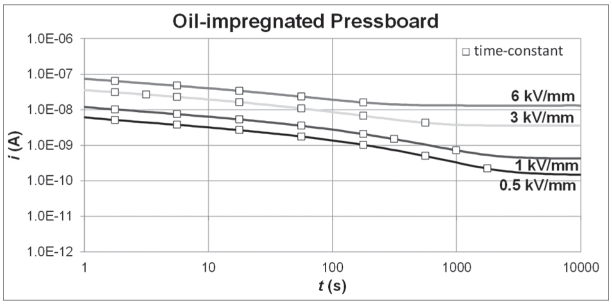

Fig. 4. Currents through oil-impregnated pressboard at different field strengths and at 90° C

The time to reach steady state is different for different field strengths: At higher field strengths, steady state is reached earlier. It seems that polarization mechanisms accelerate and time-constants are shortened at increasing field strengths.

5. INTERACTION OF PRESSBOARD AND IMPREGNATING FLUID

In order to come closer to an understanding of polarization mechanisms and conduction processes in pressboard, some pressboard samples are measured without oil-impregnation. Unfortunately, the applied voltage level is limited to a relatively small range for measurements under gas (Paschen's Law). It is not possible to increase the voltage level for more than a few 100 V to avoid an electrical flashover or a breakdown.

It has been found in previous experiments that measurements under dry air show similar currents to measurements under vacuum (for low field strength) [6]. Therefore, measurements can be performed at higher voltages, e.g., 1 kV, under air impregnation. Electrical stresses of up to 1 kV/mm can be achieved in pressboard, which is more relevant for service stresses.

Fig. 5 shows measurements of air-impregnated pressboard at 90 °C and at two different field strengths. Comparing the currents of oil-impregnated (Fig. 4) and air-impregnated pressboard (Fig. 5), it can be seen that the initial values of the currents are nearly the same for both types of impregnation. Both currents at both impregnations decrease with energization time until a steady-state value is reached.

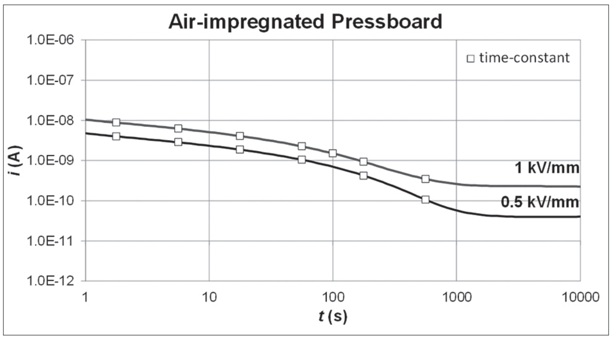

Fig. 5. Currents through air-impregnated pressboard at different field strengths and at 90° C

After 1,000 s, currents through air-impregnated pressboard are almost half an order of magnitude lower than currents through oil-impregnated pressboard. Steady-state values are reached for both types of impregnated pressboards.

The reason for different steady-state values can be found if the impregnating fluids air and oil are considered: Air has a higher resistivity than any mineral oil (many orders of magnitude). The measurement of impregnated pressboard is always determined by both the conductivity of the pressboard fibers and the conductivity of the impregnating fluid.

Moreover, measurements of oil (without pressboard) are performed and shown in Fig. 6 for measurements at 90° C and at two field strengths.

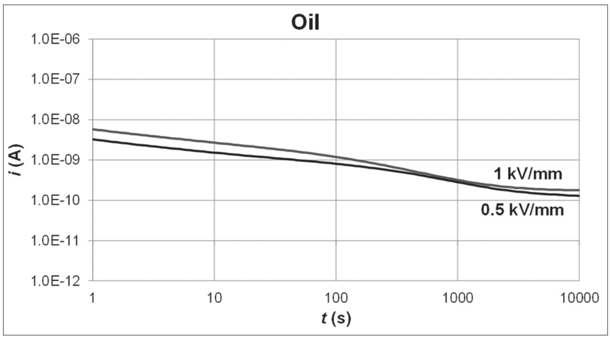

Fig. 6. Currents through mineral oil at different field strengths and at 90° C

The oil in Fig. 6 is a high resistive oil. After voltage application, the initial values are in the same range for both oil- and air-impregnated pressboard. Pressboard in Fig. 4 has been impregnated with this particular oil. Results for oil-impregnated pressboard have already been presented in Fig. 4.

The currents at any energization time are determined by pressboard and impregnation. The pressboard fiber volume is much higher than the impregnation volume. Initial values are nearly the same in Figures 4-6. Steady-state values differ, as steady-state currents through oil are much higher than steady-state currents through air. The steady-state conductivity of air is assumed to be some orders of magnitude lower than the steady-state conductivity of any oil. That is why the steady-state current of oil-impregnated pressboard is higher than at measurements of oil samples or of air-impregnated pressboard itself.

Moreover, because of different field strengths in different parts (fibers, impregnating volume) of impregnated pressboard a linear superposition of material properties of pressboard and fluids is not possible. Conduction processes are completely different in oil or gas than in pressboard. In consequence, a complex physical system arises which will be part of further research.

6. EVALUATION OF TIME-CONSTANTS FOR PRESSBOARD

By considering the current-time characteristic of pressboard impregnated with different fluids (oil and air), it can be seen that the time to reach steady state is lower at air impregnation than at oil impregnation if the same field strengths are considered.

$$\tau_{\mathrm{air+pressboard}} \leq \tau_{\mathrm{oil+pressboard}} \quad (2)$$

Moreover, it is now possible to evaluate the time-constants of pressboard for different field strengths, because displacement currents caused by the power supply are successfully eliminated for all field strengths. If the field strength is increased, time-constants are shortened and steady state is reached after shorter energization times, see Fig. 4. This field strength dependence of pressboard is a kind of nonlinear behavior.

$$\tau_{\text{higher field strength}} \leq \tau_{\text{lower field strength}} \quad (3)$$

In further research, these changes in time-constants can be implemented in the RC network elements of Chapter 3.

In general, the number of time-constants for fitting PDC measurements via the evaluation software provided by the PDC analyzer is not constant. Depending on the mathematical fitting algorithm, different numbers of RC elements and time-constants are required to fully describe the measured currents. This complicates the comparability of time-constants of different experiments.

Fig. 7 shows measurements of oil-impregnated pressboard at 1 kV/mm and at different temperatures. The fitted RC network elements and therefore the calculated time-constants are plotted as well. It is reported in [4] that higher temperatures will lead to higher currents. This can be verified by the presented measurements in Fig. 7. For steady-state values the dependence on the temperature seems to be exponential.

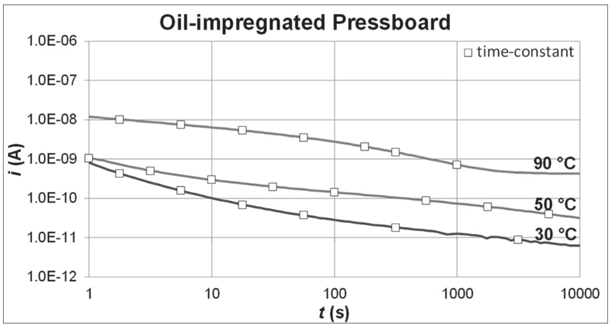

Fig. 7. Currents through an oil-impregnated pressboard sample vs. time after applying a voltage step at 1 kV/mm and at different temperatures

At 50° C, time-constants seem to occur at shorter times compared to the measurement at 3o° C. If the temperature is increased to 90° C, time-constants are shifted to even shorter times. However, it has to be noted that the values of these time-constants do not represent physical processes and mechanisms and are just the result of curve fitting.

However, time-constants seem to be shifted to shorter times after voltage application if the temperature increases. This may be explained by faster polarization mechanisms at higher temperatures.

$$\tau_{\text{higher temperature}} \leq \tau_{\text{lower temperature}} \quad (4)$$

At 90° C, steady state is reached within the time of measurement (3 hours at 1 kV/mm). In order to reach steady state, currents must be high. This is achieved by increasing the temperature or field strength or a combination of both parameters. If the currents are higher, time-constants are shifted to shorter times.

7. CONCLUSION

According to the PDC method, step-response measurements in time domain are useful to determine insulating material parameters under HVDC stresses. These measurements have been performed for air-impregnated, oil and oil-impregnated pressboard.

The current through the pressboard exponentially decreases with time due to polarization mechanisms. The steady-state current is determined by the conduction current. A network with a number of RC -elements is used to mathematically fit the measured currents.

By using an external high-voltage source, displacement currents are superimposed to polarization and conduction currents. These displacement currents distort the measured currents. A new method is described to modify the measured currents so that displacement currents caused by the external power supply are no longer obvious. Afterwards, the currents can be compared at all field strengths for the first time regardless of which power supply is used.

The measured currents of pressboard are determined by both pressboard itself (fibers) and impregnation (air or oil). It has to be noted that the pressboard fiber volume is much higher than the impregnation volume.

Because of the high fiber volume in pressboard, initial values are nearly the same for air-impregnated and oil-impregnated pressboard. Steady-state values differ as the currents through oil are at steady state much higher than the currents through pressboard fibers under air impregnation. In conclusion, the steady-state current of oil-impregnated pressboard is higher than for air-impregnated pressboard.

The time to reach steady-state is different for different field strengths and different temperatures. At higher field strength or higher temperatures, steady state is reached in a shorter time and hence time-constants are shortened as well.

Separating the effects of oil and pressboard fibers more clearly is the next step in order to come closer to an understanding of polarization mechanisms and conduction processes in pressboard used as an HVDC insulation material.

8. ACKNOWLEDGEMENT

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9. REFERENCES

[1] J. J. Alff, V. Der Houhanessian, W. S. Zaengl, A.J. Kachler, "A novel, compact instrument for the measurement and evaluation of relaxation currents conceived for on-site diagnosis 6 Interna-

tional Journal of Electrical and Computer Engineering Systems on electric power apparatus", Proceedings of the IEEE Symposium on Electrical Insulation, Anaheim, CA, USA, 2-5 April 2000, pp. 161-167.

[2] V. Der Houhanessian, "Measurement and analysis of dielectric response in oil-paper insulation systems", ETH Zürich, Switzerland, PhD Thesis, 1998.

[3] F. Schober, S. Harrer, A. Küchler, F. Berger, M. Liebschner, Ch. Krause, W. Exner, "Conductivity of Pressboard for HVDC Insulation Systems", International Journal of Electrical and Computer Engineering Systems, Vol. 4, No. 2, 2013, pp.1-7.

[4] A. Küchler, M. Liebschner, A. Reumann, Ch. Krause, U. Piovan, B. Heinrich, R. Fritsche, J. Hoppe, A. Langens, J. Titze, "Evaluation of conductivities and dielectric properties for highly stressed HVDC insulating materials", CIGRÉ Session, Paris, France, 22-27 August 2010, paper D1_106_2010.

[5] M. Liebschner, A. Küchler, Ch. Krause, B. Heinrich, C. Leu, F. Berger, "Interaction of Oil Ducts and Solid Insulation in HVDC Barrier Systems", Proceedings of the 16th International Symposium on High Voltage Engineering, Cape Town, Republic of South Africa, 24-28 August 2009, pp. 546-551.

[6] F. Schober, A. Küchler, W. Exner, Ch. Krause, M. Liebschner, F. Berger, "Interaction of Pressboard with Impregnating Fluids in HVDC Insulation Systems", Proceedings of the IEEE Electrical Insulation Conference, Philadelphia, PA, USA, 8-11 June 2014, pp. 276-280.

[7] Ch. Roongroj, N. Pattanadech, P. Praisuwanna, P. Yutthagowith, K. Thongkaemkaew, "Equivalent Circuit Approximation of Transformer Insulation by Using PDC Measurement", Proceedings of the 5th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology, Krabi, Thailand, 14-18 May 2008, pp. 925-928.