

# FEM model for describing the dielectric behavior of oil-impregnated pressboard under DC stresses

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**Abstract** – According to the worldwide growing demand for electric energy, it is necessary to construct safe and efficient power systems. HVDC (high voltage direct current) applications become more and more important due to larger distances for the energy transportation and the increasing demand for reactive power transportation. Appropriate insulation materials, i.e. mineral oil and pressboard, are widely used in HVDC components, mainly in power transformers though the knowledge about dielectric behavior of oil-impregnated pressboard under DC stresses in time domain is not sufficient. In this paper, a Finite Element Method (FEM) model is presented to describe the electrical conduction behavior of the material by separate consideration of mineral oil and pressboard. With this model the electric potential distribution under DC stress was simulated to analyze polarization and electrical conduction. The model parameters volume ratio as well as angle variations of FEM model are investigated and their influences on the current through the model are evaluated. Furthermore, geometrical and physical parameters are estimated and the results are compared to currents that are measured on oil-impregnated pressboard samples in time domain.

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**Keywords** – electrical conduction; FEM simulation; HVDC; oil-impregnated pressboard; polarization

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## 1. INTRODUCTION

HVDC (high voltage direct current) transmission is a worldwide needed technology for safe and efficient supply with electricity. Pressboard impregnated with mineral oil (transformer oil) is often used as insulation material, mainly in transformers. Those HVDC components are stressed by AC- and superimposed DC-field. Further knowledge about the behavior of mentioned materials under operation conditions is needed to improve the reliability, component design and profitability. Therefore, step response measurements in time domain are used to investigate the dielectric behavior of oil-impregnated pressboard insulations with a PDC (polarization-depolarization current) Analyzer [1], [2]. For detailed information about used test cell and measurement equipment, see references [3], [4].

Using a mathematical fitting algorithm, each current can be represented as a sum of time-

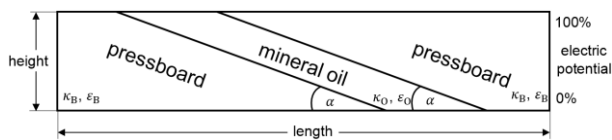
constants, which enables the presentation of the measurement as a network model containing RC elements [4], [5]. A splitting of the physical behavior of oil-impregnated pressboard to its separate insulation materials only using RC equivalent circuits is difficult.

For a better understanding of electric properties of the insulation material FEM models will be used. The model is presented in Chapter 2. Chapter 3 presents how the model can be used to describe the dielectric behavior by time domain simulations of the polarization current and the electric potential distribution. In chapter 4 and 5 it is shown, how a variation of the model parameters are affecting the simulation results. Finally, in Chapter 6 the simulation results are transferred to a larger geometry and are compared to real measurement curves.

## 2. FEM MODEL

In this chapter the FEM model used to simulate the dielectric behavior of oil-impregnated pressboard is presented. Oil-impregnated pressboard is, from a macroscopic point of view, a homogenous material. The model is based on the idea that the behavior of the oil-impregnated pressboard can be described by a “microscopic” separate consideration of mineral oil and cellulose fibers.

Due to the manufacturing process, the solid fibers of the pressboard have an anisotropic behavior. For a simplified model it is assumed, that these solid fibers have an angled position on average in the pressboard. The two insulating components mineral oil and pressboard are placed and separated as shown in Fig. 1.



**Fig. 1.** Schematic presentation of FEM model of oil-impregnated pressboard

It's expected, that physical effects of single pressboard fibers can be combined with macroscopic behavior. A modification of these two barriers by angle adjustment of  $\alpha$  results in a variation of the polarization effects and the electrical conductivity. In spite of a changing angle  $\alpha$ , the ratio of pressboard and mineral oil is kept constant.

On top of this model an anode and on its bottom a cathode is placed to simulate electric field strength through the geometric arrangement. Liquid mineral oil is surrounded by solid pressboard (fibers). So an oil duct is formed and both ends are directly linked to the electrodes. The volume and surface ratio of pressboard and oil is assumed to be between 70:30 and 80:20.

The left and right boundaries of the FEM model in Fig. 1 are defined with periodic conditions.<sup>1</sup>

In the following the length of FEM model is defined as 10 mm, the height as 1 mm. In chapter 6 an increased length is used. The total simulated current is the result of simulated current density multiplied with material sample surface from PDC measurement cell. In the following, all simulated currents are multiplied with this surface. This enables a comparison with real material measurements.

The material parameters used in the model are presented in Table 1.

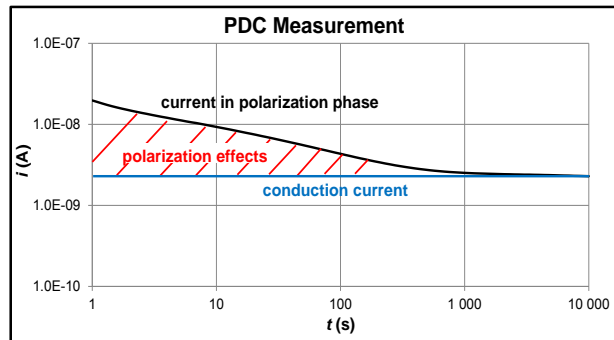
<sup>1</sup> Periodic conditions for the boundaries mean that the same model is repeated beyond the boundaries and interacts with the model.

**Table 1.** Dielectric properties of mineral oil and pressboard at 90 °C at 1 kV/mm (mineral oil nearly following [6])

Property (90 °C)	Pressboard	Mineral Oil
Permittivity	4.5	2.2
Conductivity (S/m)	1.0E-14	1.0E-12

## 3. SIMULATION OF CURRENTS IN THE POLARIZATION AND DEPOLARIZATION PHASE

During polarization phase the material sample, respectively the FEM model a voltage step is applied and the polarization current is measured. The current during the polarization phase consists of two parts - the conduction current caused by the insulation resistance of the system and the polarization part that represents charge that is stored by polarization effects inside the dielectric, Fig. 2. During depolarization phase the voltage source is short-circuited and the depolarization current is measured. This current has the opposite direction than the current during polarization phase but the depolarization current is illustrated in absolute amount. From a physical point of view, the difference between polarization and depolarization current is an approximation of conduction current, Fig 2 and Fig. 3.

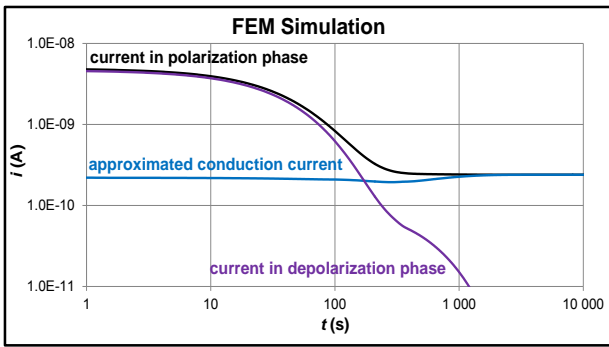


**Fig. 2.** Illustration of currents based on PDC measurement of oil-impregnated pressboard at field strength of 1 kV/mm and at 90 °C

During polarization phase a steady state is reached when polarization effects are finished and only conduction current is present.

With FEM model (Fig. 1) it seems to be possible to simulate polarization and depolarization currents, see Fig. 3.

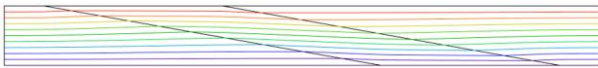
But it can be seen, that the depolarization current in the third decade does not decrease smoothly. This deviation from a smooth decrease also leads to an increase of the approximated conduction current within the third decade. In principle the conduction current should be constant in time. Further investigations and simulations are needed to explain this shape of depolarization curve.



**Fig. 3.** Simulated currents through the FEM model vs. time after applying a voltage step at 1 kV/mm during polarization phase and during depolarization phase and calculated conduction current; model parameters:  $\alpha = 10^\circ$  and ratio pressboard:oil 70:30

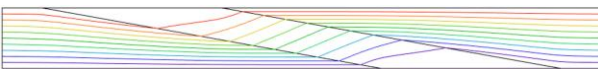
For better understanding of polarization and conduction process of the FEM model, considerations of electric potential distributions are helpful. Fig. 4 to Fig. 6 illustrate different distributions of equipotential lines 10 s, 70 s and 1000 s after the voltage step. From bottom to top electric potential is increasing. The direction of electrical field and electrical current respectively is perpendicular to the equipotential lines.

Fig. 4 shows, that 10 s after the voltage step the electric potential is nearly evenly distributed. Only refractions of the electrical field at the surface of the pressboard can be seen due to the difference in permittivity, see Table 1.



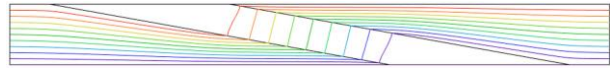
**Fig. 4.** Distribution of electric potential during polarization phase 10 s after the voltage step; model parameters: 1 kV/mm and 70:30 ratio pressboard:oil

In Fig. 5 it can be seen, that 70 s after the voltage step the distribution of electric potential changes. In the mineral oil duct the potential lines strive for an evenly perpendicular course to the barriers of pressboard and mineral oil.



**Fig. 5.** Distribution of electric potential during polarization phase 70 s after the voltage step; model parameters: 1 kV/mm and 70:30 ratio pressboard:oil

Fig. 6 shows that 1000 s after the voltage step the electric potential in mineral oil is almost perpendicular to the pressboard barriers. Hence it seems that steady state is nearly reached after 1000 s which can already be seen in Fig. 3. After this time the polarization of the pressboard surfaces is finished.



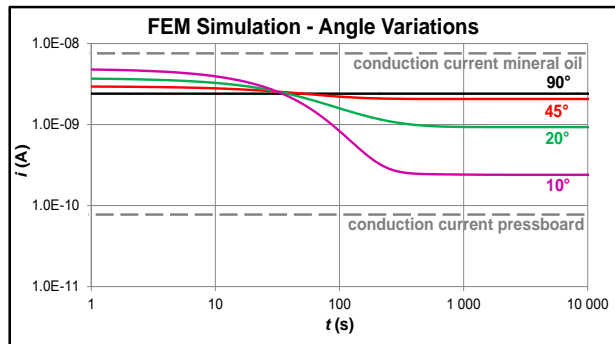
**Fig. 6.** Distribution of electric potential during polarization phase 1000 s after the voltage step; model parameters: 1 kV/mm and 70:30 ratio pressboard:oil

To reach the steady state, the surface of pressboard (fibers) has to be charged via the oil duct. In consequence, permittivity of pressboard and conductivity of oil are the most important parameters.

At steady state, conduction current is caused both by conductivity of pressboard and by conductivity of mineral oil. Which material is of greater influence depends on the geometry of the model. This is investigated in the next two chapters.

#### 4. INFLUENCE OF ANGLE VARIATIONS

In this chapter the influence of the variation of the angle  $\alpha$  on the simulation results is investigated. The field strength and other geometry parameters, especially the ratio of pressboard:oil are kept constant.



**Fig. 7.** Simulated currents during polarization phase at different angles; model parameters: 1 kV/mm and 70:30 ratio pressboard:oil

With decreasing angles, the surfaces between mineral oil and pressboard increases. This leads to distinctive polarization effects caused by the increased influence of the permittivity of pressboard. Thereby higher currents appear during the first few seconds of the polarization phase. The electrical conductivity of pressboard becomes more dominant, too.

In Fig. 7 it can be seen that currents at steady state are lower at flatter angles. This can be explained by the increasing influence of the conductivity of the pressboard. As the conductivity of board is 100 times smaller than that of oil, at flat angles the behavior is dominated by the parameters of pressboard.

On the other hand at angles close to  $90^\circ$  the conductivity of the oil duct dominates the behavior.

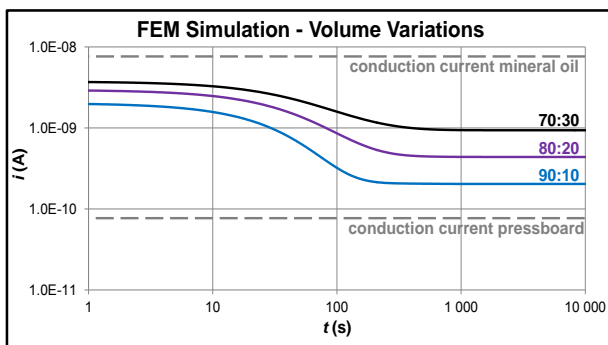
That means the electrical conductivity on steeper angles nearly reaches the conductivity of oil  $\kappa_{oil}$ .

The electrical conductivity on flatter angles nearly reaches the conductivity of pressboard  $\kappa_{pb}$ .

## 5. INFLUENCE OF VOLUME RATIO VARIATIONS

In this chapter, the influence of variations of the volume ratio between pressboard and oil is investigated.

Fig. 8 shows the simulated current during polarization phase at constant angle and field strength but with different volume ratios between pressboard and oil.



**Fig. 8.** Simulated currents during polarization phase with different volume ratios of pressboard:oil at  $\alpha = 20^\circ$  and 1 kV/mm

It can be seen that a higher amount of pressboard leads to lower currents in steady state. This can be explained by the lower conductivity of pressboard compared to oil. The higher the ratio of pressboard fibers in impregnated insulating material, the closer the simulated conductivity converges to pressboard conductivity.

## 6. COMPARISON OF FEM SIMULATION RESULTS AND PDC MEASUREMENTS

In this chapter the measured currents during the polarization phase are compared to currents simulated with the presented FEM model with increased length. To enable a comparison of the simulated currents to the measured ones, the simulation results were adapted by the ratio of the model electrode surface to the surface of the measurement electrodes used.

The simulations are done at different temperatures. As the temperature has a great influence on the conductivity of the materials used in this model, the temperature dependency of the conductivity is implemented in the simulations.

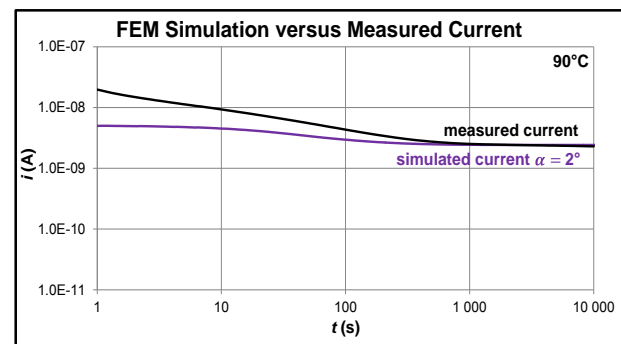
But it is assumed that a change of permittivity due to different temperatures of the materials can be neglected, also see reference [6]. Furthermore,

also the field stress dependence of conductivity of the materials is neglected in these first simulations.

So permittivity values of Table 1 are also used in following simulations.

Mineral oil and dried air-impregnated pressboard as well as a combination of both each are measured with PDC Analyzer at different temperatures (50 °C, 90 °C) and a field strength of 1 kV/mm to calculate conductivities with Charge Difference Method (CDM) [7].

In current simulation of Fig. 9 a conductivity of air-impregnated pressboard of  $\kappa_{pb} = 2.75E-14$  S/m and a conductivity of mineral oil of  $\kappa_{oil} = 1.65E-12$  S/m are used.



**Fig. 9.** Simulated and measured current during polarization phase with field strength of 1 kV/mm at 90 °C; simulation model parameters: ratio pressboard:oil 70:30,  $\alpha = 2^\circ$

In the third and fourth decade, both currents can be considered as almost identical. Hence, the very simple model, which is set up from mineral oil and air-impregnated pressboard is able to describe the conductivity (steady state behavior) of oil-impregnated pressboard. While the FEM model describes the conduction current almost perfectly, there is a deviation of the polarization effects in the first two decades, which is caused by the simplicity of the model.

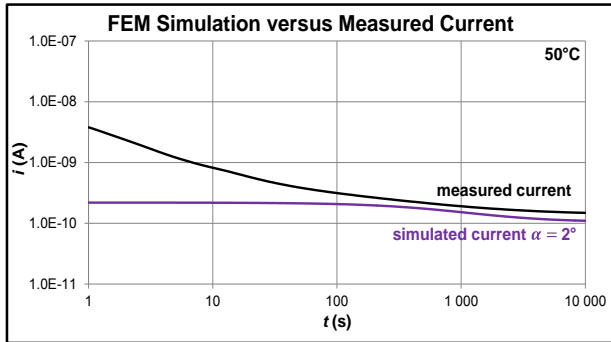
Nevertheless, investigations for different temperature stresses of 50 °C and 90 °C hereby different conductivities are performed with a constant model geometry, illustrated in Fig. 9 and Fig. 10. For simulation of current in Fig. 10 a conductivity of air-impregnated pressboard of  $\kappa_{pb} = 1.44E-15$  S/m and a conductivity of mineral oil of  $\kappa_{oil} = 7.10E-14$  S/m are used.

A decreasing of the temperature from 90 °C to 50 °C also leads to a decreased conduction current at steady state.

Fig. 10 clearly shows that the simulation model is able to describe the measured current very well in the third and fourth decade.

As already seen in Fig. 9, the FEM model is too simple to describe the polarization effects in first and second decade sufficiently. It seems that in the first two decades polarization effects are

missing and as a result the simulated current is lower than the measured one.



**Fig. 10.** Electrical conductivity with field strength of 1 kV/mm at 50 °C and 70:30 in ratio

A comparison of Fig. 9 and Fig. 10 shows that lower temperatures leads to decreased conductivities and hence the time-constants are enlarged, i.e. the curves are shifted along the time axis towards longer times [8].

## 7. CONCLUSION

In comparison to conventional RC network models, FEM models provide advanced possibilities in simulation of transient behavior and polarization effects.

A simple “microscopic” FEM model with a geometric arrangement consisting of dry pressboard (fibers) and mineral oil duct was developed to describe the transient dielectric behavior of “macroscopic” oil-impregnated pressboard.

Nevertheless, physical effects of single pressboard fibers can only moderately be combined with macroscopic behavior.

Considerations of electric potential distribution during polarization phase confirm the physical behavior of charged pressboard fibers through mineral oil (duct). Steady state is reached, when potential lines are lying perpendicular to oil/pressboard barriers.

Investigations with geometric variations of the FEM model, i.e. volume ratio of pressboard:oil and barriers angle variation were performed.

Finally a comparison of simulation results and measurement results was done. It can be shown that the rather simple model is able to describe the behavior of steady state condition of oil-impregnated pressboard very well. But due to the simplicity of the model polarization effects in short time domain are not described sufficiently.

To improve the FEM model, further polarization effects have to be implemented in order to get more time-constants. Also field strength

dependence of conductivity in FEM model has to be regarded.

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