

THE NEGATIVE DISSIPATION FACTOR AND THE INTERPRETATION OF THE DIELECTRIC RESPONSE OF POWER TRANSFORMERS

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Abstract: This paper presents the appropriate measurement circuit and interpretation scheme of the dielectric response of oil-paper insulated power transformers. The traditional three terminal measurement technique (voltage source, current input, guard wire) occasionally leads to the appearance of a negative dissipation factor. An equivalent circuit diagram along with practical measurements was used to investigate the reasons for this problem. These are guard resistance, capacitances to tank, instrument impedance and inductance of windings. Particularly the guard resistance as well as the instruments input resistance should be low. The dielectric measurement is conducted across a wide frequency range in order to discriminate between the influences of oil, interfacial polarization (transformer construction geometry) and water content. By a novel combination of time and frequency domain measurement, a very fast measurement of a wide data range can be accomplished. This is fully detailed in conjunction with measurement examples for power transformers, to illustrate the impacts of connection technique and frequency range on the accuracy of moisture determination.

1 INTRODUCTION

In recent years, dielectric response methods have been developed and frequently applied to determine the aging condition of HV insulations, particularly power transformers. Among aging parameters, water in the solid and liquid insulation is of high importance because of its detrimental effects: decrease in dielectric withstand strength, accelerated cellulose aging and the emission of bubbles at high temperatures. Therefore knowledge about the actual moisture concentration is required in order to decide on further action such as drying of the solid insulation.

Dielectric spectroscopy is able to detect probable failures of the active component, mainly the insulation system and bushings, [1]. For decades researchers looked for methods to find out the condition and the aging state of the insulation system. While the conventional tests like power factor, dissipation factor and polarization index look on narrow frequency points or areas, the newer dielectric spectroscopy methods conduct information over a very wide frequency range and thus enable for the discrimination between different effects and more dependable information about the assed condition.

This article focuses on two topics: firstly it describes the reasons for the sometimes-appearing negative dissipation factor and secondly it interprets the dielectric response for multi-layer oil-paper insulations. Case studies illustrate the knowledge.

2 MEASUREMENT - THE PROBLEM OF THE NEGATIVE DISSIPATON FACTOR

Occasionally, measuring the dissipation factor $\tan \delta$ of dielectrics leads to the appearance of negative values. As the dissipation factor indicates the quality of

insulation materials by the tangent of the ratio of resistive current I_R to capacitive current I_C , a negative current I_R would imply a negative resistive current, which is physically impossible. For bushings, the coupling of resistive surface currents to the inner capacitive layers causes this phenomenon. Yet for power transformers this explanation is not easily adaptable.

2.1 Measurement circuit

As dielectric spectroscopy aims to determine the aging condition of power transformer insulation, the capacitance between high and low voltage windings C_{HL} is of highest importance. This insulation path contains most of the solid insulation material, is easy to model and can be guarded. Figure 1 depicts the typical capacitances of a two winding power transformer as well as a connected instrument for measuring C_{HL} .

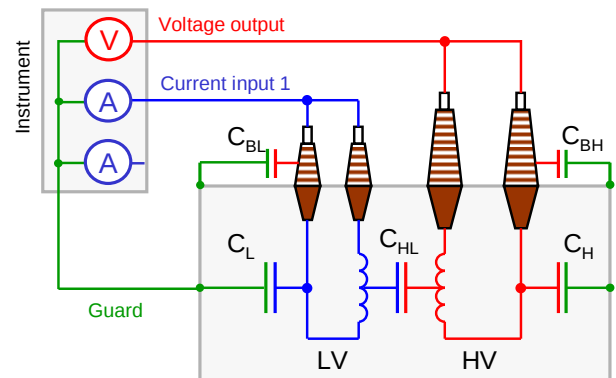


Figure 1: Capacitances and measurement circuit for a two winding transformer

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. It is worth to point on the complex

and frequency-dependent nature of all capacitances; they include "pure" capacitance C' and dielectric, resistive losses C'' . For this, resistance R is used later. In (1), C_0 is the "empty" geometrical capacitance.

$$\underline{C}(\omega) = C'(\omega) - jC''(\omega) = C_0[\varepsilon'(\omega) - j\varepsilon''(\omega)] \quad (1)$$

Because of the very small values, measuring these capacitances requires sophisticated techniques. The winding capacitances range from about 1 nF for distribution transformers to 40 nF for special set-ups of large power transformers. Each bushing lies between 300 and 800 pF. For a typical C_{HL} capacitance of 6,6 nF and an applied voltage of 200 V_p, the corresponding measurement current is then 414 μA_p at 50 Hz, but only 7,5 nA_p at 1 mHz. Fortunately, the resistive part of the current increases the amplitude for decreasing frequencies; still the indicated range remains similar.

2.2 Test specimen and equivalent RC circuit

The power transformer used for the following investigations on negative dissipation factor is a 6,5 MVA, 47 kV/27,2 kV transformer, built in 1962. Figure 2 shows this equipment.



Figure 2: 6,5 MVA, 47 kV/27,2 kV power transformer

Figure 3 depicts the equivalent circuit diagram for the transformer with an instrument connected to measure the capacitance C_{HL} . The capacitances are $C_{HL} = 6,6$ nF; $C_H = 2$ nF and $C_L = 8$ nF. The bushing capacitances could not be measured because of the absence of a measuring tap, they are therefore included in C_H and C_L . In parallel to the capacitances, Figure 3 depicts also the losses of the dielectric for a frequency of 50 Hz, these are $R_{HL} = 151$ MOhm; $R_H = 250$ MOhm and $R_L = 25$ MOhm. Additionally the impedance of the instruments voltage source and the current input are shown as well as the guard impedance.

Beginning with a much more complex equivalent circuit the drawing depicted in Figure 3 was developed, which concentrates on the most important items. For a comprehensive modelling of the dielectric response a more detailed RC network would be necessary, still here the connection technique is in the centre of interest. The following paragraphs elucidate its importance and influence on frequency sweeps of dissipation factor.

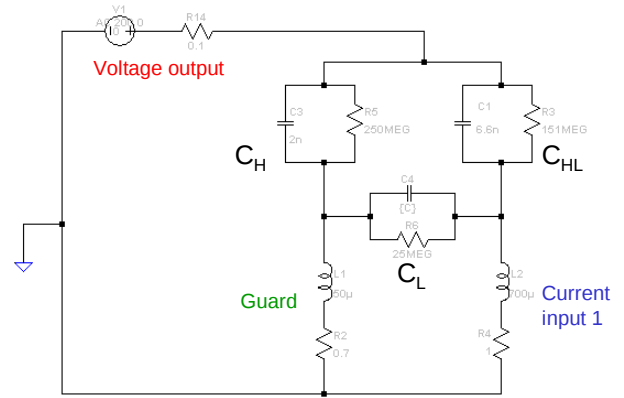


Figure 3: Equivalent circuit diagram

Before variations of specific parameters are investigated, the dissipation factor of the interwinding impedance including C_{HL} including R_{HL} without any parallel circuits (C_H , C_L , guard and input resistance) was computed between 10 kHz and 10 mHz. This is displayed in Figure 4 and serves as reference for further investigations. The dissipation factor is calculated from the phase shift between current input 1 and voltage output. For frequencies below 6 kHz, the RC-network behaves resistive, above this its nature becomes capacitive.

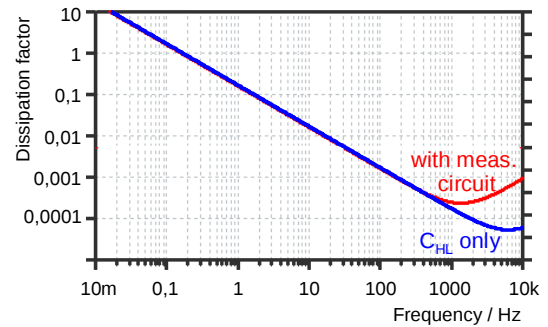


Figure 4: Reference dissipation factor of the interwinding insulation between HV and LV winding

Figure 4 also displays the influence of the surrounding measurement circuitry including the impedances HV to tank, LV to tank, guard and input impedance. Already the existence of the surrounding circuit influences the dissipation factor over frequency, shifting the transition from resistive to capacitive behaviour to 1,3 kHz. Since the current and the voltage are not directly measured at the interwinding impedance C_{HL} , the dissipation factor can now become negative without having a "negative resistive current". The circuit evolves from a simple two terminal network to a quadrupole.

2.3 Guard impedance

The guard plays the key role in the correct measurement of low losses of insulation materials. Basically, a three-terminal-circuit is required to guard away the influence of resistive surface currents and to shield external electrical fields. An increase of guard impedance will consequently increase the voltage drop over the guard. Figure 3 makes visible how this voltage drop influences the current flowing in the input

channel, particularly in conjunction with a low impedance Z_L (high capacitance C_L and/or low resistance R_L). Figure 5 depicts the influence of the guard resistance on the dissipation factor as simulated using the equivalent circuit of Figure 3. The parameter R_G was 0,1; 0,5; 1; 2; 5 and 10 Ohm. For a guard resistance of 10 Ohms the dissipation factor turns negative for frequencies higher than 1,7 kHz.

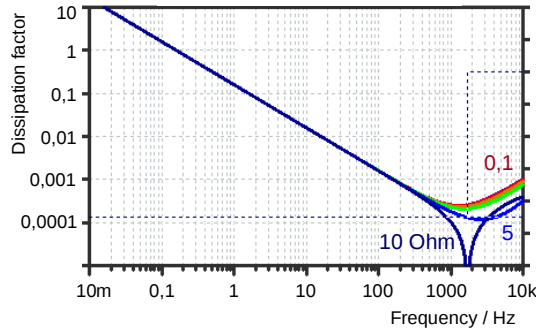


Figure 5: Simulated influence of guard resistance on dissipation factor over frequency

The effect of guard impedance was also tested on a dielectric response measurement system Omicron DIRANA 1, [2]. Figure 6 depicts how an increase of guard resistance from 100 Ohm to 100 kOhm causes the dissipation factor to turn negative for high frequencies. Obviously, the effect is not that strong as for the simulation shown in Figure 5, where the dissipation factor turns negative already for 6,8 Ohms instead of 300 Ohms under real conditions. However, a measurement without guard wire or with a high resistance due to corroded metals or lacquer layer can disturb the dissipation factor measurement.

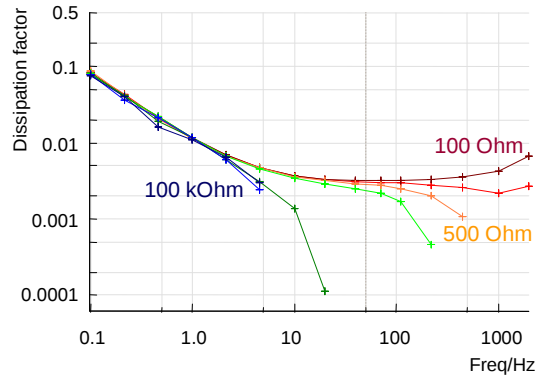


Figure 6: Measured influence of guard impedance on dissipation factor over frequency

2.4 Capacitance LV winding to tank

The capacitance C_L , including the capacitance LV winding to tank, the bushing capacitance and input wire capacitance, also plays an important role in the correct measurement of dissipation factor over frequency. In the equivalent circuit of Figure 3 this impedance couples the path of the measurement current with the guard path. Figure 7 depicts the result of a parameter sweep of $C_L = 0,8; 4; 8; 16$ and 80 nF, where 8 nF is the capacitance of the real transformer.

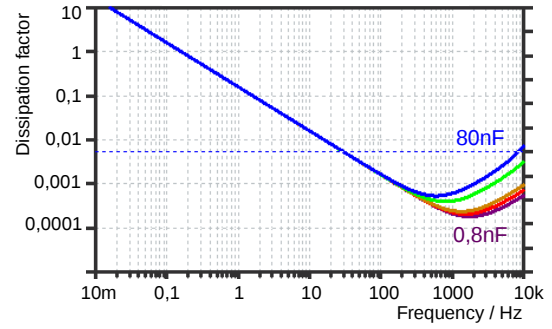


Figure 7: Simulated influence of capacitance C_L on dissipation factor over frequency

The conjunction of a guard resistance sweep between 0,1 and 10 Ohms with a capacitance C_L of 80 nF (ten times that of real C_L) depicts Figure 8. Now the dissipation factor turns negative already with 4 Ohm guard resistance instead of 6,8 Ohm for the usual capacitance C_L of 10 nF. In contrast to the capacitance C_L , the resistance R_L has only a minor influence on the results, therefore its variation is not depicted.

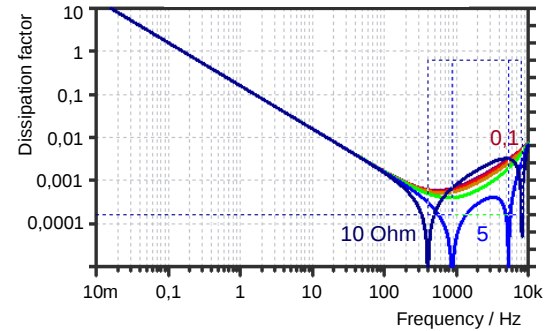


Figure 8: Simulated influence of guard resistance on dissipation factor for a capacitance C_L of 80 nF

2.5 Capacitance HV winding to tank

The capacitance C_H influences the measurement result as well. The capacitance C_H includes the HV winding to tank, the bushings and the output wire. Figure 9 shows a parameter sweep of C_H for 0,2; 1; 2; 4 and 20 nF, not leading to a negative dissipation factor.

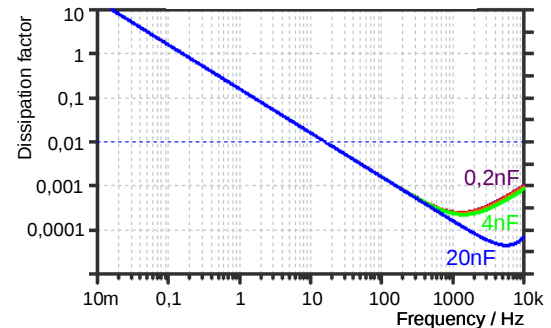


Figure 9: Simulated influence of capacitance C_H on dissipation factor over frequency

As for the variation of C_L , the influence of C_H increases with increasing guard resistance. Figure 10 illustrates the effect of increasing guard resistance (0,1 to 10 Ohm) on dissipation factor while the capacitance C_H is 30nF. Now already a resistance of 1 Ohm causes a

negative dissipation factor. Again, the resistance R_H plays a negligible role.

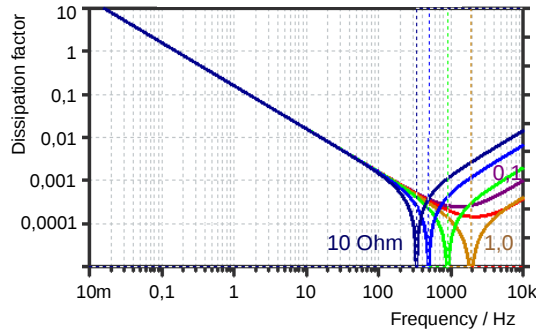


Figure 10: Simulated influence of guard resistance on dissipation factor for a capacitance C_H of 30 nF

During measurements on power transformers, the effect of negative dissipation factor combined with high C_L or C_H was observed particularly during rainfall. In this situation, the guard currents increase leading to a higher voltage drop over the guard impedance.

2.6 Input impedance of instrument

Similar to the guard impedance, the input impedance plays an important role in measuring the dielectric dissipation factor. Particularly the resistance value influences the high frequencies. Figure 11 shows a variation of input resistance of 0,1; 0,5; 1; 2; 5 and 10 Ohm. The inductance of the input plays no role, similar to the inductance of the guard. The lower the input resistance, the more accurate becomes the measurement. With $R_I = 0,1$ Ohm the dissipation factor curve is similar to that without surrounding circuit.

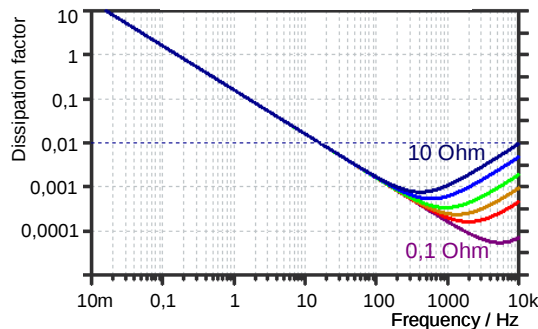


Figure 11: Simulated influence of input resistance

2.7 Winding inductance

The inductance of the windings may influence dielectric response measurements. Ideally, for a dielectric response measurement the windings of one voltage level are shorted. Practically, in order to save time, users may leave out bushings, which are hardly accessible because of their height. In such case, a part of the winding inductance will be in series to the measurement current of the dielectric response instrument. This adds an inductive component to the impedance Z_{HL} of Figure 3. For a three-phase Δ/Y transformer the bushings of the LV and HV side were not short-circuited. Figure 11 compares the

measurement results of this wrong connection to that of the correctly shorted circuit. Again the high frequency part of the dielectric response is effected by the winding inductance.

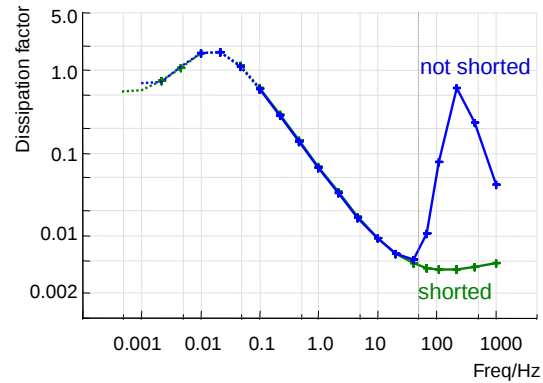


Figure 12: Dielectric response of a distribution transformer for shorted and not shorted windings

3 ANALYSIS OF THE DIELECTRIC RESPONSE

For oil-paper-insulated power transformers, the dielectric response consists of three components: The response of the cellulose insulation (paper, pressboard), the response of the oil and the interfacial polarization effect. Moisture, temperature, insulation geometry, oil conductivity and conductive aging by-products influence the dielectric response.

3.1 Superposition of dielectric properties

Figure 13 displays the dissipation factor of only pressboard with a moisture content of 1, 2 and 3 % measured at 20°C, [3]. Figure 14 shows the dissipation factor of solely oil with a conductivity of 1 pS/m measured at 20°C. Note, that at low frequencies the losses are much higher compared to pressboard and that the dissipation factor is just a line with a slope of -20 dB / decade, which is due to the fact that insulation oil shows conductive behavior nearly without polarization processes.

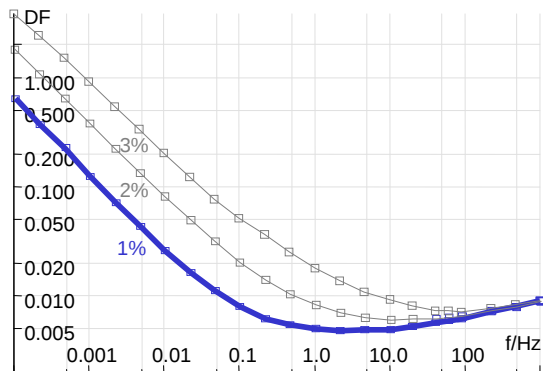


Figure 13: Dissipation factor of pressboard only having moisture contents of 1, 2 and 3 %

The dielectric properties of pressboard and oil are superimposed together with the interfacial polarization process. Interfacial polarization is typical for non-

homogeneous dielectrics with different permittivity or conductivity. Here charge carriers such as ions accumulate at the interfaces, forming clouds with a dipole-like behavior. This kind of polarization is effective only below some ten Hertz.

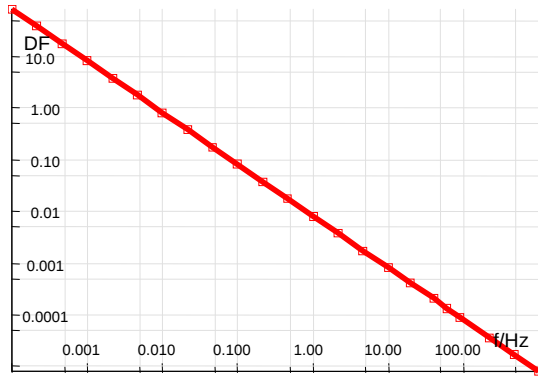


Figure 14: Dissipation factor of oil only having a conductivity of 1 pS/m at 20°C

Figure 15 displays the dissipation factor of pressboard having 1 % moisture content and oil together with the interfacial polarization effect (insulation geometry). The frequency range of 1000-10 Hz is dominated by the cellulose insulation, however also the measurement cables and the connection technique influence this region. Oil conductivity causes the steep slope at 1-0.01 Hz. Dissolved conductive aging by-products, soot and high molecular weight acids increase the oil conductivity and thus influence this area. The interfacial polarization (insulation geometry, ratio of oil to pressboard) determines the local maximum or "hump" at 0.003 Hz. The higher the ratio of oil to pressboard, the more dominating is this effect. Finally, the properties of the cellulose appear again at the frequencies below 0.0005 Hz, here reflecting moisture, the manufacturing process and low molecular weight acids. The frequency limits correspond to Figure 15, but will vary in a wide range with moisture, oil conductivity, insulation geometry, temperature and amount of conductive aging by-products.

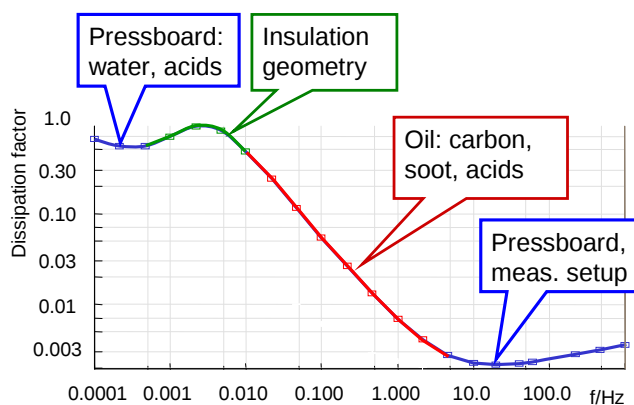


Figure 15: Dissipation factor of pressboard and oil together with the interfacial polarization effect (insulation geometry)

3.2 The effect of moisture

Moisture particularly increases the losses in the low frequency range of the dielectric response of pressboard. Thus, the point of inflexion on the left hand side of the area dominated by insulation geometry is required for a reliable moisture determination.

Since pressboard also dominates the high frequency area above 10 Hz in Figure 15, it might appear that it is sufficient to measure this frequency range. However, moisture especially affects the low frequency branch of the dissipation factor curve. Figure 13 illustrates, that the high frequency part of the dissipation factor curve is very similar for various moisture contents, but the low frequency part differs. Additionally, the measurement circuit effects especially this high frequency part of the dielectric response.

With increasing moisture content and oil conductivity, the curve shifts toward higher frequencies, but the shape remains similar. Figure 16 depicts the dissipation factor over frequency for 3 % moisture content and 10 pS/m oil conductivity at 20°C insulation temperature.

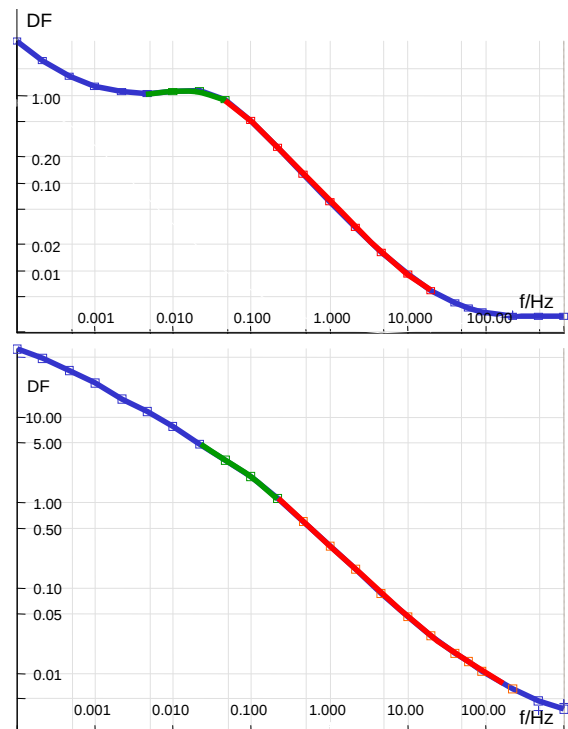


Figure 16: Dissipation factor of an oil-paper-insulation at 20°C insulation temperature with pressboard having 3 % moisture content and oil with a conductivity of 10 pS/m (upper figure) and the same insulation at 50°C with a corresponding oil conductivity of 43 pS/m (lower figure)

Figure 16 illustrates also the influence of temperature on the same insulation system. At 50°C the losses of pressboard along with the oil conductivity increase while the shape of the curve remains similar.

3.3 Case study: new transformers

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. Figure 17 depicts the dielectric response in the representation of dissipation factor over frequency. Transformer A shows much lower losses than transformer B, so from a first glance at the dissipation factor one may conclude that the second transformer is in a 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 13). Moisture analysis software actually determined the moisture content in the cellulosic insulation of both transformers to be 0,4 %, 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).

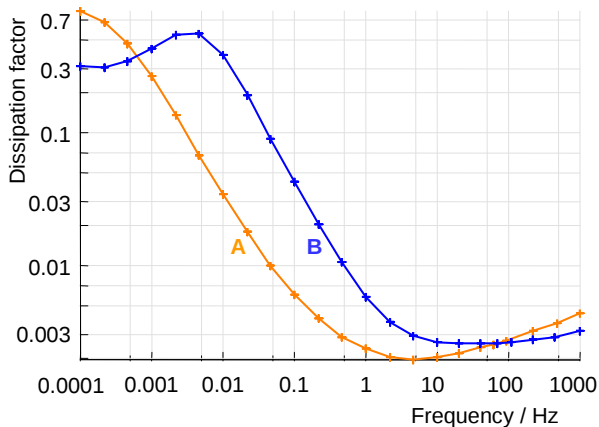


Figure 17: Dissipation factor over frequency for two new transformers

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.

4 CONCLUSIONS

This paper discusses two topics related to the dielectric response of power transformers: the reasons for the occasionally appearing negative dissipation factor and the proper interpretation of the dielectric response. The findings are:

- The typical measurement circuit for the interwinding capacitance C_{HL} forms a frequency dependent bridge because of the winding-to-tank capacitances C_L and C_H together with the guard. Since the current and the voltage are not directly measured at the interwinding impedance C_{HL} , the dissipation factor can now become negative. The circuit forms a quadrupole instead of a two terminal network.

- The higher the capacitance C_L and C_H in relation to the desired capacitance C_{HL} , the likelier appears a negative dissipation factor.
- The higher the guard resistance and the instruments input resistance, the likelier appears a negative dissipation factor.
- The resistivity of the winding-to-tank insulation R_L and R_H as well as the inductance of the guard wire and the instruments input are of negligible influence.
- The inductance of the windings may cause errors in case they are not properly short-circuited.
- The accuracy of the simulations allows for a qualitative evaluation only, for quantitative use a more sophisticated network would be needed.

As for the interpretation of the dielectric response:

- A clear separation of the contributions by the solid insulation, the insulating liquid and the interfacial polarisation effect is possible by conducting the dissipation factor over a very wide frequency range, e.g. 1000 Hz to 0,1 mHz. The necessary frequency range decreases for hot or wet insulations, e.g. 1000 Hz to 10 mHz.
- A case study demonstrates that particularly for new transformers, the very low frequencies are important for moisture analysis using dielectric response methods. Limiting the frequency range would make the discrimination between the conditions of oil and cellulose impossible.
- For determining water, the low frequencies are of highest importance because they are most sensitive to moisture.
- The very low frequencies are secondly not effected by the surrounding measurement circuit, as the simulations and measurements show.
- For a fast, time-saving measurement of the dielectric response, the combination of time and frequency domain appears to be advantageous [4].

5 REFERENCES

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