Advanced Insulation Diagnostic by Dielectric Spectroscopy

By

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Abstract

This paper discusses and compares dielectric spectroscopy in time and frequency domain to traditional dielectric measurements such as dielectric dissipation factor at power frequency and polarization index.

Condition assessment of oil-paper-insulated power transformers, particularly of water content, is becoming increasingly important for aged transformers and also for quality control of new transformers in the factory. The demand for sophisticated and at the same time reliable and easy to use diagnostic techniques drove the development of dielectric response methods. The first approach, called Recovery Voltage Method, is now outdated. The newer methods, Polarization and Depolarization Currents and Frequency Domain Spectroscopy, have proven their suitability for transformer diagnostics and are now frequently used.

This paper describes in detail the interpretation of dielectric response measurements in frequency domain. Since especially the low frequencies reflect water concentration, their measurement is of outmost importance for reliable data analysis. Beside a frequency sweep, the response of a dielectric to a voltage sweep is experimentally investigated and discussed.

Special focus is given on a comparison of the currently available dielectric spectroscopy methods to traditional measurement techniques like dielectric dissipation factor tests at power frequency and 0.1 Hz, dielectric adsorption ratio and the polarization index. The traditional methods suffer from a limited time or frequency range which impedes the discrimination of specific dielectric properties. If for example increased losses appear, it is impossible to discriminate whether they are caused by the insulating oil or the cellulose insulation. Examples of Dielectric Spectroscopy transformer measurements illustrate the advantages of analysis in a wide frequency range.

Introduction to Electrical Insulation Tests

Power transformers are the most expensive links in the chain of transmission network for electrical energy connecting generation to utilization. Nowadays three factors stress them: the increased demand for electrical energy, whereas the average age of transformers increases as well and maintenance strategies change forced by the cost pressure in liberalized energy markets. Electric utilities try to suspend the investment in new devices and shift maintenance from time based to condition based strategies. To realize this strategy the demand for new diagnostic methods arises, methods which reliably evaluate the actual condition of the equipment.

Transformer Aging as a Worldwide Issue. In all developed countries large proportions of the transformer fleets are approaching the end of their design life. For example in the United States the average age of large electrical transformers is 35 years; the design life is 40 to 50 years [1]. The authors conclude: “The data we see indicates that of the 110’000+ large electrical transformers installed in the United States, up to 2 % will fail this year; that is 2200 transformers. … Utilities need quality, reliable, maintenance free solutions that provide timely information on the transformers health.” Economical interests boost this statement and it mirrors a worldwide trend.

In Germany, a recent investigation found the average age of transformers for 110 kV rated voltage is 31 years, for 220 kV 34 years and for 380 kV 30 years, [2]. Figure 1 illustrates failures of power transformers classified by voltage level and inducing subsystem and the dependence on operating time. It is important to precisely know the error rate of the equipment and develop appropriate diagnostic procedures.

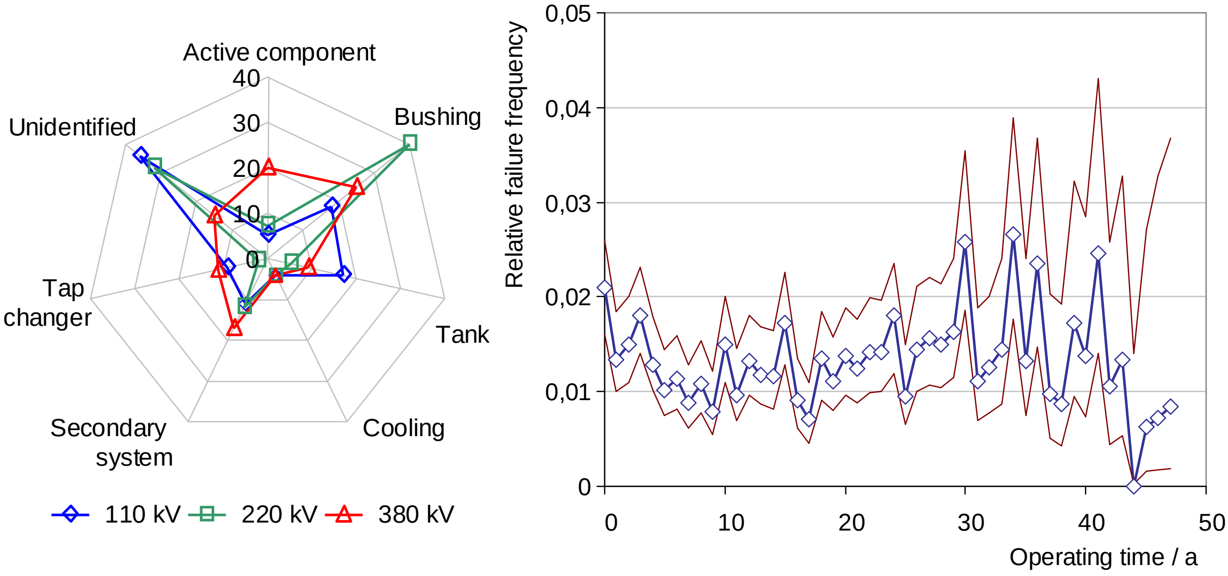

Figure 1:
Failures at power transformers classified by voltage level and location (left) and as a function of operating time (right). For the relative failure frequency a 90 %-confidence interval is depicted as well.

Electrical insulation tests are able to detect probable failures of the active component, mainly the insulation system and of the bushings. Therefore, researchers looked for decades for methods to find out the condition and the aging state of the insulation system. The dissipation or power factor has been used for decades to evaluate the losses in insulation materials. Figure 2 illustrates the equivalent circuit for losses in insulation materials and the corresponding vector diagram. Any solid or liquid insulation can be modeled by a capacitance C, representing the "ideal" behavior of insulation, and a resistor R, representing the electrical losses. The dissipation factor $\tan \delta$ indicates the quality of insulation materials by the tangent of the ratio of resistive current I_R to capacitive current I_C. The power factor is the cosine of the ratio of resistive current I_R to total current I. For small angles, dissipation and power factor are identical.

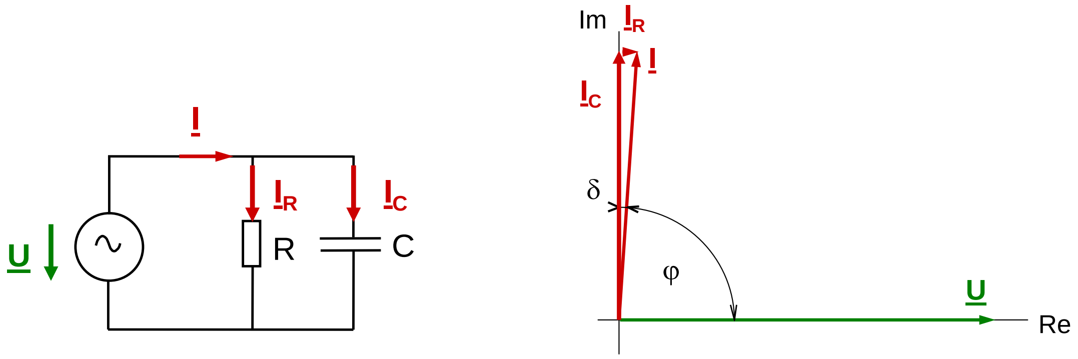

Figure 2: Equivalent circuit for insulation materials (left) and corresponding vector diagram

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 describes the current state of knowledge about the frequency and voltage dependent characteristics of oil-paper-insulations; it then lists the available measurement methods with their specific advantages and compares them at practical study cases.

Dielectric Behavior of Oil-Paper-Insulations

Response to a Frequency Sweep

Applying a frequency sweep over a very wide range means to measure 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.

Superposition of Dielectric Properties. Figure 3 (left) displays the dissipation factor of only pressboard with a moisture content of 1, 2 and 3 % measured at 20°C. Figure 3 (right) 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.

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.

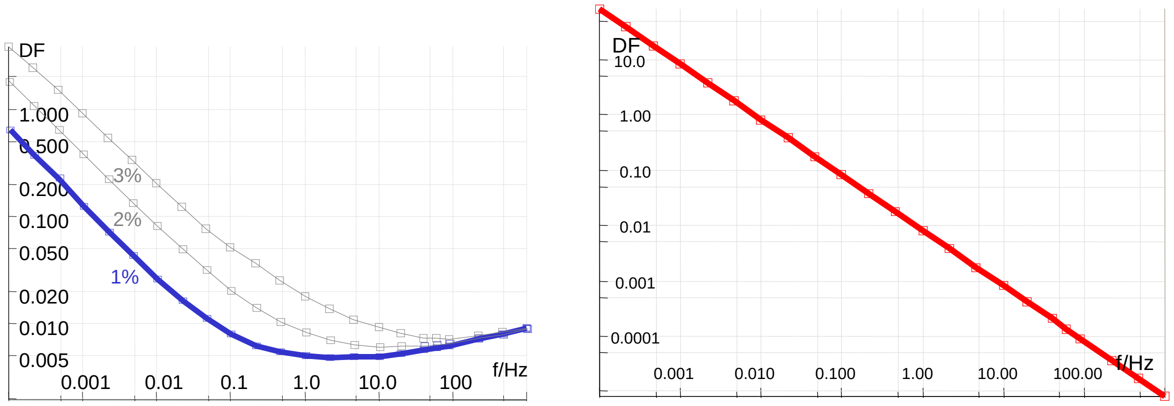

Figure 3:
Dissipation factor of pressboard only having moisture contents of 1, 2 and 3 % (left) and dissipation factor of oil only having a conductivity of 1 pS/m at 20°C

Figure 4 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 4, but will vary in a wide range with moisture, oil conductivity, insulation geometry, temperature and amount of conductive aging by-products.

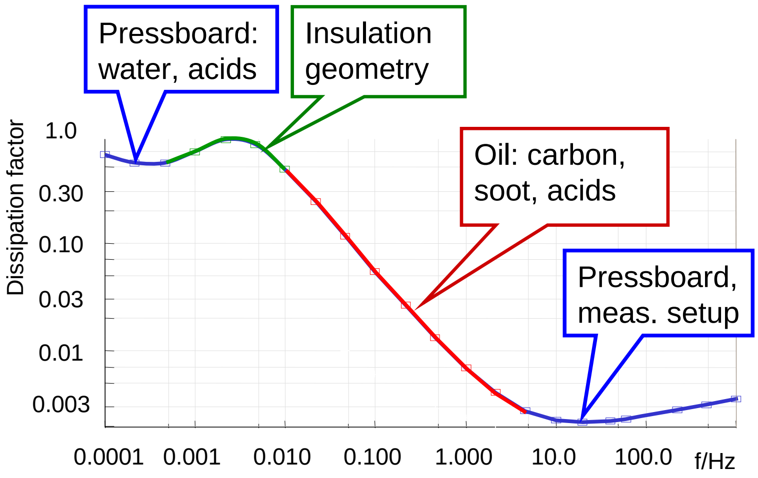

Figure 4:
Dissipation factor of pressboard and oil together with the interfacial polarization effect (insulation geometry)

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 4, 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 3 illustrates, that the high frequency part of the dissipation factor curve is very similar for various moisture contents, but the low frequency part differs. Consequently, if the measurement range is restricted to the high frequencies, the accuracy of water determination will be very low allowing only for a rough discrimination between wet and dry.

With increasing moisture content and oil conductivity, the curve shifts toward higher frequencies, but the shape remains similar. Figure 5 (left) depicts the dissipation factor over frequency for 3 % moisture content and 10 pS/m oil conductivity at 20°C insulation temperature.

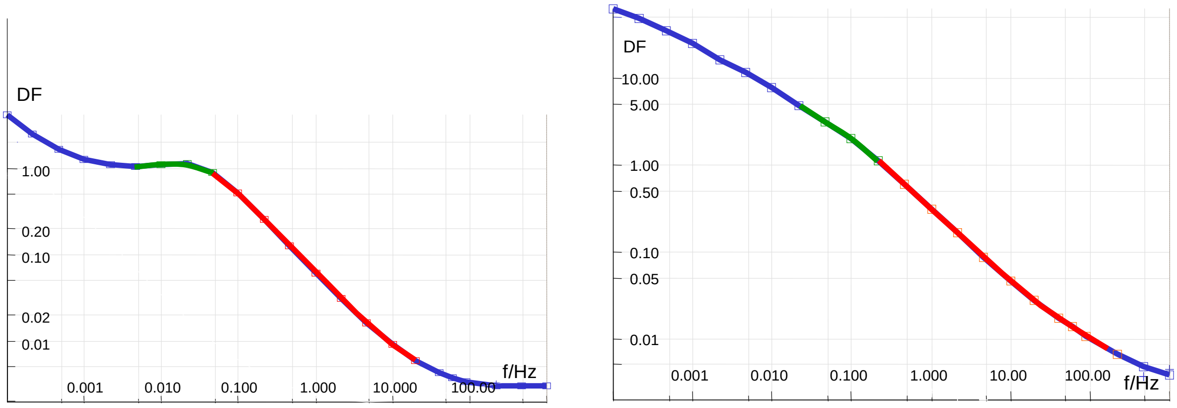

Figure 5:
Dissipation factor of an oil-paper-insulation at 20°C insulation temperature with pressboard having 3 % moisture content and oil with a conductivity of 10 pS/m (left) and the same insulation at 50°C with a corresponding oil conductivity of 43 pS/m (right)

The Effect of Temperature. Figure 5 (right) illustrates 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.

Conclusively, a frequency sweep of dissipation factor of oil-paper-insulations as depicted in Figure 4 and Figure 5 provides information about the pressboard, the oil and the interfacial polarization effect.

Response to a Voltage Sweep

Applying a voltage sweep on oil-paper-insulations is an old diagnostic procedure and also known as "tip-up test". This variation of the conventional capacitance and dissipation factor measurement makes use of the fact that the power or dissipation factor will change with applied AC voltage. Here the test voltage is increased from e.g. 6 kV to 36 kV and the dissipation factor recorded. The frequency is kept constant at e.g. 0.1 Hz. According to the common interpretation, the magnitude of change indicates aging of the insulation.

To investigate what insulation properties are reflected by a voltage sweep, a large insulation model called “Pancake Model” was used, [3]. The model consists of eight pancake shaped coils with oil ducts between them. The ratio of barriers and spacers to oil ranged from 15 to 90 %, simulating the main insulation of different transformer geometries. Service-aged transformer oil (conductivity 16.5 pS/m) filled the tank. The moisture content in cellulose was 1.1 %, measured at paper and pressboard samples.

Figure 6 (left) displays the dissipation factor at 0.1 Hz as a function of voltage for various ratios of oil to pressboard; that is 15-90 %. From the results it becomes obvious, that a high amount of oil increases the dissipation factor. A measurement of dissipation factor on a single frequency point will reflect not only the material condition (e.g. aging) but also the insulation geometry. The diagram further depicts the voltage dependence of the dissipation factor. It becomes obvious, that a high amount of oil increases the voltage dependence. Figure 6 (right) proves this assumption. Here the dissipation factor of oil alone is depicted as a function of the applied field strength; the higher the field strength, the lower the dissipation factor. In science, this effect is known as Garton effect [4]. The dissipation factor of insulation oil itself depends on conductive aging by-products such as soot, acids and moisture [5].

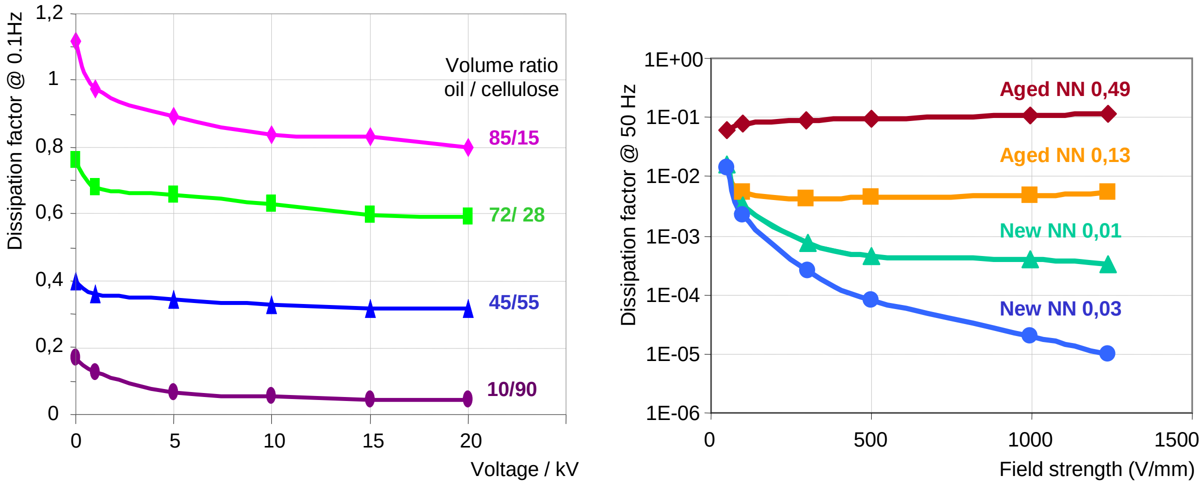

Figure 6:
Dissipation factor at 0.1 Hz for the various insulation geometries of the pancake model (left) and dissipation factor of four oils with various aging condition and acidity (neutralization number NN) depending on applied field strength (right)

Conclusively, a voltage sweep of dissipation factor at a power transformer mainly reflects the condition and voltage dependence of the oil in conjunction with the insulation geometry.

Electrical Insulation Test Methods

Capacitance, Dissipation or Power Factor Measurement at Mains Frequency

The dissipation or power factor at one single frequency point has been used for decades to classify insulation materials. Standards give various limits for power and dissipation factor. For example [6] states that in case of new oil-filled transformers and reactors, the power factor should not exceed 0.005. It further recommends for most older transformers a power factor of < 0.005, power factors between 0.005 and 0.01 may be acceptable; power factors > 0.01 should be investigated.

The first instrument to measure an unknown capacitance and its dissipation factor was the Schering Bridge. This is basically a four-arm alternating-current (AC) bridge circuit whose measurement depends on balancing the loads on its arms. For easier balancing of the bridge a high measurement voltage of some kV was required and for practical reasons the frequency was mostly limited to power frequency. These historical conjunctures found its way into standards and field test practices, where a test voltage of typically 10 kV and a limited frequency range close to power frequency are used.

Application for Power Transformers. Figure 7 depicts the dissipation factor for a new, a moderately aged and a heavily aged transformer at similar temperatures around 25°C. As it can be seen, the dissipation factor at power frequency (50-60 Hz) will reflect the cellulose insulation for the new transformer and the condition of the oil for the moderately aged and the aged transformer. A dissipation factor measurement at 0.1 Hz reflects the oil for the new and the moderately aged transformer while it shows the cellulose for the heavily aged transformer. Conclusively, dissipation factor measurements at one single frequency enable only for a limited assessment of the insulation condition, a discrimination of the various effects is impossible.

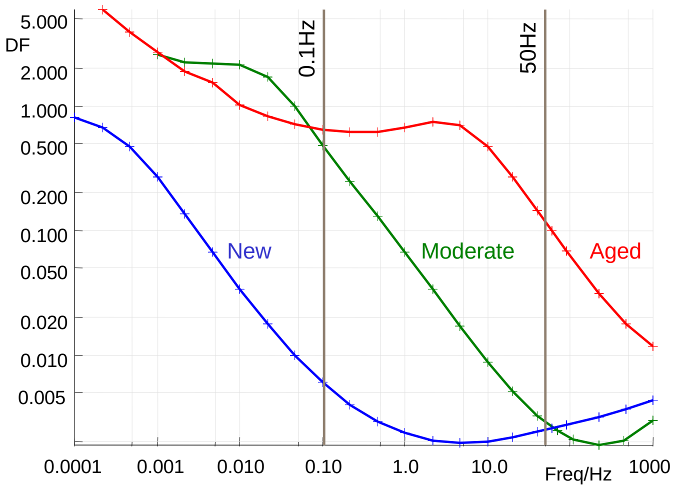

Figure 7:
Dissipation factor of three transformers in different aging conditions

Voltage Sweep – Tip Up Test. Here the test voltage is increased up to several kV and the dissipation factor recorded. According to the common interpretation, the magnitude of change indicates aging of the insulation. Looking at Figure 7, the voltage sweep will stress different materials depending on the condition of the dielectric. For the depicted new transformer, the voltage sweep at power frequency will test the pressboard; resulting in a low voltage dependence of the dissipation factor. For the transformer in "moderate" condition, a mixture of oil and solid insulation will be stressed; the voltage dependence will be more distinct. Finally, the "aged" transformer will show the strongest voltage dependence of dissipation factor since here the oil area is exposed to the electric field.

Another issue related to voltage sweeps is the dimension of the tested insulation. It is not the voltage itself that causes the effects, but the field strength. The field strength depends on the geometry of the tested insulation (gap between conductors), which is unknown to the tester. For a narrow gap, the stress will be high but low for a large gap. Therefore it would be more meaningful to make a field strength sweep. Since the geometric conditions of the insulation are almost always unavailable, the voltage sweep is of limited benefit for transformer insulations. For bushings, on the other hand, a high voltage sweep can indicate partial breakdowns and a defective connection to the outer capacitive layer.

Dielectric Absorption Ratio and Polarization Index

The dielectric absorption ratio DAR relates the DC resistance measured at 60 s to that at 15 s; the polarization index is the ratio at 10 min to that of 1 min. Figure 8 (left) depicts the dielectric response of two new transformers in frequency domain. For transformer B, the polarization index mirrors the insulation geometry whereas for transformer A it shows the influence of the oil. The polarization index of transformer B is worse than that of A. On the other hand, the moisture content of both transformers was identical with 0.4 %. The differences in the dielectric response arise from different oil qualities, not from the insulation dryness.

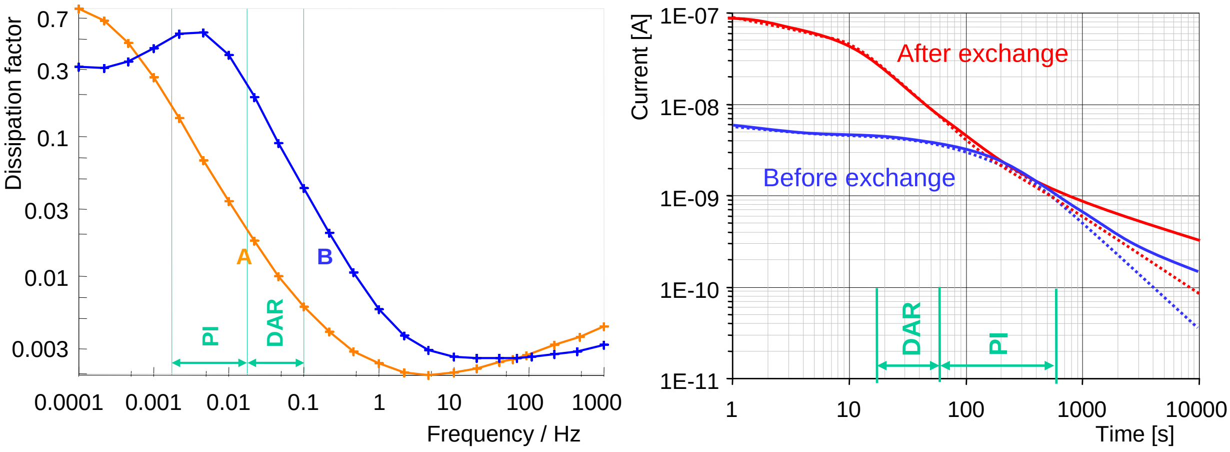

Figure 8:
Dielectric absorption ratio DAR and polarization index PI with the dielectric response of two new transformers in frequency domain (left) and with the influence of an oil exchange in time domain (right)

A second test led to similar results. For the large insulation model as described at Figure 6 and [3], the original oil having a conductivity of 1.6 pS/m was exchanged by aged oil with 16.5 pS/m. The moisture content of the cellulose insulation remained unchanged at 1.1 %. Figure 8 (right) shows the polarization and depolarization currents in both conditions and also the dielectric absorption ratio and the polarization index. Due to the oil exchange, the DAR increased from 1.25 to 4.43 and the PI from 3.69 to 6.34 although the moisture content remained identical. The increased oil conductivity caused this dramatic change. As a higher DAR and PI are considered to be better, these parameters actually call the transformer filled with bad oil better than one with new oil.

Both values, PI and DAR, are defined for the narrow time range which is dominated by oil conductivity and are unable to discriminate between the influence of the different materials and the interfacial polarization effect, which is similar to conventional dissipation factor tests.

Methods Applying a Frequency Sweep

Frequency Sweep Close to Power Frequency. Newer diagnostic methods involve a frequency sweep around power frequency for gathering more information about the insulation condition. Figure 9 (left) shows the measurement circuit of a recent dissipation factor bridge. In contrast to the traditional Schering Bridge the currents are measured directly, no balancing path is used and the bridge is frequency independent. The diagram of Figure 9 (right) depicts the dissipation factor of the HV-LV capacitance C_{HL}, the HV-tank capacitance C_H and the LV-tank capacitance C_L of a new transformer. On the background of the interpretation scheme of Figure 3 this measurement mainly reflects the pressboard. Towards the low frequencies also some influence of the oil becomes visible.

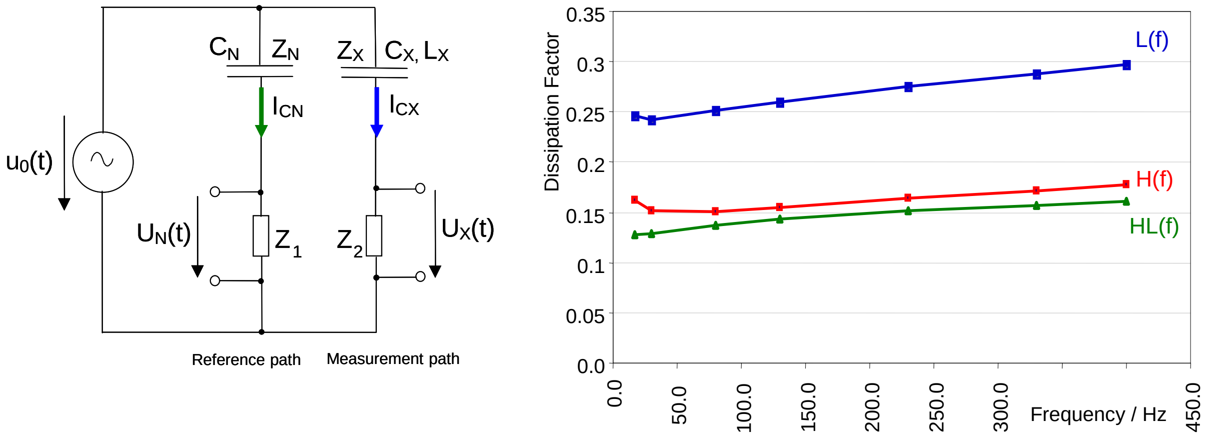

Figure 9:
Measurement circuit of a recent dissipation factor bridge (left) and dissipation factor of C_{HL}, C_H and C_L of a new power transformer (right)

Such combination of frequency sweep with high measurement voltage unites the advantages of frequency sweep and measurement voltage; however the narrow frequency range limits the validity.

Dielectric Spectroscopy – Dielectric Response Measurement

Dielectric spectroscopy conducts the properties of insulation systems across a wide frequency range of e.g. 1000 Hz to 0.0001 Hz. This frequency span over 7 decades enables for discrimination between different effects and finally allows for the determination of moisture in the solid insulation. Measurements in time and frequency domain have been used for one decade. Today, a new device combines the advantages of both measurement domains in order to have a very fast measurement particularly of the low frequencies, Figure 10. An advanced analysis algorithm not only calculates the moisture content but also compensates for other conductive aging by-products [7].

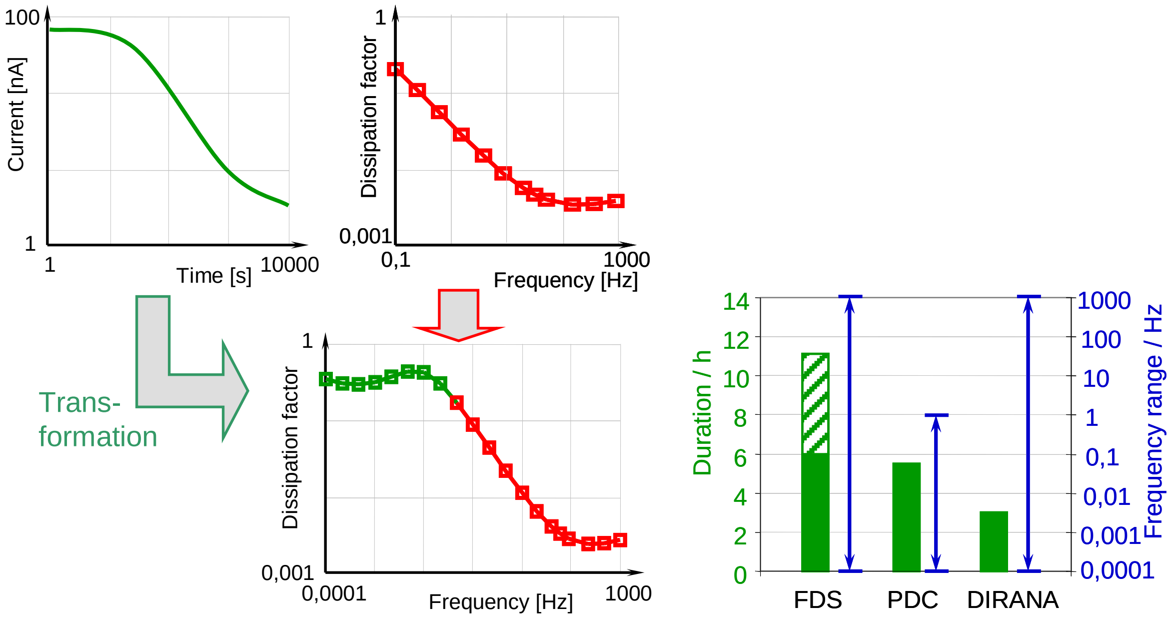

Figure 10:
Combination of time and frequency domain measurements (left) and required time duration and acquired frequency range for the different measurement techniques (right)

According to the current state of science, dielectric spectroscopy allows for the most comprehensive diagnostic and evaluation of insulation systems.

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Biography

Maik Koch leads the product management for HV testing equipment of Omicron Energy, Austria. He graduated as a Doctor of Philosophy at the University of Stuttgart in Germany in 2008. His fields of research are ageing and moisture determination in power transformers using chemical and dielectric analysis methods. He collaborates in working groups of Cigrè and IEEE.

Michael Krueger is head of the OMICRON competence center primary testing.

He studied electrical engineering at the University of Aachen (RWTH) and the University of Kaiserslautern (Germany) and graduated in 1976 (Dipl.-Ing.). In 1990 he received the Dr. techn. from the University of Vienna. Michael Krueger has 30 years experience in high voltage engineering and insulation diagnosis. He is member of VDE, Cigré and IEEE.

Markus Puetter is product manager for primary testing solutions at OMICRON energy, for the CPC100 product family and the dissipation / power factor measuring system MI600. He has 10 years experience in developing primary testing solutions for high voltage equipment. He studied electrical engineering at the University of Paderborn / Soest and graduated in 1976 (Dipl.-Ing.).

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