

# Information within the Dielectric Response of Power Transformers for Wide Frequency Ranges

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**Abstract** – Dielectric response analysis of power transformers in the frequency domain is being used widely to diagnose its ageing condition and moisture content. The Frequency Domain Spectroscopy (FDS) measurements are normally carried out between 1 kHz and 100  $\mu$ Hz. As low frequency measurements result in long measuring times, measurements in a higher frequency range were investigated to determine their suitability for ageing diagnostics. Unfortunately, winding resonance effects were noticed at higher frequencies and it appears that the response at higher frequencies is not purely of dielectric nature. Higher frequencies are therefore unsuitable to determine the insulation ageing of power transformers. For low frequencies, the dielectric response reflects the properties of the oil, the interfacial polarization effect and the cellulose material. Conducting the measurement over a wide frequency range enables for discriminating between these different properties and increases the accuracy of moisture calculation. However, the frequency range depends on the insulation condition so that new, dry insulations require a very low stop frequency (e.g. 100  $\mu$ Hz) while for conductive (wet, hot) insulations 10 mHz can be sufficient.

**Index Terms** — moisture determination, oil-paper insulation, dielectric response, frequency domain spectroscopy

## I. INTRODUCTION TO DIELECTRIC RESPONSE ANALYSIS

In recent years, diagnostics to determine the state of a power transformer has become more and more important due to technical and economical reasons. The main concern for a power transformer is its insulation system (oil-impregnated-paper, OIP), which essentially determines its lifetime. Dielectric response analysis is an offline diagnostic method which basically measures the complex capacitance and dielectric dissipation factor of the insulation within a very wide frequency range and subsequently calculates the moisture content [1].

Due to the necessity of shutting down the transformer, the time duration of dielectric response measurements is also a cost factor. For identifying the necessary frequency range – and therefore the time need – the information within the dielectric response was investigated. The first chapter of this paper goes towards the higher frequencies of more than 1 kHz.

Particularly for this frequency range, very few references can be found in the literature.

The second part details the physical reasons for the typical s-shaped dissipation factor curve of power transformer insulations for frequencies below 50 Hz and derives the necessary frequency range. Examples of field measurements conclude the paper.

## II. DIELECTRIC MEASUREMENTS AT HIGH FREQUENCIES

### A. Measurements on Oil-Paper-Insulation Models

In order to determine the dielectric response of power transformers at higher frequencies, it was quintessential to understand the dielectric response of the insulating materials which build the insulation system of a transformer namely oil and cellulose [2], [3]. Laboratory measurements were therefore conducted on an oil-paper-insulation model. The cellulose material with predetermined moisture was impregnated with oil and kept in a climate chamber to control temperature. Dielectric measurements were then carried out using Novocontrol Dielectric Analyzer (Alpha-A) at various temperatures (Figure 1).

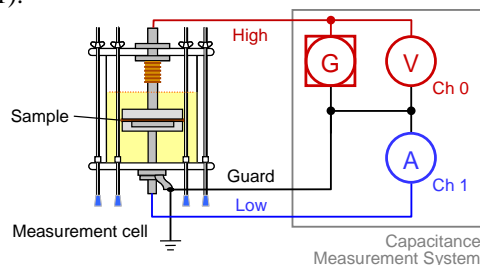


Figure 1: Test setup for the dielectric response measurements on pressboard samples

The response shows the typical S-shaped curves one normally obtains from FDS measurements. An example is shown in Figure 2 for a moisture content of 5 %. For this set-up, no unknown effects were noticed in the higher frequency region above 1 kHz.

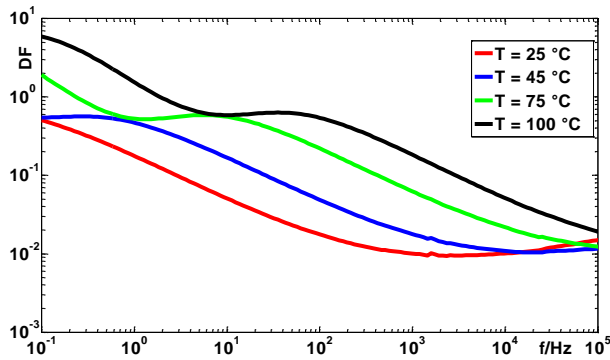


Figure 2: Dissipation factor of oil impregnated pressboard with 5% moisture content for various temperatures

### B. Measurements on a distribution Transformer

The dielectric response of a transformer insulation system was then measured on various distribution transformers. Figure 3 represents one of these measurements on a distribution transformer manufactured in 1974, 400 kVA, 20/0.4 kV. Up till around 1 kHz the dissipation factor shows the expected dielectric behavior. At higher frequencies resonance occurrences were noticed which were not detected with a conventional FDS measurement. The dissipation factor rises rapidly culminating in resonance peaks between 10 kHz and 100 kHz. This type of resonance occurrences were noticed on all the measured distribution transformers.

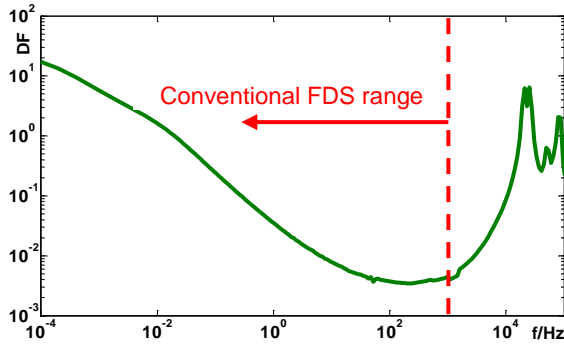


Figure 3: Dissipation factor of a distribution transformer with the extended frequency range above 1 kHz

### C. Measurements on a transformer winding/coil model

In order to obtain a better understanding of the occurring resonance effects, a transformer model was built. Copper Coils were used as these have very low inductances. Spacers and cellulose were placed between the coils to exemplify the transformer insulation. An existing HV-Winding from a distribution transformer was also used together in this test setup. The whole setup was then immersed in insulating oil.

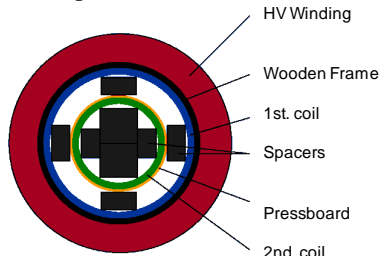


Figure 4: Replica of windings and main insulation duct of a power transformer

The dielectric response was measured for various different configurations:

- HV Winding – 1<sup>st</sup> coil
- HV Winding – 2<sup>nd</sup> coil
- 1<sup>st</sup> Coil – 2<sup>nd</sup> coil

The obtained dielectric response from the test setup is shown in Figure 5. Resonance occurrences similar to those from the distribution transformer could be seen for the measurement HV-1<sup>st</sup> coil. These resonance peaks are somewhat reduced and shifted on the frequency axis for the measurement HV-2<sup>nd</sup> coil. The measurement 1<sup>st</sup> coil-2<sup>nd</sup> coil however shows no such resonance effects. Merely a small peak could be noticed. Measurements after removing the HV-Winding from the test setup showed no such peaks. It seems that the resonance effects were caused by the presence of the coil and as such is not a part of the dielectric behavior of oil-paper insulation system.

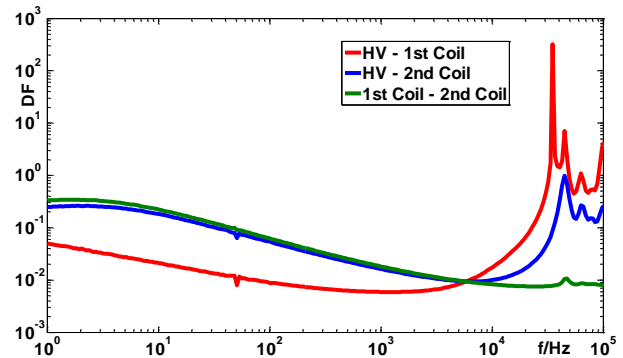


Figure 5: Dissipation factor characteristics for the main insulation duct model

### D. Measurements on HV OIP-Apparatus

The dielectric response obtained from the distribution transformer and the insulation duct model was then compared with those from a large power transformer.

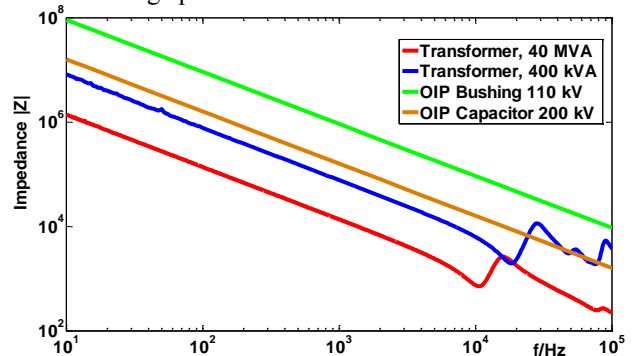


Figure 6: Comparison of the dielectric response of various HV-apparatus with OIP insulation

The on-site measurements were carried out using FRA (Sweep Frequency Response Analysis) equipment which obtains impedance curves of the device under test. Nevertheless the results from the distribution transformer are also shown in the impedance form instead of the dissipation factor for better comparison. The dielectric responses of HV-Apparatus with OIP insulation but without coil systems for example bushings and capacitors were also measured. These dielectric responses are shown in Figure 6.

It is noticed that resonance peaks similar to those obtained from the distribution transformer (blue line) also occur on large power transformers. The shift in the frequency axis could be caused by the larger inductance that the large transformer possesses. If one compares the transformer response with a bushing or capacitor, it can be seen that the latter show no signs of resonance occurrences, as one would expect from a purely dielectric response.

### III. INTERPRETATION OF THE DIELECTRIC RESPONSE AT LOW FREQUENCIES

#### A. Superposition of dielectric properties

This section describes the physical background for the typical s-shaped dielectric response of transformer insulations by looking at the contribution of the single materials and their superposition to the overall response. Figure 7 displays the dissipation factor of a cellulose material (pressboard) with a moisture content of 1, 2 and 3 % measured at 20°C. The setup used for these measurements shows Figure 1. Pressboard samples were impregnated with oil and water was added, until the desired moisture content was reached. The samples were then measured in a guarded cell, placed in a climatic chamber; details on sample preparation are given in [4].

For frequencies above 1 Hz the curve is flat, which means polarization effects dominate the response. For lower frequencies, losses dominate the response resulting in a steep increase in dissipation factor. This area is particularly sensitive to moisture while the high frequency part does not show such sensitivity.

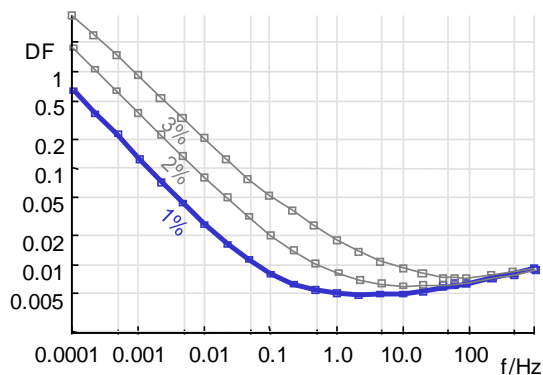


Figure 7: Dissipation factor of pressboard only having moisture contents of 1, 2 and 3 %

Figure 8 shows the dissipation factor of only oil with a conductivity of 0.01, 1 and 100 pS/m measured at 20°C. These measurements were conducted in a shielded measurement cell according to IEC 247, [4]. At low frequencies, the losses of the oil are much higher compared to pressboard and the dissipation factor is just a line with a slope of  $-20$  dB / decade. For mineral oil, the conductive losses dominate the dielectric response.

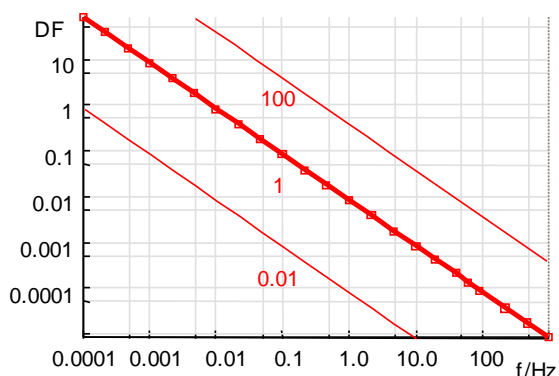


Figure 8: Dissipation factor of oil only having a conductivity of 0.01, 1 and 100 pS/m at 20°C

The dielectric properties of pressboard and oil are superimposed together with the interfacial polarization process. Interfacial polarization is typical for non-homogeneous dielectrics and originates from differences in permittivity and conductivity. Charge carriers such as ions accumulate at the interfaces, forming clouds with a dipole-like behavior. In principle, this kind of polarization is effective only below some ten Hertz. The larger the difference, the more intense is the effect. For example, highly conductive oil with cellulose materials of low conductivity (dryness) will show a very dominant interfacial polarization effect. Further, the effect depends on the volume ratio of the two involved materials, namely oil and cellulose, and therefore on the insulation geometry of the power transformer. Figure 9 illustrates the calculation result of this effect for a ratio of barriers to oil of 30 %, of spacers to oil of 15 %, an oil conductivity of 1 pS/m and moisture content in pressboard of 1 %.

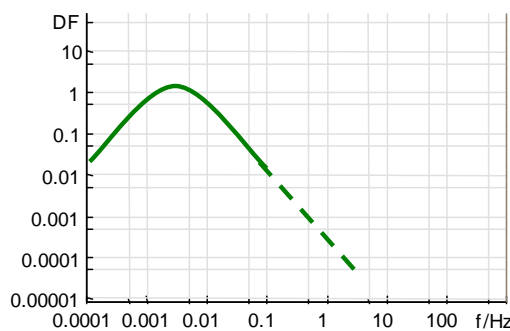


Figure 9: Interfacial polarization between liquid and solid insulation

Figure 10 displays the dissipation factor of pressboard having 1 % moisture content and oil of 1 pS/m conductivity together with the interfacial polarization effect (insulation geometry). Figure 10 and Figure 11 are calculated by software based on the so called XY-model, which models the superposition of oil and pressboard together with the interfacial polarization process. Cigré Task Force D1.01.09 proposed the use of this model, [1].

The frequency range of 1000-10 Hz is dominated by the cellulose insulation, however also the inductances of the coils, the measurement cables and the connection technique influence this region. Oil conductivity causes the steep slope at 1-0.01 Hz. Dissolved conductive ageing 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, low molecular weight acids and other conductive ageing by-products. The frequency limits correspond to Figure 10, but will vary in a wide range with moisture, oil conductivity, insulation geometry, temperature and amount of conductive ageing by-products.

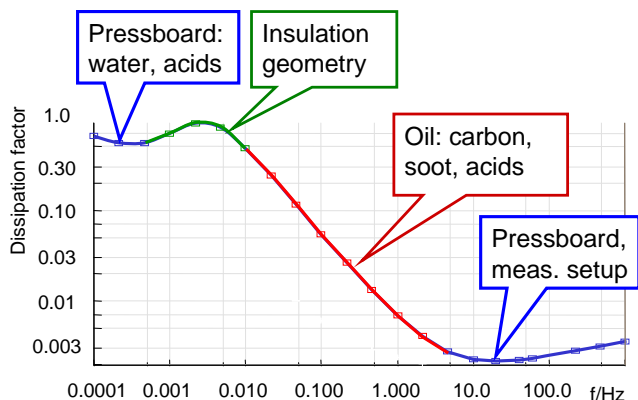


Figure 10: Dissipation factor of pressboard and oil together with the interfacial polarization effect (insulation geometry)

### B. 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 10, 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 7 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 11 depicts the dissipation factor over frequency for 3 % moisture content and 10 pS/m oil conductivity at 20°C insulation temperature.

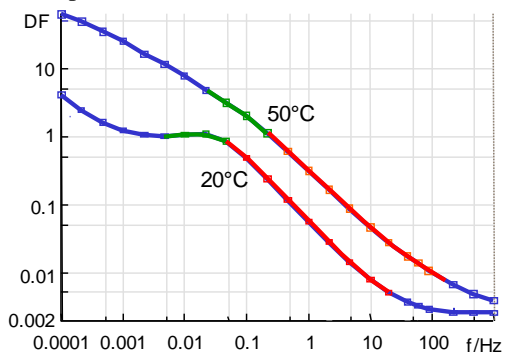


Figure 11: Dissipation factor of an oil-paper-insulation at 20°C insulation temperature with pressboard having 3 % moisture content and oil with a

conductivity of 10 pS/m and the same insulation at 50°C with a corresponding oil conductivity of 43 pS/m

Figure 11 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.

If determination of moisture is the aim of dielectric response, the necessary frequency range depends on ageing state and the temperature (losses) of the insulation system. For new, dry transformers a stop frequency of 0.1 mHz is required while for wet, hot transformers 10 mHz deliver sufficient information for reliable moisture analysis.

### C. Oil Removal for a Large Power Transformer

A large power transformer (manufactured in 1963, 100 MVA, 220/110/10 kV) was designated for scrapping so the oil was drained out. The dielectric response was measured before and after oil removal to illustrate the effect of oil. Figure 12 displays the dielectric response as dissipation factor. Since the measurement temperatures were different with 22 and 10°C, the curves need to be temperature-corrected for 10°C. For the measurement with oil a large "hump" is visible, originating from the interfacial polarization effect (insulation geometry), while it nearly disappears for the measurement without oil. For the latter, the cellulose material dominates the dielectric response.

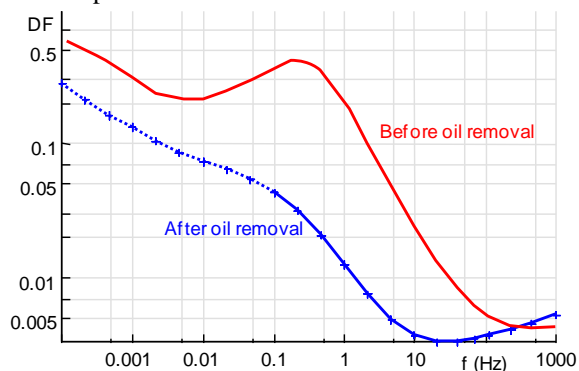


Figure 12: Dissipation factor for a large power transformer before and after oil removal at 10°C

### D. Influence of Insulation Geometry and Oil Conductivity on a Large Insulation Model

An insulation model of the size of a large distribution transformer contains four different geometric set-ups and allows for demonstrating the influence of insulation geometry resp. interfacial polarization. The four set-ups have a volume ratio of oil to cellulose of 85/15, 75/25, 50/50 and 15/85 %. Additionally to the influence of geometry, that of oil conductivity was investigated by exchanging the original oil (1.1 pS/m) by more conductive oil (13 pS/m). During all investigations, the water content in cellulose remained at 1.0-1.1 %.

Figure 13 proves that with an increasing amount of oil, the interfacial polarization process is more prominent and the dielectric properties of the cellulose insulation are for a large frequency range hidden behind the oil and the interfacial polarization effect.

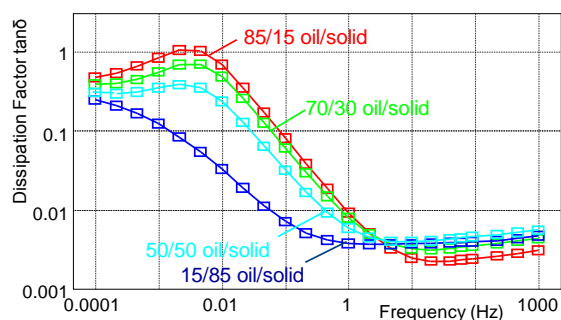


Figure 13: Influence of interfacial polarization (insulation geometry) on the dielectric response

Figure 14 shows the influence of oil conductivity on the dielectric response of the set-ups having a ratio of oil to cellulose of 75/25 and of 15/85. For the ratio of 75/25, the oil area (steep increase of dissipation factor between 10 and 0.01 Hz) of the dielectric response shifts towards higher frequencies due to the oil exchange. For the ratio 15/85 the change is less dominant, however since the oil penetrates the cellulose it also changes its dielectric behavior.

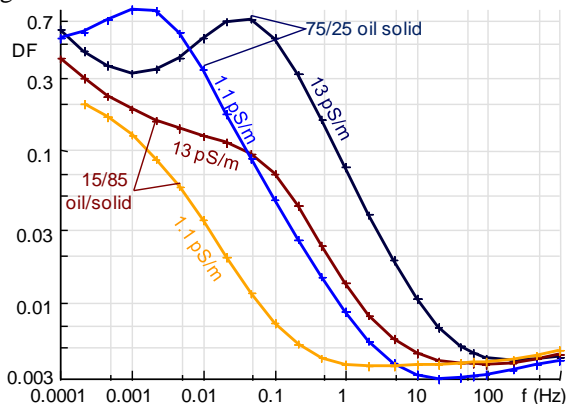


Figure 14: Influence of oil conductivity on the dielectric response for a ratio of oil to cellulose of 75/25 % and 15/85 %

#### E. Accuracy of Moisture Analysis

The dielectric response of the model with four insulation geometries as described above was measured for a frequency range of 1 kHz-1 mHz and for 1 kHz-0.1 mHz, that is one additional decade towards lower frequencies. Automatic analysis software [5] calculated the moisture content for the four geometries and the two different frequency ranges for the four geometries and the two different frequency ranges. Figure 15 demonstrates how the limitation of the stop frequency to 1 mHz decreases the accuracy of moisture determination: The calculated moisture content in cellulose depends now on geometry and is higher than the true moisture content of 1.0-1.1 %. Since the geometry has been known, this information was provided to the software. Not having this information – as it is typical for on-site assessment of power transformers – would result in a higher degree of uncertainty for moisture analysis. Measuring down to 0.1 mHz makes the analysis independent from geometry and the moisture result more consistent. Conclusively; the wider the acquired frequency range, particularly towards the low frequencies, the higher is the accuracy of moisture analysis.

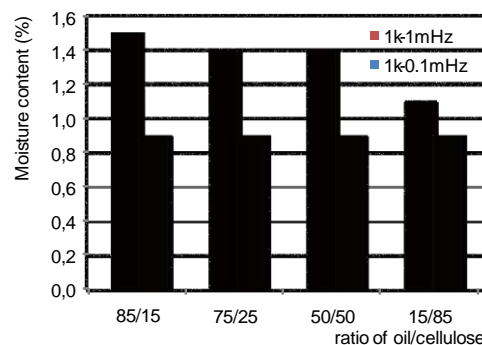


Figure 15: Results of automatic moisture analysis for a frequency range of 1 kHz – 1 mHz and for 1 kHz – 0.1 mHz

#### IV. CONCLUSIONS

In the higher frequency range, winding resonances dominate the dielectric response. Although the corresponding high or low voltage coils are short-circuited for the FDS measurements, this is not adequate to prevent the observed resonances as depicted in Figure 3. The resonances are probably caused by the interference of the coil inductance with the interwinding capacitance. Measurement results published in [3] support this assumption. As resonances occur in the higher frequency dielectric response of power transformers, this range should not be used to estimate the ageing condition of the dielectric of power transformers.

As for the interpretation of the dielectric response at low frequencies one can conclude: A clear separation of the contributions by the solid insulation, the insulating liquid and the interfacial polarization 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. For determining water, the low frequencies are of highest importance because they are most sensitive to moisture. These are secondly not effected by the surrounding measurement circuit and the coil inductances. For a fast, time-saving measurement of the dielectric response, the combination of time and frequency domain appears to be advantageous [6].

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