INTERPRETATION OF THE DIELECTRIC RESPONSE OF INSTRUMENT TRANSFORMERS, BUSHINGS, CABLES, ROTATING MACHINES AND POWER TRANSFORMERS

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Abstract: This paper describes the physical background of the dielectric response for different insulation systems as instrument transformers, bushings, rotating machines and power transformers, derives the necessary frequency range and provides guidance for correct interpretation. For any type of insulation consisting of oil and paper, existing analysis principles can be applied; just the modeling needs to be adapted to the new application. This is the case for OIP bushings, OIP cables, current transformers and voltage transformers. The paper describes these needed adaptations of the modeling for correct analysis of such insulations and for calculation of the water concentration. In contrary to oil-paper insulation systems, rotating machines consist of different insulation materials like VPI resin and asphalt. Here, the effect of ageing is not well understood and moisture plays a minor role. Therefore analysis is based on a qualitative comparison of actual data to historically obtained values. All conclusions are based on measurements on laboratory models as well as on wide experiences gathered with real HV equipment.

1 INTRODUCTION

In recent years, dielectric response analysis has been proven as a reliable analysis tool for assessing the ageing condition of power transformers. Dielectric response analysis measures dielectric properties of insulation systems over a very wide frequency or time range and calculates condition variables like oil conductivity and insulation wetness by use of mathematical modelling, [1]. It is applied as a non-intrusive on-site test for periodical assessments of the aging condition of insulation systems. The following list gives an overview on the historical development of the method.

1920 Schering Bridge. Looking at its historical development, one can understand dielectric response analysis as a successor of the well-known dissipation factor test, used for quality assessment in the factory and condition monitoring on-site. The German professor Harald Schering published the related technique already in 1920, [2].

1991 Recovery Voltage Method RVM. When the first dielectric response method, called RVM, became known to the public, it received wide attention since it claimed to determine the moisture content in the cellulose material of power transformers, [3]. However, the related interpretation scheme is today known to be "not correct", [1].

1998 Polarization and Depolarization Currents PDC. Based on extensive research at the ETH Zurich, the PDC method was developed featuring a scientifically approved interpretation scheme, [4]. It measured charging and discharging currents in time domain from 1 s to 1000 s and concentrated on the application for power transformers.

2000 Frequency Domain Spectroscopy FDS. The FDS measures the dielectric response in frequency domain (1000-0,001 Hz), was first developed for cables [5] and today features a scientifically approved interpretation scheme for power transformers as well.

2008 Combination of PDC and FDS. With the aim of saving measurement time, two dielectric response techniques were combined and an approach for compensating for conductive ageing by-products other than water introduced, [6].

Today, more and more efforts are undertaken to widen the application range to other high voltage equipment as instrument transformers, bushings, cables and rotating machines. This paper depicts the measurement circuit for each application and tries to give a general interpretation of the dielectric response for the different insulation systems.

Basically, discrimination is possible between homogeneous and inhomogeneous insulation systems. An oil-paper insulated power transformer is a typical inhomogeneous insulation system, where the main insulation consists of paper, pressboard barriers and distinctive oil gaps. In contrast to this, the insulation systems of all other HV equipment in the scope of this investigation may be considered as being homogeneous. Here, one material dominates the dielectric response; whereas the others are negligible.

2 POWER TRANSFORMERS

2.1 Measurement Circuit

A dielectric response measurement is a three terminal measurement that includes the output voltage, the sensed current and a guard. The guarding technique insures for an undisturbed measurement even at onsite conditions with dirty insulations and electromagnetic interferences. For two winding transformers, the voltage output is connected to the HV winding, the current input to the LV winding and the guard to the tank. Figure 1 depicts the main capacitances of a two winding power transformer as well as a connected instrument for measuring C_{HL}.

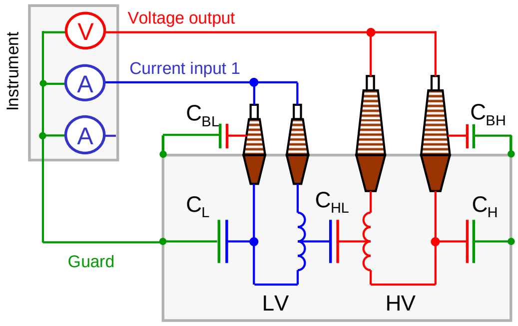

Figure 1: Capacitances and measurement circuit for a two winding transformer

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.

The test can be performed in

- Time domain while applying a DC voltage. The corresponding technique is called Polarization and Depolarization Currents PDC.
- Frequency Domain while applying an AC voltage leading to Frequency Domain Spectroscopy FDS or Dielectric Frequency Response DFR.

Both test techniques reflect the same fundamental polarization and conduction mechanisms and can be combined.

2.2 Interpretation

The main insulation of power transformers consists basically of two materials, the liquid insulation (mineral oil) and the solid insulation (paper and pressboard). These two have individual dielectric responses, but the superposition of oil gaps and pressboard barriers results in a third effect; the interfacial polarization. Each phenomenon dominates a certain frequency range.

Figure 2 depicts the dielectric response of cellulose insulation (paper, pressboard), measured at defined temperature (22°C) and water contents (1, 2 and 3 %) in the laboratory, [2]. For the 1 % curve, polarization dominates the frequencies from 1 kHz to 1 Hz, whereas for lower frequencies conduction mechanisms dominate the response, seen from the slop of the dissipation factor curve.

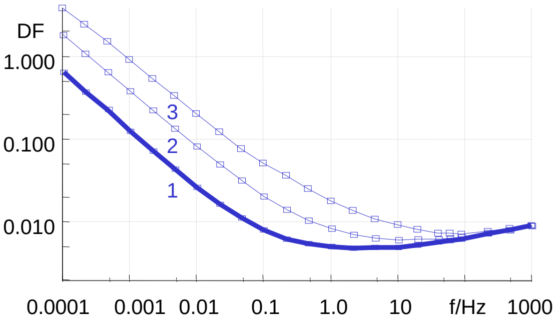

Figure 2: Dielectric response for paper/pressboard with 1, 2 and 3 % water content at 22°C

In contrast to cellulose materials, the oil shows only conductive behaviour, where the dissipation factor shows a slope of -1/decade over the whole frequency range, Figure 3. These measurement results were obtained in shielded cells under laboratory conditions, [6].

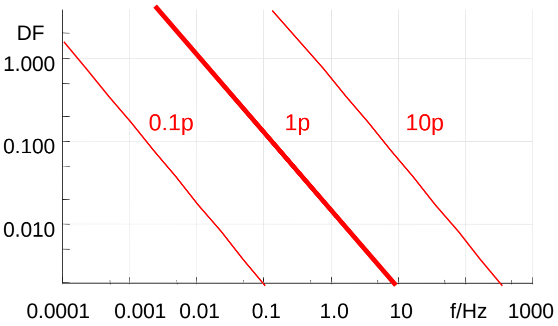

Figure 3: Dielectric response of oil with 0,1; 1 and 10 pS/m

Figure 4 shows the dielectric response of an oil-paper insulated power transformer with the common interpretation of different frequency ranges. In the following explanations we will try to elucidate the physical background of the curve shape.

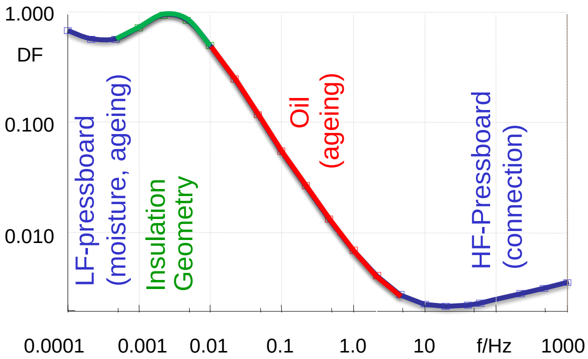

Figure 4: Typical interpretation of the dielectric response of oil-paper insulated power transformers

For increasing the clarity of the explanations, the so-called XY model will be used. The XY model tries to emulate the behaviour of the main insulation gap, where the relative amount of barriers is accumulated to the parameter X and the relative amount of spacers/sticks is accumulated to Y, Figure 5.

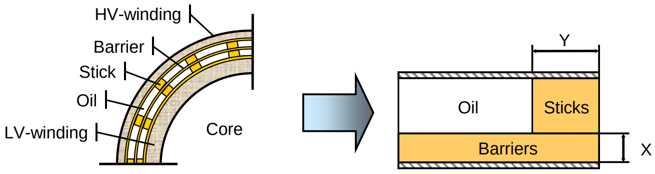

Figure 5: Representation of a cylindrical transformer insulation by the XY-model

HF Pressboard Region: In the high frequency pressboard region (here 5-1000 Hz), the losses in the solid insulation are higher than these in the oil, so the currents flow through sticks and spacers from HV to LV winding, Figure 6. Though this region gives information about the cellulose material, its sensitivity to moisture is small, as Figure 2 illustrates.

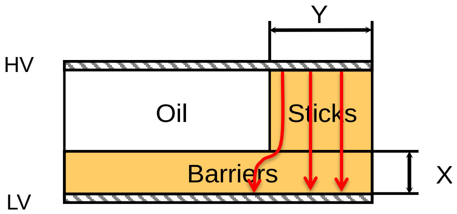

Figure 6: Current distribution for high frequencies

Oil Region: With decreasing frequency, the losses in the oil are higher than these in the sticks; therefore the currents tend to flow through the oil gap into the barriers, Figure 7. Because of the bigger volume (ca. 75 %) and the much higher conductivity (10-100fold) this area is dominated by the oil. It is worthy to note that the slope in this area is not identical to that of oil only since part of the current path consists of barriers having lower conductivity.

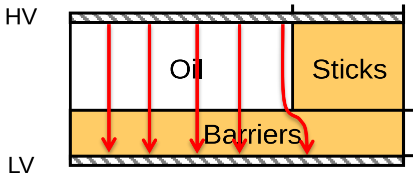

Figure 7: Current distribution for middle frequencies, i.e. the oil region

Insulation Geometry: With further decreasing frequency, here 0,01-0,005 Hz, space charges become accumulated in the oil gaps. These lower the conductivity of the oil channels so that currents flow partly through oil, partly through sticks into barriers, Figure 8. The accumulation of space charges can also be understood as interfacial polarization. This area is heavily influenced by the transformers insulation geometry (design) and ratio of conductivity and permittivity of the two involved materials (oil / cellulose). The larger the difference in conductivity and the more oil is present in relation to cellulose; the higher is this loss peak in the dissipation factor curve,

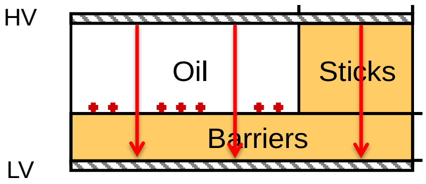

Figure 8: Space charges influence current distribution at low frequencies

Low Frequency Pressboard: If frequency decreases further (here below 0.005 Hz), space charges in oil ducts dramatically decrease the oil ducts conductivity, therefore the currents flow through sticks and barriers; i.e. in the cellulose material, Figure 9. In contrast to the high frequency pressboard area, this area shows highest sensitivity to conductive components as moisture and ageing by-products in the pressboard and paper, compare Figure 4. For diagnostic testing of power transformers, this frequency range should be part of the test record.

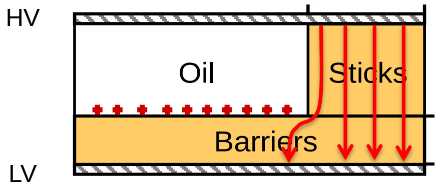

Figure 9: Current distribution for very low frequencies down to DC

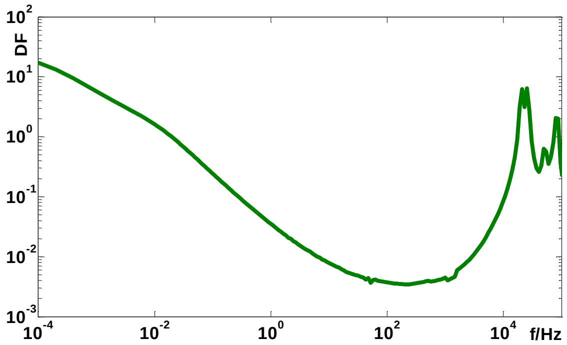

Figure 10: Dissipation factor for up to 100 kHz with resonancies for f > 2 kHz

It might be of the readers interest to see if higher frequencies than the here used 1 kHz give further information about the insulation condition. The authors of [7] found that above around 5 kHz resonancies between the insulation capacitance and the coils inductance dominate the measurement result and impede with interpretations regarding insulation ageing, Figure 10. However, this is the range where another diagnostic method, Frequency Response Analysis FRA, detects mechanical deformations in transformers.

Two remarks should complete the explanations:

Firstly, the position of the indicated areas (pressboard, oil etc.) changes with different conductivity and permittivity so that they shift along frequency axis. For example, for systems of low conductivity (low losses, low temperature, low water content), the characteristics appear only at very low frequencies, while it is for systems with high losses (aged transformers) the characteristics appear for higher frequencies; thus a stop frequency of 0,1 Hz may be sufficient in certain cases.

Secondly, the representation as dissipation factor does not allow for clear discrimination between polarizability and conductivity. Therefore the representation of real part and losses of permittivity $\varepsilon = \varepsilon' - j\varepsilon''$ should be used, which on the other hand results in a loss of clarity.

2.3 Case Study: 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; Figure 11 illustrates the effect of the oil. Since the measurement temperatures were different with 22 and 10°C, the curves needed to be temperature-corrected for 10°C. For the measurement with oil a distinctive maximum 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 determines the dielectric response over the whole frequency range.

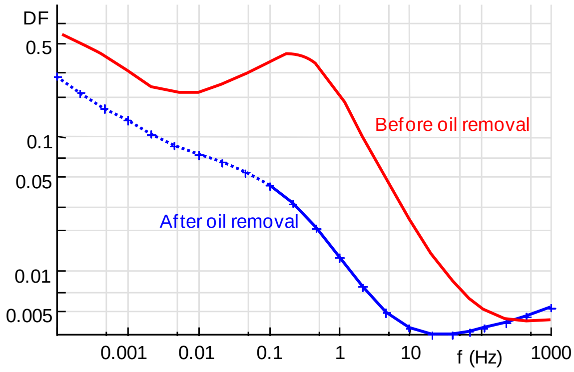

Figure 11: Dissipation factor for a large power transformer before and after oil removal at 10°C

3 INSTRUMENT TRANSFORMERS

3.1 Measurement Circuit

The insulation of inductive current and voltage transformers having primary voltages of more than 110 kV consists of oil-impregnated paper, wrapped around the active part, with aluminium foils for field grading. Though there are various constructions of instrument transformers used, from the dielectric point of view they can be differentiated in such with shield between high and low voltage winding and such without shield. The shield is internally connected to the tank and thus makes the application of a guarded measurement impossible. Unfortunately, most instrument transformers are of the shield type design. Figure 12 depicts the connection diagram and the current paths in the insulation for a current transformer of the common bar primary, live tank design.

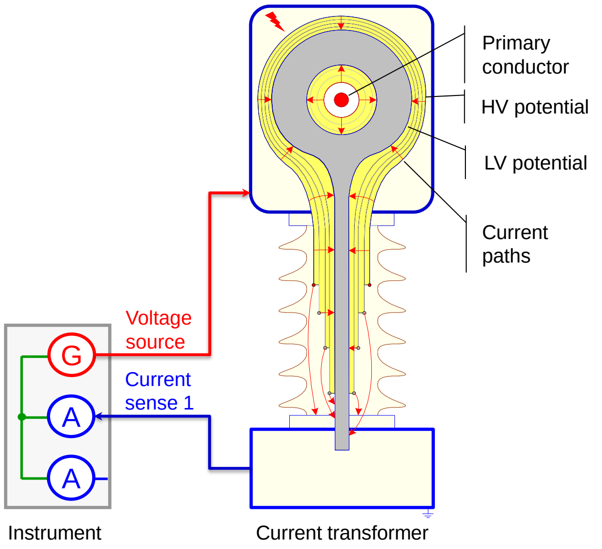

Figure 12: Connection diagram and current paths for dielectric response measurement on a CT

3.2 Interpretation

The main insulation of instrument transformers consist of oil-impregnated paper and, in contrast to power transformers, contains no explicit oil gaps. Figure 13 shows the dielectric response of instrument transformers in various ageing conditions. Due to homogeneous insulation design, the dielectric response equals that of paper / pressboard alone as already introduced in Figure 2. Conclusively, software packages for analysing the dielectric response of oil-paper insulations are able to interpret instrument transformers too. Limitations are seen in the influence of materials other than oil-impregnated paper, which are used to increase the short-circuit strength of these devices. Another conclusion from the absence of free oil gaps and interfacial polarisation is that the necessary frequency range for interpretation can be limited to 1 kHz to 10 mHz; which is in contrast to power transformers where much lower frequencies are needed.

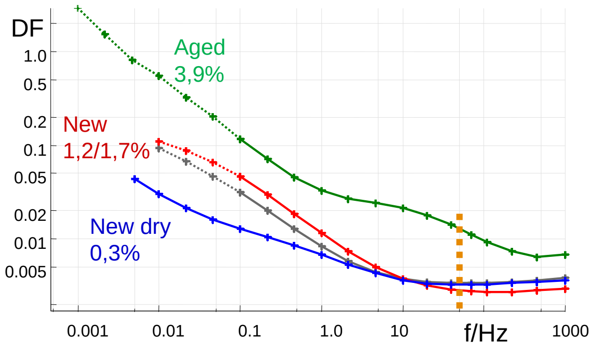

Figure 13: Dielectric response of instrument transformers with different moisture contents in paper

4 BUSHINGS

4.1 Measurement Circuit

All HV bushings are of condenser type, so conductive layers like aluminium foils grade the electric field. Most HV bushings of voltages above 110 kV feature measurement taps, there the last field grading layer is accessible. Then, for the typical measurement circuit, voltage is applied to the HV conductor, current is measured at the tap and the guard is connected to the flange; Figure 14.

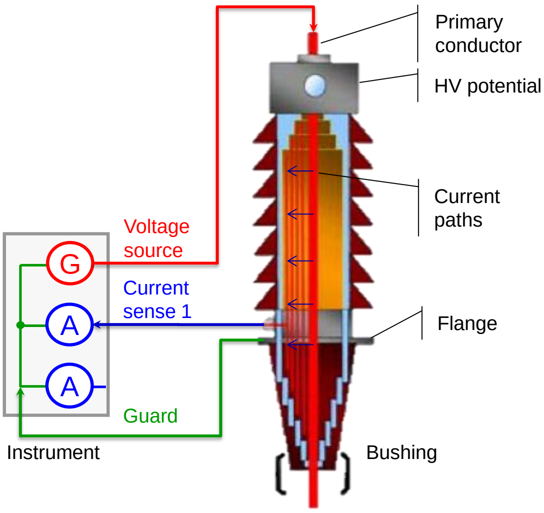

Figure 14: Measurement circuit for HV bushings

4.2 Interpretation

Regarding the insulation system, bushings can be discerned in three types: (1) Resin bonded paper type RBP, (2) Resin impregnated paper type RIP and (3) Oil impregnated paper type OIP bushings. Figure 15 displays measurement results for all bushing types. The dielectric of OIP bushings consists of oil-impregnated paper, wrapped around the HV conductor with field grading layers in between. Thus, the interpretation is similar as for oil-paper insulated instrument transformers and present interpretation software based on the XY-model can be used, Figure 5. For RBP and RIP bushings the moisture solubility is much smaller and failure modes are rather related to mechanical defects (cracks) and electrical ageing, detectable by partial discharge measurements. As for the necessary frequency range, due to the absence of oil gaps and of the interfacial polarisation process, the range 1 kHz-10 mHz is sufficient.

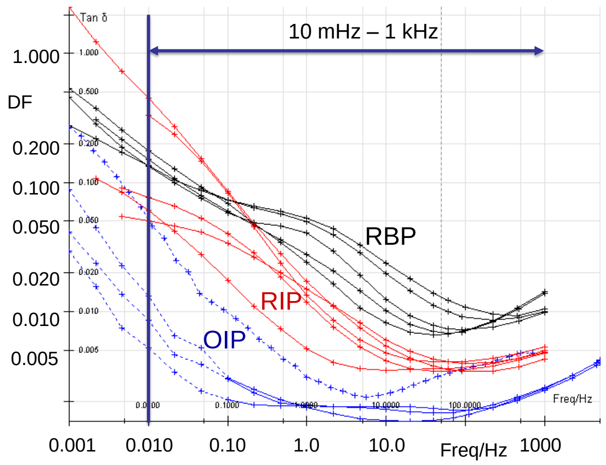

Figure 15: Typical dielectric responses for RBP, RIP and OIP bushings

5 CABLES

The dielectric of today's HV cables consists of oil-impregnated paper or cross-linked polyethylene XLPE. For oil-paper insulated cables, similar considerations apply as for other insulations consisting of oil-impregnated paper; due to the absence of major free oil gaps, interfacial polarization plays a secondary role and the moisture content can be analysed using software based on the XY model, Figure 5. For XLPE cables, electrical ageing mechanisms (e.g. water treeing) dominate over chemical mechanisms, therefore partial discharge measurements are of high significance. Generally, for all cables the dielectric dissipation factor has a limited significance because of its integral nature which may disregard local weak spots. Figure 16 depicts dielectric responses of various cables.

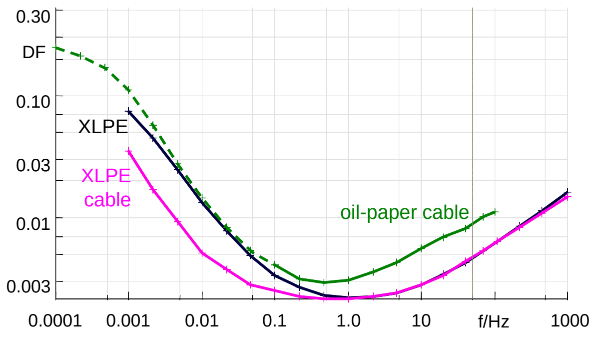

Figure 16: Dielectric Response of XLPE and oil-paper insulated cables

6 ROTATING MACHINES

6.1 Measurement Circuit

For a rotating machine, the winding-core insulation can be tested, which is the typical set-up, or the winding-winding insulation, showing more sensitivity to the insulation of the end windings. Figure 17 depicts the corresponding connection diagram, where voltage is applied to the core, currents are simultaneously measured from two windings and the third winding is guarded.

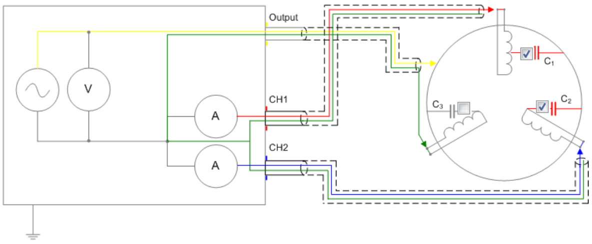

Figure 17: Set-up for winding-core measurements of a rotating machine

6.2 Interpretation

Typical insulation materials are vacuum pressure impregnation with resin (VPI) and asphalt for older machines. These materials tend to absorb only small quantities of moisture and the detection of local defects by partial discharge measurements are common practice. From a dielectric point of view the insulation can be considered as being homogeneous. Figure 18 depicts the dielectric response of a VPI resin insulated generator of 6 MVA with a winding-core capacitance of 160 nF and a winding-winding capacitance of 2,2 nF. It is remarkable that the curve shape is rather flat in comparison to oil-paper insulated equipment; for rotating machines polarization processes dominate the dielectric response. Attempts have been made to determine the influence of water, but more understanding is needed to understand the aging mechanisms and their effect on the dielectric response, [8]. Today, analysis is based on a qualitative comparison of actual data to historically obtained values.

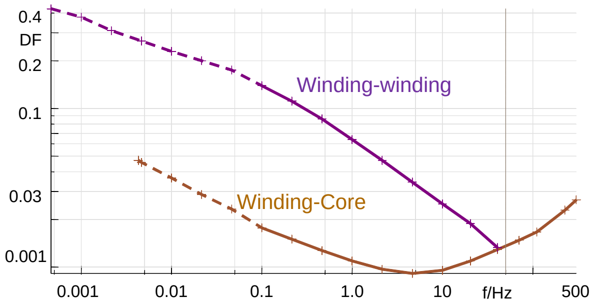

Figure 18: Dielectric response of a 6 MVA generator measured winding-core and winding-winding

7 CONCLUSION

Today, dielectric response analysis is applied to a variety of insulation systems. Best understanding for its interpretation has been accumulated for oil-paper insulated power transformers. Particularly for the analysis of insulation systems of different material, as e.g. rotating machines, more research and experiences are needed. The following table tries to give a review on the application areas of dielectric response analysis.

Criterion	*Power transformers*	*Instrument transformers*	*OIP Bushings*	*Rotating machines*
Material	Oil and paper /pressboard	Oil-impregnated paper	Oil-impregnated paper	VPI resin, asphalt
Features	Frequency dependent superposition of oil, cellulose and interfacial polarisation	Cellulose material dominates		VPI resin material dominates featuring high polarizability
Aging	Strong influence of moisture and other products			Small influence
Moisture determination	Possible with high certainty	Possible	Possible	Comparison with older tests
Necessary frequency range	1 kHz -100/ 0.05 mHz depending on condition	1 kHz - 10 mHz	1 kHz - 10 mHz	1 kHz - 10 mHz

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