NEW APPROACH TO ASSESS THE INSULATION CONDITION OF INSTRUMENT TRANSFORMERS

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Abstract: Dielectric response analysis is an advanced technique, providing information about the insulation condition of the measured test object. It is typically used for power transformers, where the water content in the solid cellulosic insulation can be assessed. Water in oil-paper/pressboard insulations is decreasing the dielectric strength, accelerating the ageing and causing the bubble effect at high temperatures. Also instrument transformers are oil-paper/pressboard insulated and therefore exposed to the harming effects of water. This paper introduces a new approach to use the dielectric response analysis for condition assessment of instrument transformers. A data analysis algorithm compares the measured dielectric properties of the actual instrument transformer to modelled dielectric properties. The modelling is described in concerns of water content, oil conductivity and geometry. To confirm the validity of this model, measurements on several instrument transformers in service were performed. The selected examples presented in this paper show, that the dielectric response is well modelled and the moisture content can be derived. Also ageing effects can be observed.

1 INTRODUCTION

Instrument transformers are important apparatuses used in transmission and distribution networks all over the world. Being not as expensive as e.g. power transformers, instrument transformers were rather replaced than repaired. However, a defect instrument transformer can explode, what may cause extensive damages of surrounding plant sections. The results of an international failure survey [1] show, that that ageing is still one of the main causes for failure besides design fault and inadequate manufacturing quality. To avoid failures with expensive secondary damages, several tests can be performed to determine the condition of instrument transformers. The choice of tests and the testing frequency is widely varying from utility to utility. In the mentioned survey also the used maintenance techniques prior failure are listed (Table 1).

Table 1: Maintenance strategy used prior to failure from 3004 reported failures [1]

Maintenance strategy	How often used
Regular visual inspection	95%
Check of oil level and/or pressure gauge	61%
Secondary voltage monitoring for CVTs	15%
Insulation resistance checks	11%
DGA and/or moisture of oil	7%
Thermovision inspection	4%
DF measurement at mains frequency	2%

Not all used techniques are adequate to prevent of failures caused by a bad insulation condition. The three mainly used techniques provide no or only limited information about the insulation condition. The insulation resistance can confirm ageing, but often only for extremely bad insulation condition. The DGA and moisture in oil is often avoided due to the limited available oil volume. The dissipation factor measurement can provide information about the insulation of instrument transformers. However, e.g. moisture, oil properties and temperature strongly influence the dissipation factor reading at mains frequency, what causes uncertainties in analysis. To overcome this issue, the dissipation factor measurement can be done in a wide frequency range. Using this so called dielectric response measurement it is possible to distinguish between different effects for a more detailed analysis of the insulation condition.

2 DIELECTRIC RESPONSE MEASUREMENT ON INSTRUMENT TRANSFORMERS

Dielectric response methods have been developed to deduce moisture in paper and pressboard from dielectric properties like polarization currents and dissipation factor [2]. They are typically used to assess the condition of power transformers, but can also be applied to other oil-paper/pressboard-insulations like bushings, cables or instrument transformers. Due to the wide frequency range it is possible to distinguish between different effects and gain information about the insulation condition itself, moisture in the solid insulation or oil conductivity [3].

2.1 Ageing and moisture in oil paper insulations

Common instrument transformers are oil paper isolated, which is ageing during their life span. The ageing of the insulation is depending on some influencing factors, like e.g. the temperature, present oxygen, water or acids (Table 2). Especially water in the solid insulation can be critical [4]. Existing water causes hydrolysis, which is the dominating ageing reaction and produces additional water as a chemical product (Figure 1). Therefore the water is a strong accelerator for ageing of the solid insulation.

Table 2: Overview about ageing mechanisms in cellulosic materials

Reaction	Oxidation	Hydrolysis	Pyrolysis
Condition	Oxygen	Water, acid	High temperature
Activation energy		37-163kJ/mol at W=4-0,5%	230 kJ/mol
Ageing products	Water, decreased DP	Furanes, water, decreased DP	Decreased DP, furanes, H_2O, acids, CO, CO_2

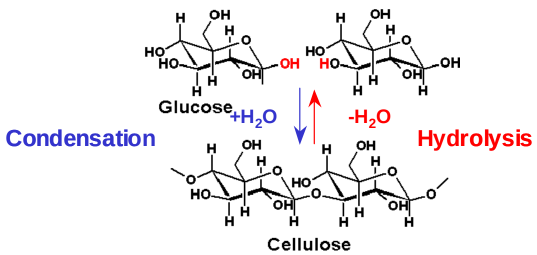

Figure 1: Schematic drawing of hydrolysis in cellulosic materials

Typically, new oil-paper-insulations have a very low water content of 0.5% or less in the solid insulation. During service the water content is increasing due to e.g. leakages and hydrolysis. Above 2.2% water content the solid insulation is called moderately wet [3], what is typical for instrument transformers being in service for several years. At the physically end of life, the insulation is often wet having a water content of 3.5% or above. Even though water content in the solid insulation is no direct measurand for ageing, it is a strong indicator for the condition of the solid insulation.

2.2 Dielectric response of instrument transformers

The setup for the dielectric response measurement is the same as for traditional dissipation factor measurement at mains frequencies. The resulting curves are similar to the single response of cellulosic material without any oil [5], since the insulation itself consists mainly of paper material. As it can be seen in Figure 2, the slope is rather flat and the influence of moisture is most obvious at low frequencies. Figure 3 shows the dielectric response curves of four current transformers of the same type. All of them were manufactured and in service since 1963, having nearly identical slopes, suggesting a similar ageing behaviour. Like for the cellulosic material only, the dielectric dissipation factor is decreasing with increasing frequency, usually having a minimum around 1-100 Hz. Especially at low frequencies, the slope of the curves seems to be linear.

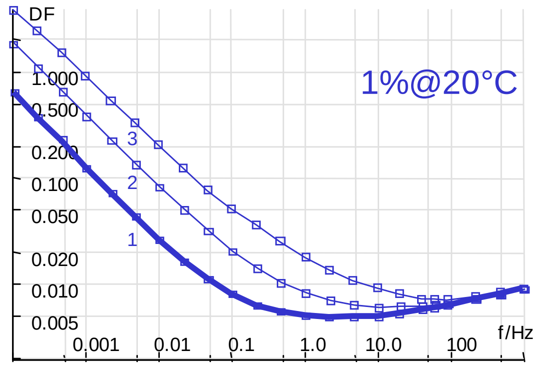

Figure 2: Dielectric response of cellulosic material at 20°C with 1% (2% and 3%) water content

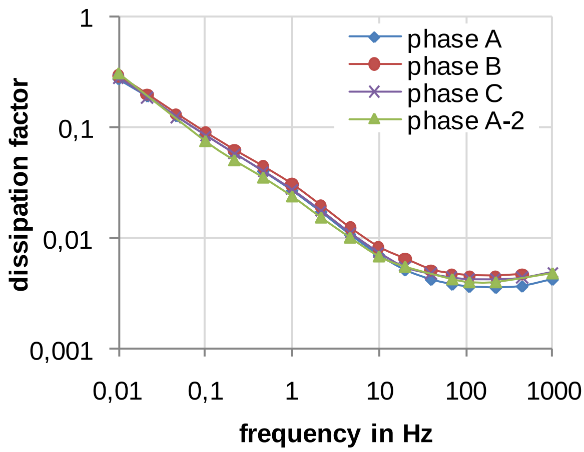

Figure 3: Dielectric response four current transformers of the same type, manufactured in 1963 (110N / 260kV), having a water content of 1.8 – 1.9% and an oil conductivity of 3 – 6 pS/m

Comparing instrument transformers of different age and condition (Figure 4), significant differences between the curves can be found. Newly manufactured and very dry instrument transformers have a very flat response. Both, water content and ageing result in a steeper slope at lower frequencies. However, the values for the dissipation factor at mains frequencies are in the same range as for new ones. Only for heavily aged and wet instrument transformers the dissipation factor at mains frequency is significantly enhanced. The slope of this curve clearly differs compared to the others. Having very high dissipation factors at all frequencies the curve shows a hump, which is not apparent for the other curves.

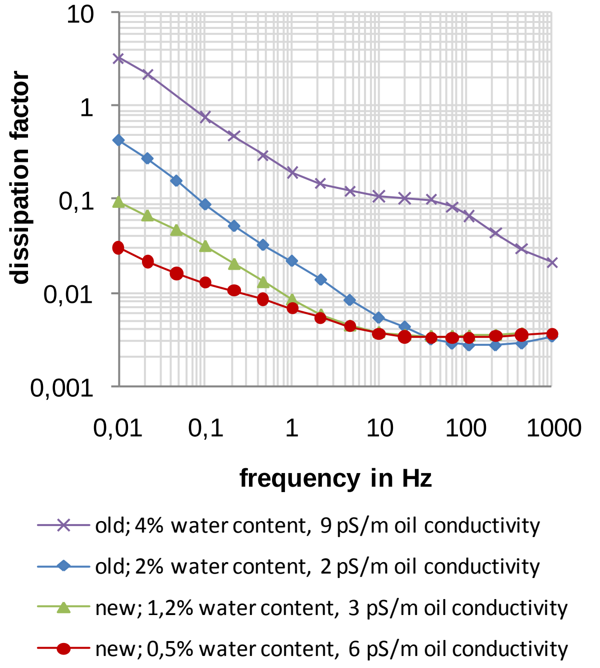

Figure 4: Dielectric response of instrument transformers of different age and condition

As for other oil-paper-insulations, different factors are influencing the curve. Besides moisture, these are mainly the temperature as well as the oil conductivity [6]. Higher temperatures and higher oil conductivities are shifting the curves towards higher frequencies (Figure 5).

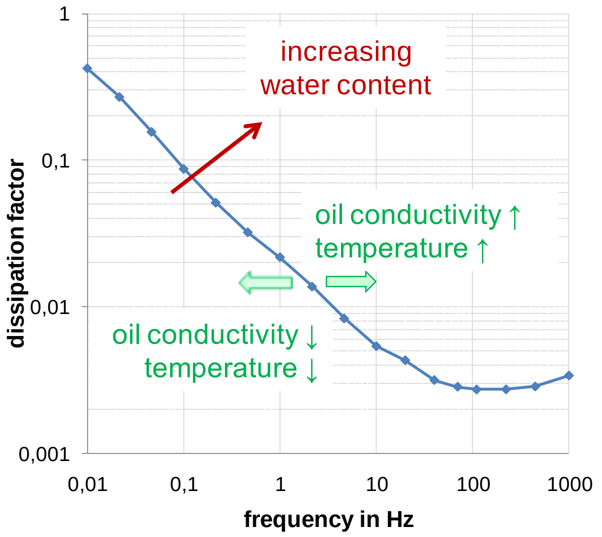

Figure 5: Main influences on measured dielectric response curves

2.3 Moisture determination

The moisture determination using the dielectric response curves is based on a comparison between the measured curve and a modelled curve (Figure 6). The curve modelling is done with help of a data base including data about the material properties of cellulosic material with different water contents and temperatures. Using the so called XY-model [6], a dielectric response is calculated under consideration of the insulation geometry, temperature, oil and moisture content. A fitting algorithm aligns the modelled curve to the dielectric response of the real insulation and automatically delivers the oil conductivity, the water content in the cellulose material as well as the moisture saturation.

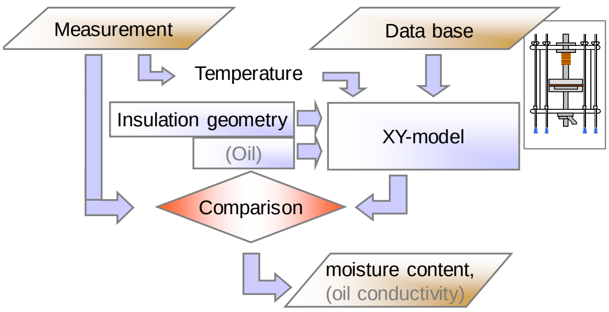

Figure 6: Calculation of the water content based on comparison of the measured dielectric response to a modelled curve

The used XY-model is developed to model the properties of oil-paper insulations, initially for power transformers. The model takes into account the amount of barriers and spacers of the insulation. The main part of the insulation in instrument transformers (70% - 90%) is consisting of paper, enwrapping the inner conductor and therefore having similar behaviour as barriers. Also oil gaps exist, as between spacers of power transformer insulations. Therefore it is assumed, that the XY-model can be applied to instrument transformers.

However, not the whole insulation of instrument transformers is cylindrical as for power transformers. Figure 7 shows a principle layout of the insulation of instrument transformers. The parts inside the bushings are cylindrical, but not the parts inside the tanks. Therefore investigations were necessary to find out if the model is adequate for instrument transformers as well. An analysis of several instrument transformer measurements was done. It showed that this approach is adequate for the dielectric response analysis on instrument transformers, even though the accuracy of the calculated water content might be not as high as for power transformers. Other geometry models which considered different internal designs more specifically did not provide a higher accuracy for all cases. Therefore the simple XY-model was used for further analysis of the dielectric response curves of instrument transformers.

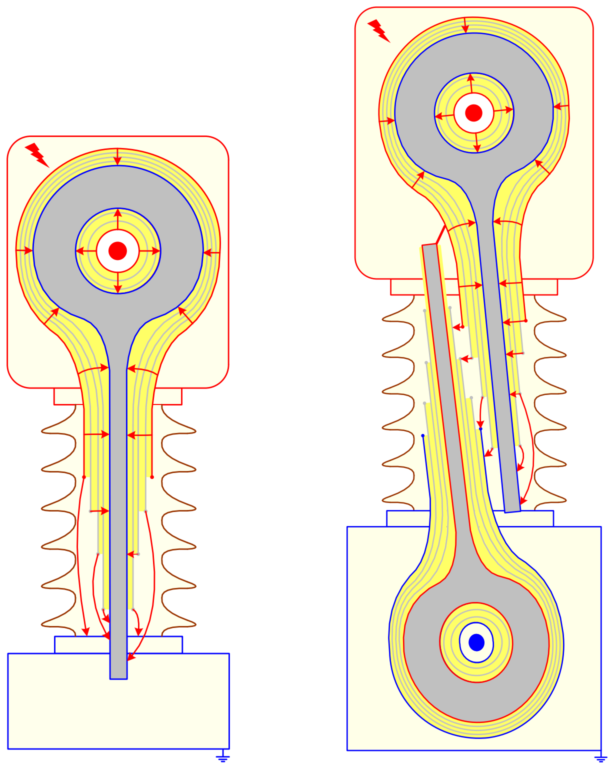

Figure 7: Schematic drawing of the insulation inside a CVT (left) and a CT (right), the losses (current flow through the insulation) are marked with arrows

3 ASSESSMENT OF INSULATION CONDITION USING DIELECTRIC RESPONSE

In this investigation more than 30 instrument transformers of different types and designs were measured and the results are used in the following chapter to identify meaningful parameters to assess the insulation condition. Since there is no direct quantification for ageing, the water content in the solid insulation is used as an indicator for the insulation condition. However, using the dielectric response more measured parameters are gained, which can be used for decision trees in asset management.

3.1 Relationship between moisture and dissipation factor at different frequencies

A typical measurement providing information about the insulation condition of high voltage assets is the dissipation factor measurement at mains frequency (Figure 8). This value tends to increase for higher moisture contents in the solid insulation.

The dissipation factor at 50 Hz is having very similar values for dry insulations and insulations with a water content up to about 3%. This is reasonable, since the slope of the dissipation factor has the smallest steepness and its minimum around mains frequencies. Even when the curves are shifting towards higher frequencies due to moisture, the increase of the dissipation factor at 50 Hz will be small. A high measured dissipation factor of more than 0.01 would therefore indicate already a high water content, what is usually a sign for bad insulation condition. However, the value seems not to be capable to display the increasing moisture for dry and moderate insulations.

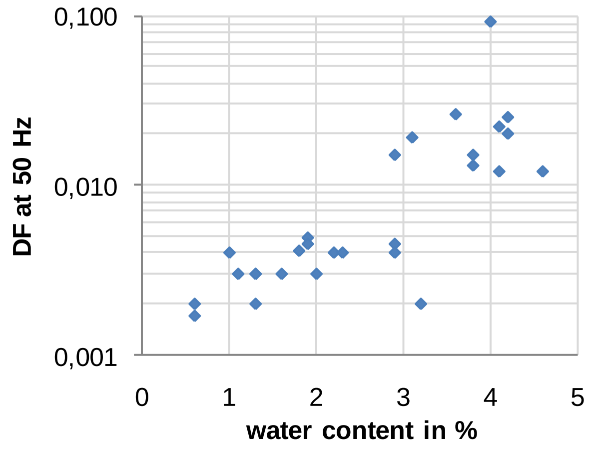

Figure 8: Dissipation factor at 50 Hz and water content for various instrument transformers of different condition

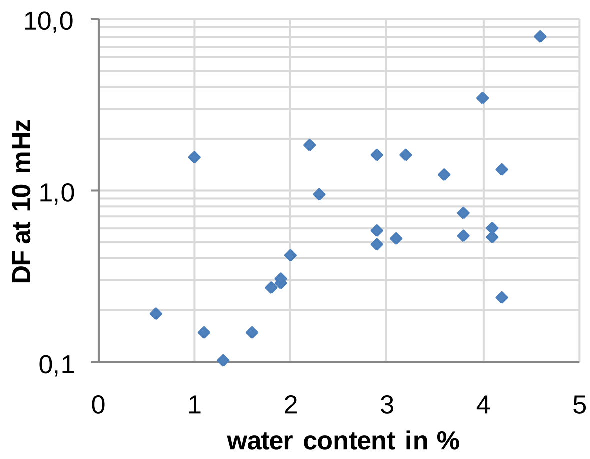

Figure 9: Dissipation factor at 10 mHz and water content for various instrument transformers of different condition

The dielectric response enables to analyze also lower frequencies, e.g. the dissipation factor at 10 mHz (Figure 9). This value also tends to increase with increasing water content in the solid insulation. As it can be seen in Figure 4, moisture is increasing the slope of the dissipation factor curve leading to higher values at 10 mHz. Therefore it is more sensitive to progressive moisture in first stages compared to the dissipation factor at 50 Hz.

3.2 Oil conductivity of instrument transformers in service

The oil conductivity of the measured instrument transformers seem to be widely spread for all frequencies and there is no direct relation between both was observed (Figure 10). Since the oil conductivity strongly influences the slope of the dielectric response, it is very important to differentiate between the effect of moisture ingress and oil conductivity. This is not possible with a measurement at mains frequency. Only a wide frequency range enables to differentiate between the effects of moisture and oil conductivity [3].

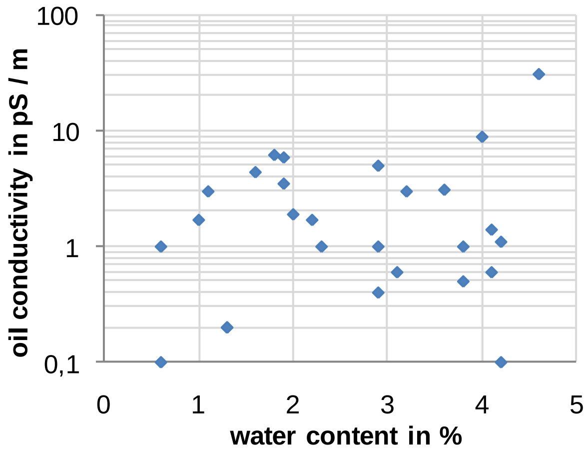

Figure 10: Oil conductivity and water content for various instrument transformers of different condition

3.3 Frequency dependent capacitance

An ideal insulation has a stable capacitance for all frequencies. However, the capacitance of real insulations is slightly increasing towards low frequencies (Figure 11). This increase can be visualized using the ratio of the capacitances at 10 mHz and 50 Hz which is listed in Table 3. According to the results the ratio seem to increase with increasing age and moisture. For the new and dry instrument transformer we are nearly ideally with a ratio of 1.05. The old and wet instrument transformer has a much higher ratio of 2.85.

Table 3: Ratio of capacitances at 10 mHz and 50 Hz for four examples mentioned in Figure 11

	Water content	Oil conductivity	Ratio C_{10mHz}/C_{50Hz}
Old 1	4%	9 pS/m	2.85
Old 2	2%	2 pS/m	1.25
New 1	1.2%	3 pS/m	1.10
New 2	0.5%	6 pS/m	1.05

An overview of all measurement results shown in Figure 12 confirms this finding. The ratio of capacitances seem to correlate with water content. For water contents up to 3% most ratios are 1.3 or below.

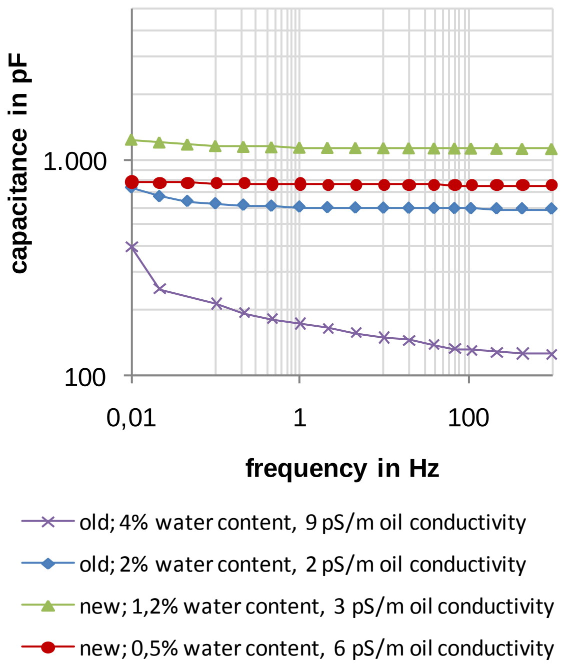

Figure 11: Frequency dependent capacitances of various instrument transformers depending on frequency

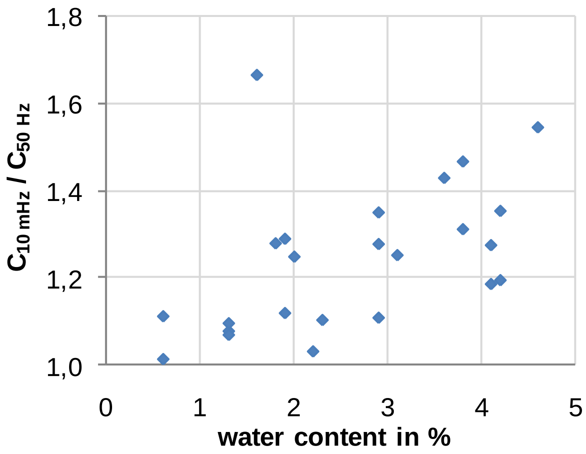

Figure 12: Ratio of capacitance values between 10 mHz and 50 Hz

4 INTERPRETATION SCHEME

For an effective asset management a reliable scheme is needed for funded decisions on the condition of the single power assets. In Figure 13 an example for an interpretation scheme is given, using the discussed values gained by the dielectric response. Besides the dielectric response, other measured values could be used. However, this schemes is constricted to the dielectric values, moisture and oil conductivity all with reference to 25°C.

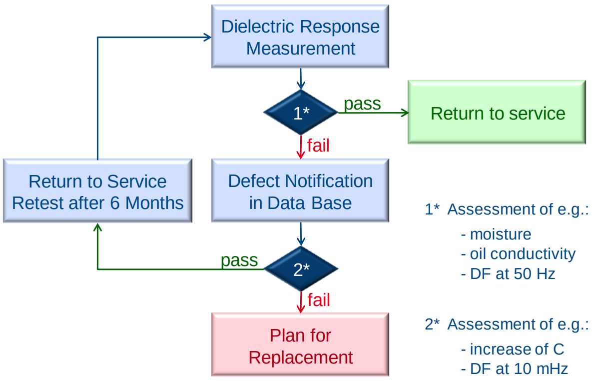

Figure 13: Example for a decision tree based on the results of the dielectric response

The interpretation scheme consists of a two step decision tree. The first step can be done in line regularly testing, e.g. every second year or even every fifth year, depending on the maintenance strategy. If this analysis of the dielectric response is passed, the instrument transformer can return to service. If an instrument transformer fails, it probably has a defect or ageing or moisture ingress is progressive. Further analysis of the dielectric response should be done. The second step uses the lower frequency data for further interpretation. If an instrument transformer passes the test, retesting after e.g. six months should be recommended. For instrument transformers, which fail, a replacement plan should be formulated. Following values might be used for the analysis of the dielectric response:

Step 1: regularly testing

- DF at 50 Hz (e.g. $DF_{50Hz} < 0.01$)
- Water content (e.g. w.c.< 2,2%)
- Oil conductivity (e.g. $\sigma_{oil} < 10$ pS/m)

Step 2: conspicuous instrument transformers

- DF at 10 mHz (e.g. $DF_{10mHz} < 1$)
- Capacitance ratio (e.g. $C_{10mHz}/C_{50Hz} < 1.3$)

As mentioned before, this interpretation scheme is an example how the dielectric response curves can be used for a condition based maintenance. It might be necessary to adapt it according to the individual strategy.

5 CONCLUSION

The dielectric response analysis, typically used for power transformer can also be applied to instrument transformers. The measurement of the dielectric properties over a wide frequency range enables to distinguish between main influencing effects like moisture content, oil conductivity and temperature. So the dielectric response analysis of instrument transformer enables a funded condition assessment of the insulation. Besides water content in the solid insulation and oil conductivity, further values like the dissipation factor and capacitances at different frequencies can be used to gain information about the insulation condition. A possible interpretation scheme helps to conclude a further plan of action.

6 REFERENCES

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