MINIMIZING DIELECTRIC TESTING TIME

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Abstract: The water content in the paper insulation is one of the most important parameters for the remaining lifetime of power transformers. Dielectric frequency response (DFR) measurements in a large frequency range allow users to measure this moisture content without the disadvantages of conventional techniques like oil samples. However, up to now, the measurement time of those measurements was quite long and could take many hours, depending on the condition of the asset. Additionally, it was difficult to estimate the required frequency range and therefore the required measurement time. Measuring a too small frequency range leads to shorter measurement times but is likely to cause inaccurate results for the water content whereas measuring a too large frequency range causes unnecessary long measurement and outage times. The current paper shows two methods to decrease the required measurement time significantly. At first, a method is shown how the required frequency range can be reliably detected. The presented technique is based on the individual physical properties of the measured asset and applicable to all oil-paper insulated assets. It can be easily automated so no expert knowledge is required. Additionally, a second method is shown where the required frequency range can be measured faster using an advanced, time domain based technique named PDC+. A case study of 19 dielectric power transformer measurements is used to prove both techniques are working reliably on real power transformers in real test situations on site. The combination of both methods enables even inexperienced users to conduct accurate DFR-based moisture assessments on power transformers within the shortest possible measurement time.

1 INTRODUCTION

Water is a danger to all oil-paper insulations as it can lead to increased losses, aging, partial discharges and in the end to a failure of the insulation. The consequences can reach from a reduced lifetime to a complete destruction of the asset. In power transformers, water leads to a decrease of polymerization of the paper and thereby to an accelerated aging of the paper [1] [2]. Therefore, for power transformers, the water content can be used to determine the aging status of the insulation.

However, determining the water content of a power transformer is not a trivial task. The vast majority of the water resides in the paper/pressboard insulation where extracting samples is difficult. Indirect determination via the water content of the oil is prone to multiple errors [3].

Dielectric frequency response (DFR) measurements are an alternative technique for the determination of the water content of the. They are non-invasive and give the result on site without a delay. One drawback of those measurement up to now was the long measurement time which was required to measure the large frequency range.

2 MOISTURE DETERMINATION BY DFR

DFR measurements determine the dielectric properties of an oil-paper insulated asset in a very wide frequency range, usually from the lower kHz region to a few mHz or even µHz. The setup is usually the same like for a dissipation factor measurement, so for a 2-winding power transformer, the insulation between HV and LV is measured. The big advantage of using a very broad frequency range is the possibility to differentiate between different influence factors. This makes the method usable for the identification of water and aging [6].

This method is capable of determining an absolute amount of the water content in oil paper insulations. Therefore, the broadband dielectric measurement is compared to a simulated measurement, generated from a database and including the influences of geometry and oil [3] [5]. The latter is achieved by using the so called “X-Y-model” which represents a simplified, universal transformer [1] [2] [9]. With this method, also the conductivity of the oil is determined.

The dielectric response of a power transformer has a characteristic form, including a local maximum in the losses which is called “hump” (Figure 1). It consists of different parts which are influenced by moisture, the insulation geometry (i.e. the amount of barriers and spacers), the oil conductivity and the temperature.

The main influence of moisture on the measured tan(δ) spectrum is at the low frequencies left of the so-called “hump”. Therefore, it is imminent to measure this part of the spectrum in order to achieve reliable results for the water contents [3].

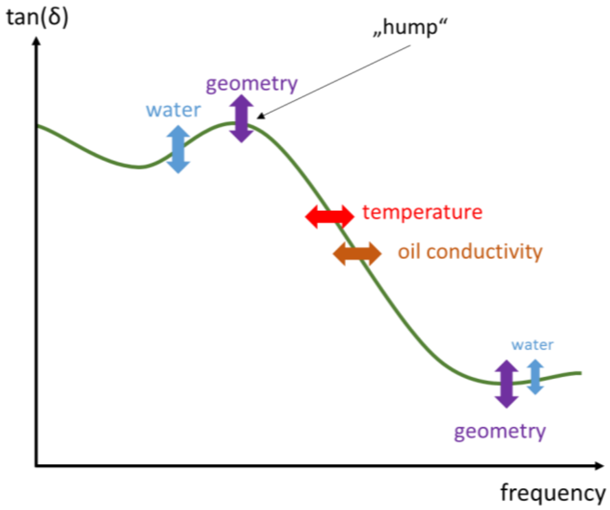

Figure 1: Characteristic dielectric response curve of a power transformer winding with the different influence factors

3 TIME SAVING PART 1: DETERMINATION OF THE OPTIMUM FREQUENCY RANGE

As the previous chapter shows, the measured frequency range for DFR moisture determination must range from high frequencies to the low frequency area which is influenced by moisture. High frequencies are measured very fast but the lower the frequency, the larger the measurement time. Therefore, if the minimum required frequency range can be determined, this would prevent a too long measurement time.

A set of power transformer measurements on more than one hundred different assets made it possible to determine to which frequency range it is possible to “cut” the measured curve without losing accuracy in moisture determination. The result is that it if the stop frequency is more than 1.5 decades lower than the “hump”, the result is still accurate whereas a stop frequency less than 1.5 decades below the “hump” frequency decreases the accuracy of the moisture determination. This corresponds well with the findings of other sources [10].

With this knowledge it is possible to identify the minimum required frequency range once the frequency of the “hump” is known.

5.1 3.1 IDENTIFYING THE “HUMP”

Identifying the “hump” might sound simple if curves such as displayed above (Figure 1) are considered as the “hump” is clearly visible as a local maximum and can be detected easily by algorithms. However, there are combinations of oil conductivity and moisture values which result in a curve without such a local maximum (Figure 2). Although in some cases the position of the hump could be “guessed”, it would be desirable to have a reliable method to determine the hump and thereby the frequency range where moisture influences the dielectric curve.

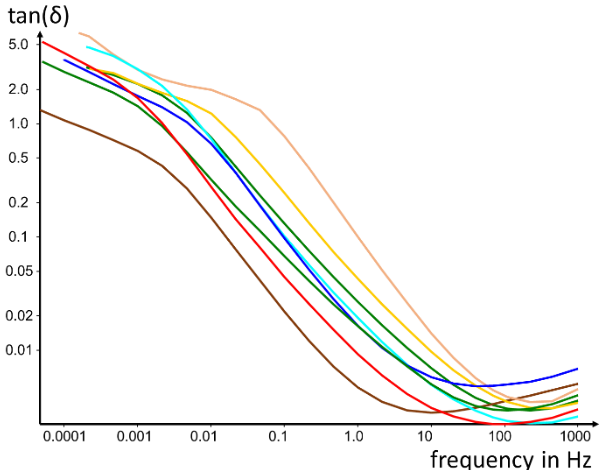

Figure 2: Dielectric response curves of power transformer without a clearly visible “hump”.

In order to determine such a principle, the tan(δ) curve is investigated in detail: The “hump” represents the area where the tan(δ) starts to decrease when the frequency decreases. As the tan(δ) is the ratio between losses and polarization, such a decrease happens if either the losses decrease more than the polarization or when the polarization increases more than the losses.

In case of power transformer measurements, the latter is the case: For frequencies much higher than the hump frequency, the polarization stays constant but the losses increase, which causes the tan(δ) to increase with decreasing frequency (Figure 3).

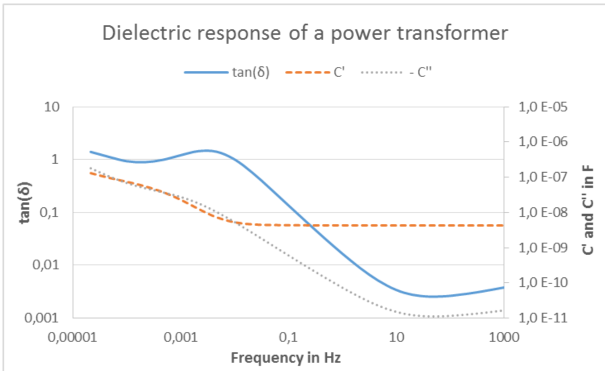

Figure 3: Dielectric response of a power transformer with a visible “hump”.

At the beginning of the hump, the polarization starts to increase more than the losses which causes the tan(δ) to decrease. After the local minimum below the hump, the increase of the losses is again larger than the increase of the polarization so the tan(δ) increases again with decreasing frequency.

As the polarization remains constant above the hump frequency for the whole measurement range, the increase of the polarization can be used to reliably detect the "hump". For the following investigation, the used definition of the "hump" frequency was that the value of C' is 1.5 times the value of C' at 50 Hz:

$$C'(f_{hump}) = 1.5 \cdot C'(50\ Hz) \qquad (1)$$

where: f_{hump} = Frequency of the "hump"

Using this equation, the "hump" can be reliably determined even if no local maximum is visible at the tan(δ) curve.

This practical finding can also be verified by theoretic considerations. Pure oil doesn't show any change in polarization in the investigated frequency range [10] whereas oil impregnated cellulose (i.e. pressboard without barrier and spacer structure) does show such a polarization (Figure 4) [3].

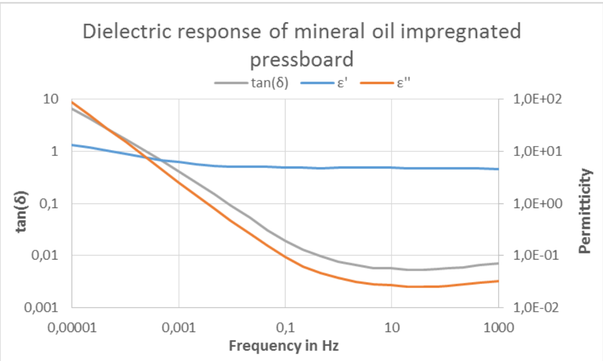

Figure 4: Dielectric response of mineral oil impregnated pressboard.

Once the "hump" frequency has been reached in the measurement, the required stop frequency which is 1.5 decades below the "hump" frequency can be determined. This helps not only to reduce the test time but also avoids inaccurate measurements with too short frequency ranges.

4 TIME SAVING PART 2: OPTIMIZING THE MEASUREMENT PRINCIPLE

There are various principles to measure the dielectric response, using measurements in frequency as well as time domain. Examples are frequency domain spectroscopy (FDS), polarization depolarization current (PDC), recovery voltage method (RVM) etc. Also combinations are possible and can help to combine advantages of different principles [5]. As all of those measurement principles, when performed in a correct way, can measure the dielectric properties of the asset in a certain frequency or time range, the results can be converted into each other [4] [8]. The most used form of presenting the obtained data is in frequency domain, i.e. the property (e.g. tan(δ)) is displayed in a chart versus the frequency.

The advantage of time domain measurements is the time saving as one single measurement can be used to determine the dielectric properties at multiple frequencies. To achieve the data in frequency domain, a conversion is required. Various principles exist which can be used for conversion [11] [12]. All measurements in time domain are made over a finite interval of time. To transfer the data into frequency domain, it is necessary to estimate the measurement data outside this interval (Figure 5).

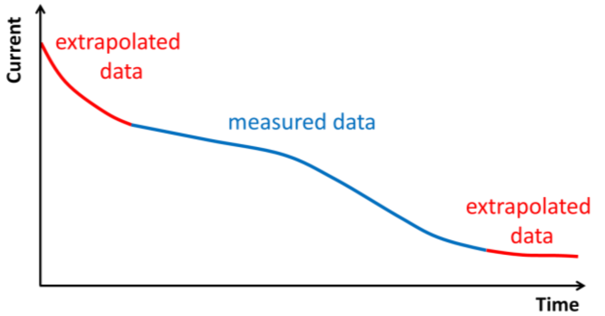

Figure 5: Schematic polarization current measurement with extrapolation for short and long times

As the data in time domain needs to be extrapolated to fulfil the integration limits of the Fourier transformation, this function can also be used to calculate additional data in frequency domain which saves additional measurement time.

The algorithm used in this investigation for conversion from time to frequency domain automatically calculates the dielectric response in the whole applicable frequency range, regardless the actual measurement time. The data which is presented is restricted in frequency range, which depends on the measurement time. A conventional setting was that the minimum frequency is the inverse of the measured time (Formula 2).

$$f_{\mathrm{min}} = 1/t_{\mathrm{measured}} \qquad (2)$$

where: f_{min} = minimal frequency presented
$t_{measured}$ = measured time

Whereas this principle provides an advantage in terms of measurement speed compared to FDS measurements, the measurement time can still be quite long, e.g. about 6 hours for a measurement down to 50 µHz. Other settings, e.g. the example in (Formula 3) with a factor of 0.1 would lead to a 10 times shorter measurement time for the same frequency range.

$$f_{min} = 0.1 * 1/t_{measured} \quad (3)$$

where: f_{min} = minimal frequency presented
$t_{measured}$ = measured time

The lower the factor, the faster the measurement.

In order to find out which factor still is able to determine reliable results, existing time domain measurements were cut and “extrapolated” using the same factor. For a factor of e.g. 0.1, a measurement of e.g. 10000 s was cut to 1000 s and extrapolated using (Formula 2) to a minimum frequency of 100 µHz. The result was compared with the original measurement of 10000 s which was converted to frequency domain using (Formula 1). Of course, other factors than 0.1 are possible and also were used.

The finding was that in all cases, a factor of 0.3 (which reduces the measurement time by about 2/3) provided correct results. In most cases, even higher factors up to 0.05 (increasing the measurement speed by the factor of 20) and below were possible without loss of accuracy. However, the maximum factor was dependent on the individual curve shape and absolute measurement time, i.e. for very long measurements, a lower factor was possible. The finding that lower factors can be used to shorten the testing time corresponds well with other investigations [12].

In order to optimize the measurement speed, an automatic algorithm was created which dynamically uses a factor between 0.3 and 0.05, which shortens the time domain measurement time in a range from 1/3 to 1/20. The real factor used is based on the stability of the calculated result in frequency domain. This technique was called “PDC+”.

5 CASE STUDIES

5.1 TEST DATA

The function of the new algorithms is presented using 19 measurements made with the OMICRON DIRANA system on power transformers. The conventional and newly developed algorithms are used on the same raw time domain data so the calculations were made with both conversion algorithms (PDC and PDC+) using exactly the same measurement data. This way, influences of variations in sample properties (temperature, pre-polarization etc.), external influences (noise, connections) are avoided and differences in the results are only caused by the algorithms.

The measurements were all performed in the required frequency range (see chapter 3) for both technologies. For the following calculations, only the time of the PDC/PDC+ measurement is considered as the time for the FDS measurement for higher frequencies stays constant for both technologies and is quite short (about 308 seconds) compared to average PDC measurement times.

5.2 COMPARISON PDC AND PDC+

The PDC+ algorithm shows an average reduction of the measurement time to about one third of the conventional PDC measurement time in the required frequency range (Table 1). The average relative deviation is below 0.1 %, the maximum absolute deviation about 1.1 % for a value of more than 300 %. A change of 0.1 wt.% in water content causes an absolute change of more than 15 % in tan(δ) at such frequencies, so the difference is negligible for the analysis of the water content.

Table 1: DFR test times and results using conventional PDC and PDC+ conversion algorithms for 19 different measurements on power transformers

Nr	Required stop frequency	Measurement time		Time saving by PDC+	tan(δ) at required stop frequency		
		PDC	PDC+		PDC	PDC+	relative deviation
1	681 µHz	1468 s	470 s	998 s	98,28%	98,32%	-0,04%
2	147 µHz	6803 s	2200 s	4603 s	309,35%	309,33%	0,01%
3	700 µHz	1429 s	470 s	959 s	129,10%	129,08%	0,02%
4	316 µHz	3165 s	1110 s	2055 s	467,20%	467,44%	-0,05%
5	316 µHz	3165 s	1060 s	2105 s	78,87%	78,86%	0,01%
6	681 µHz	1468 s	490 s	978 s	56,00%	56,15%	-0,27%
7	316 µHz	3165 s	1060 s	2105 s	194,94%	194,94%	0,00%
8	3000 µHz	333 s	120 s	213 s	75,54%	75,53%	0,01%
9	3000 µHz	333 s	120 s	213 s	205,00%	204,97%	0,01%
10	681 µHz	1468 s	450 s	1018 s	87,79%	87,79%	0,00%
11	7000 µHz	143 s	50 s	93 s	64,03%	64,40%	-0,58%
12	7000 µHz	143 s	50 s	93 s	202,58%	202,06%	0,26%
13	681 µHz	1468 s	480 s	988 s	154,63%	154,62%	0,01%
14	1000 µHz	1000 s	320 s	680 s	67,01%	67,01%	0,00%
15	316 µHz	3165 s	1050 s	2115 s	124,33%	124,34%	-0,01%
16	681 µHz	1468 s	480 s	988 s	76,99%	76,99%	0,00%
17	316 µHz	3165 s	1020 s	2145 s	212,93%	212,93%	0,00%
18	316 µHz	3165 s	1050 s	2115 s	304,34%	305,45%	-0,36%
19	1000 µHz	1000 s	320 s	680 s	65,75%	65,75%	0,00%

Whereas the PDC+ algorithm leads to a reduction of the measurement time to about 1/3, the automatic determination of the frequency range has an even higher potential to reduce the measurement time.

Table 2 shows the reduction of the measurement time if the automatic setting of the frequency range is used in combination with conventional PDC and PDC+. Even if the required stop frequency is close to the set stop frequency, e.g. for measurement number 2, the time saving is significant. For larger differences, it is even higher.

Table 2: Time saving by automatic frequency range setting and PDC+ for 19 different measurements on power transformers

Nr	Stop frequency		Original PDC measurement time	Time domain measurement time		Total measurement time
	Original	Required		PDC	PDC+	FDS & PDC+
1	200 µHz	681 µHz	5000 s	1468 s	470 s	778 s
2	99 µHz	147 µHz	10101 s	6803 s	2200 s	2508 s
3	99 µHz	700 µHz	10101 s	1429 s	470 s	778 s
4	99 µHz	316 µHz	10101 s	3165 s	1110 s	1418 s
5	99 µHz	316 µHz	10101 s	3165 s	1060 s	1368 s
6	99 µHz	681 µHz	10101 s	1468 s	490 s	798 s
7	99 µHz	316 µHz	10101 s	3165 s	1060 s	1368 s
8	99 µHz	3000 µHz	10101 s	333 s	120 s	428 s
9	99 µHz	3000 µHz	10101 s	333 s	120 s	428 s
10	495 µHz	681 µHz	2020 s	1468 s	450 s	758 s
11	100 µHz	7000 µHz	10000 s	143 s	50 s	358 s
12	100 µHz	7000 µHz	10000 s	143 s	50 s	358 s
13	100 µHz	681 µHz	10000 s	1468 s	480 s	788 s
14	1000 µHz	1000 µHz	1000 s	1000 s	320 s	628 s
15	215 µHz	316 µHz	4651 s	3165 s	1050 s	1358 s
16	100 µHz	681 µHz	10000 s	1468 s	480 s	788 s
17	100 µHz	316 µHz	10000 s	3165 s	1020 s	1328 s
18	215 µHz	316 µHz	4651 s	3165 s	1050 s	1358 s
19	100 µHz	1000 µHz	10000 s	1000 s	320 s	628 s

6 CONCLUSIONS

The dielectric frequency response is a proven method to assess the water content of power transformers. Using advanced software algorithms, the limitations of the past in terms of long measurement times and required expert knowledge for measurement and analysis can be solved without any compromises in accuracy. On the contrary, they even increase the reliability as common mistakes like too short frequency ranges and misinterpretations can be avoided. Those improvements allow a simple and reliable use of DFR test sets for moisture analysis on oil-paper insulated power transformers and other assets even for less experienced users.

REFERENCES

[1] Sokolov et al., “Moisture Equilibrium and Moisture Migration within Transformer Insulation Systems”. Cigré Working Group A2.30, Technical Brochure 349, Paris, 2008.

[2] S. M. Gubanski, et al., “Dielectric Response Diagnoses for Transformer Windings”, CIGRÉ Task Force D1.1.14, Technical Brochure 414, Paris, 2010.

[3] M. Koch, Reliable Moisture Determination in Power Transformers, Sierke Verlag, 2008.

[4] W. S. Zaengl, "Applications of Dielectric Spectroscopy in Time and Frequency Domain for HV Power Equipment," IEEE Electrical Insulation Magazine, vol. 19, no. 6, pp. 9-22, 2003.

[5] M. Krueger and M. Koch, "A fast and reliable dielectric diagnostic method to determine moisture in power transformers," in IEEE International Conference on Condition Monitoring and Diagnosis (CMD), 2008.

[6] U. Graevert, "Dielectric Response Analysis of Real Insulation Systems," in Proceedings of the 2004 IEEE International Conference on Solid Dielectrics (ICSD), 2004.

[7] T. Leibfried, A. J. Kachler, A. Kuechler, W. S. Zaengl, V. D. Houhanessian and B. Breitenbauch, "Ageing and Moisture Analysis of Power Transformer Insulation Systems," in CIGRE Session, Paris, 2002.

[8] A. K. Jonscher, Dielectric relaxation in Solids, Chelsea Press, 1983.

[9] CIGRE, "CIGRE Technical Brochure 414: Dielectric Response Diagnoses for Transformer Windings," CIGRE, 2010.

[10] D. Giselbrecht, „Dielektrische Modellierung von Öl-Papier-Isolationssystemen im Frequenzbereich zur Diagnose von Leistungstransformatoren“, Cuvillier Verlag, 2008

[11] M. Koch, F. Kaufmann, “Transforming Dielectric Response Measurements from Time to Frequency Domain”, Nordis conference Gothenburg, 2009

[12] F. I. Mopsik, „Precision time-domain dielectric spectrometer“,Review of Scientific Instruments 1984 55:1, pp. 79-87