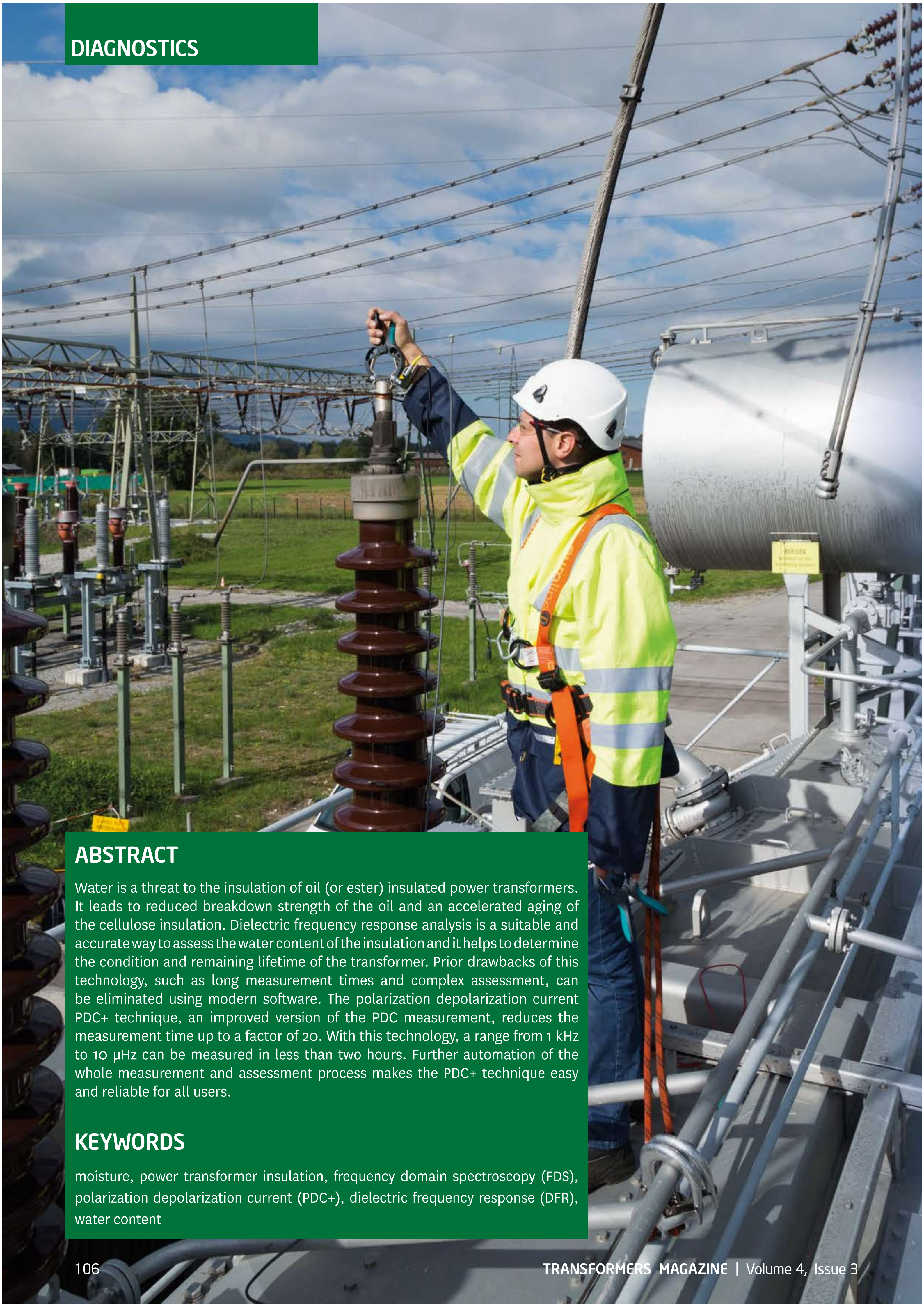

ABSTRACT

Water is a threat to the insulation of oil (or ester) insulated power transformers. It leads to reduced breakdown strength of the oil and an accelerated aging of the cellulose insulation. Dielectric frequency response analysis is a suitable and accurate way to assess the water content of the insulation and it helps to determine the condition and remaining lifetime of the transformer. Prior drawbacks of this technology, such as long measurement times and complex assessment, can be eliminated using modern software. The polarization depolarization current PDC+ technique, an improved version of the PDC measurement, reduces the measurement time up to a factor of 20. With this technology, a range from 1 kHz to 10 μHz can be measured in less than two hours. Further automation of the whole measurement and assessment process makes the PDC+ technique easy and reliable for all users.

KEYWORDS

moisture, power transformer insulation, frequency domain spectroscopy (FDS), polarization depolarization current (PDC+), dielectric frequency response (DFR), water content

Martin ANGLHUBER

Why is water killing power transformer insulation?

Water is a slow but deadly poison for power transformers

1. Water in power transformers

Water is the foundation for life on our planet. It is essential for every living plant or creature. But there is one place where water greatly reduces life: the oil-paper insulation of power transformers. This insulation consists of paper and pressboard elements which provide the mechanical stability of the insulation. The main component of paper and pressboard is cellulose. It consists of glucose molecules which are linked and form a chain (Figure 1). The average number of glucose molecules in a cellulose chain (which is also called "degree of polymerization" or "DP" in short) is about 1,200 for new paper. These large chains give the paper the mechanical strength it requires to fix the windings, even in rough conditions such as when a short circuit has occurred.

Unfortunately, these chains can be split by water molecules, which reduces the mechanical force they can withstand. A small amount of moisture (typically between 0.3 wt.% to 0.5 wt.%; wt.% being percentage by weight) is always present in the paper of a power transformer, even if it is dried perfectly. At elevated temperatures, the water molecules split the cellulose chains, causing shorter chain lengths and – as a byproduct – even more water. So a self-accelerating process is taking place which increasingly reduces the mechanical stability of the transformer insulation. The speed of this process is highly dependent on the temperature but also on the moisture content (Figure 2). Although the higher temperatures displayed in the chart are unlikely to be reached by the average temperature of the transformer, local hot spots have to be considered.

When the average length of a cellulose chain, which is expressed by the degree of polarization (DP), in paper is 200 or below, it is usually considered at the end of its life because the mechanical strength is then so heavily reduced that it cannot withstand higher stresses.

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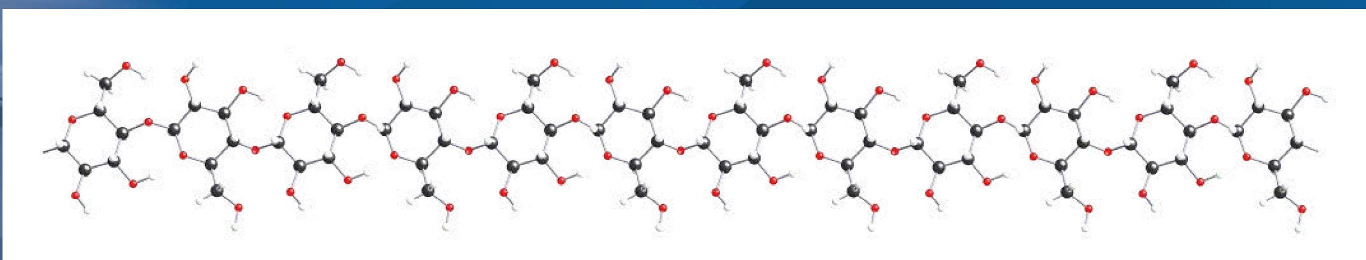

Figure 1. Part of a cellulose molecule showing 12 glucose molecules (schematic)

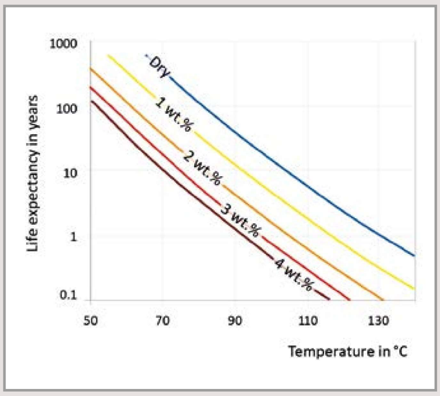

Figure 2. Dependency of life expectance of paper insulation on moisture content and temperature [1]

Water reduces the lifetime of oil-paper insulation of power transformers

As aging produces more water molecules, the water content of a power transformer is a very good indicator for the age of the transformer insulation. It allows not only an assessment of the remaining lifetime but also correct condition based maintenance: a moderately wet power transformer with 3 wt.% water content might be dried, which reduces the water content and thereby slows down the aging. If a power transformer has a water content of e.g. 5.5 wt.%, which is very wet, the paper is usually in a very aged state and drying would not help as it cannot un-age the paper. If it has only 1 wt.% and is therefore dry, drying would be a waste of time and money.

In a mineral oil filled power transformer, the amount of oil is about 10 times larger than the amount of cellulose insulation [2]. However, as water is barely soluble in oil, the vast majority (>99 %) of water is located in the cellulose insulation and not in the oil. Oil samples of power transformers contain water only in the lower ppm (parts per million) range whereas the range for water in the cellulose is usually in the area of 0.3 % to 6 %. The water content of the oil is highly dependent on temperature, oil condition and impurities [2]. Small errors in sampling and handling result in high deviations of the final result [2]. The water content in the cellulose provides a much more reliable value for condition assessment, as it is barely influenced by those parameters. Unfortunately, sampling of cellulose for moisture analysis is a very difficult task as the solid insulation of a power transformer is not easily accessible.

2. Moisture determination via dielectric frequency response analysis

A simple and reliable way to determine the amount of moisture in a power transformer is dielectric frequency response analysis (DFR) [3]. When a material absorbs water, it changes its dielectric properties, such as conductivity, capacity and dielectric losses. This principle is used, for example, in humidity sensors. Cellulose also shows such a dependency of dielectric values at different water contents.

2.1 Measurement principle

In dielectric moisture analysis of power transformers, the whole main transformer insulation is used as a humidity sensor. The measurement device is connected to the bushings and determines the dielectric properties of the insulation. The connection is very simple, like in a normal power factor/tan(δ) measurement. Typically, the main insulation from the high voltage to the low voltage side (CHL) is measured as it contains most cellulose. The result provides the average water content of the transformer. For analogue to power factor/tan(δ) measurements, a guard is used to bypass unwanted influences (Figure 3).

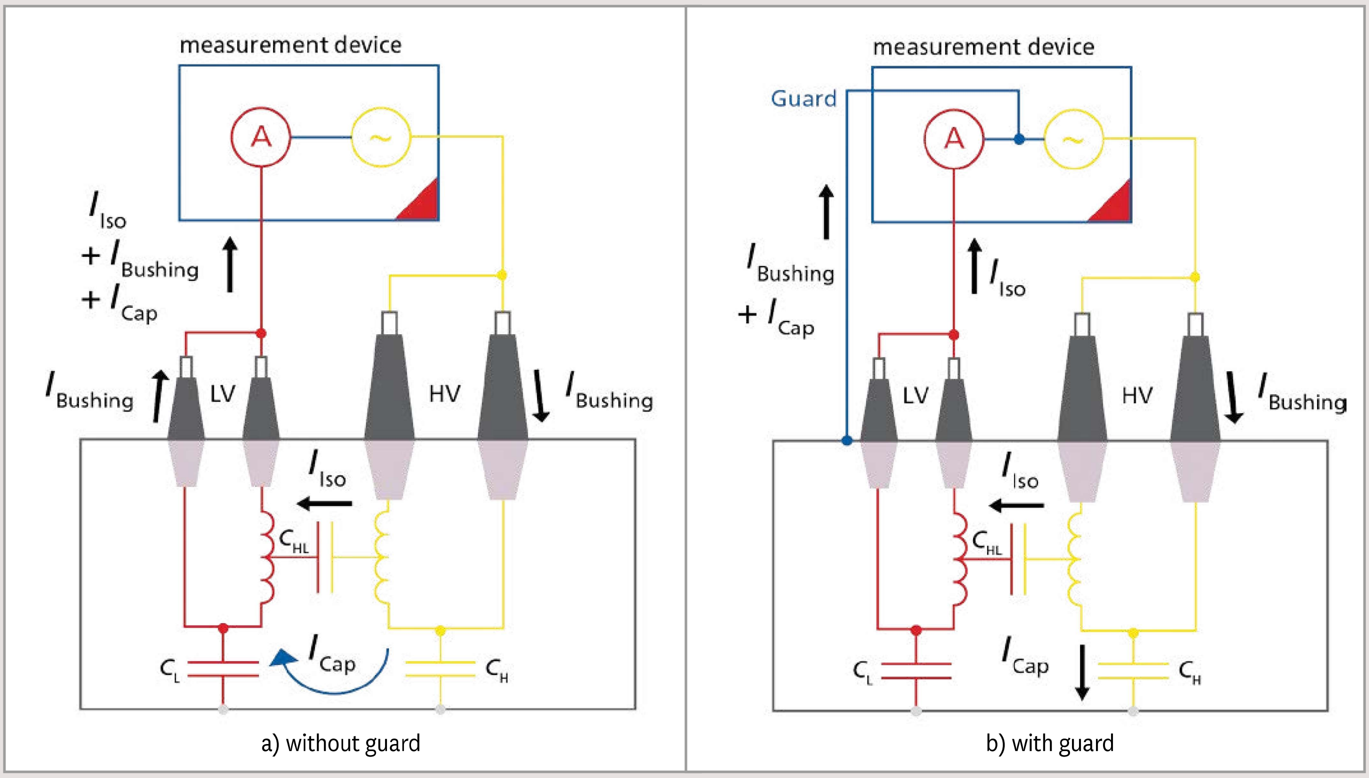

Figure 3. CHL measurement on a two-winding transformer without and with guard

As moisture influences the dielectric properties of cellulose, especially at very low frequencies, the measurement is performed down to the µHz region. Figure 4 shows the dielectric losses (tan(δ)) of four power transformers in a frequency range from the µHz region up to some hundred hertz. Each curve has a characteristic shape which includes a more or less pronounced "hump" at lower frequencies. The region below the hump, around one to two decades from the "hump" peak, is highly influenced by the water in the paper insulation. Determining this frequency region is essential.

2.2 Result assessment

The assessment of the curves is a complex process as many parameters are influencing the dielectric properties [2]. However, modern measurement software, which include a database of dielectric

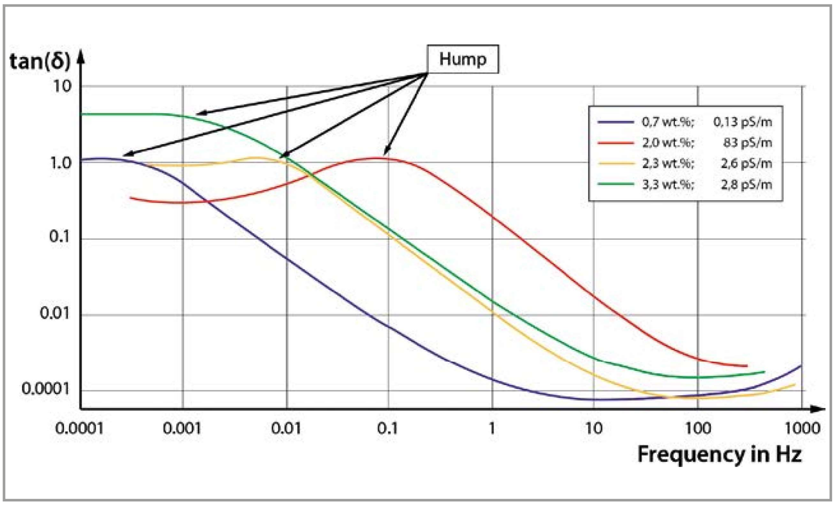

Figure 4. Broadband dielectric response of four different power transformers at 20 °C

DFR is a simple and reliable way to measure the amount of moisture in power transformer insulation

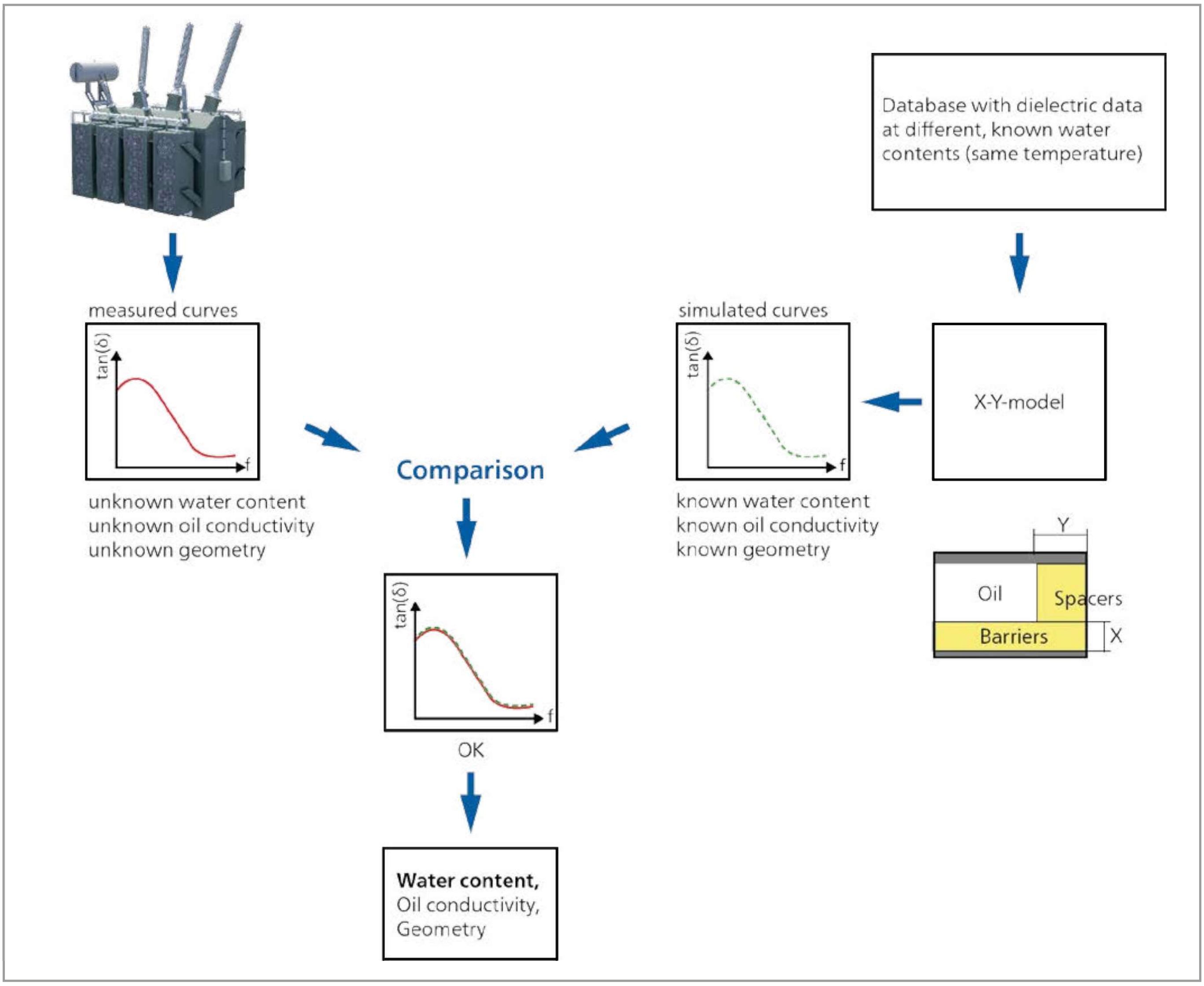

Figure 5. Principle of the water content assessment of power transformers

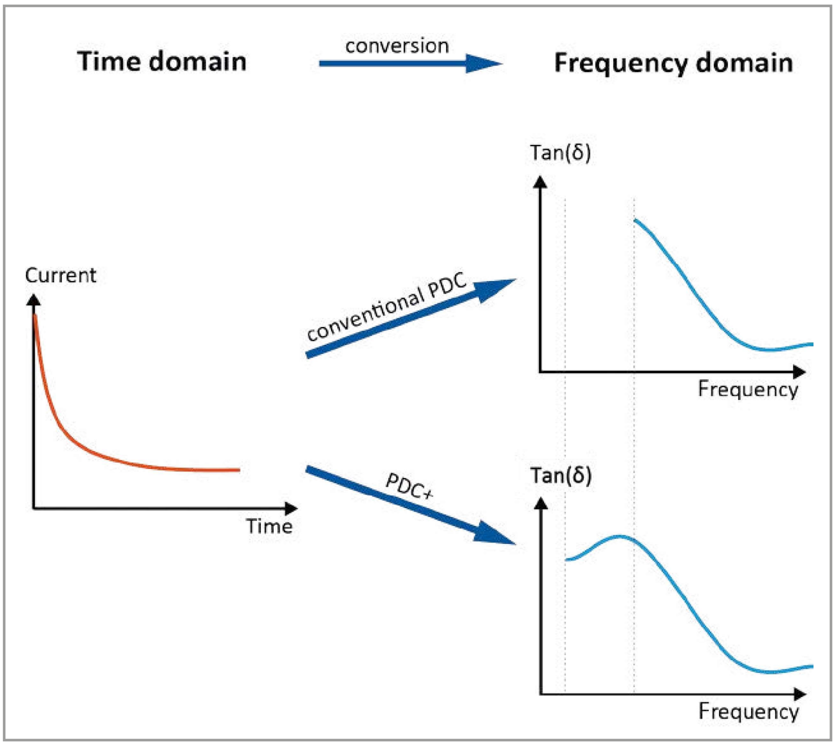

Figure 6. Conversion from time to frequency domain for conventional PDC and PDC+

Combined with modern software, the new PDC+ method allows much shorter measurement times

properties of pressboard at various water contents and temperatures, help users to automate this process.

The principle of the assessment is to simulate a transformer insulation using the database and to model barriers and spacers with the so called X-Y-model [4]. This way, no "fingerprint" or previous measurement is required and all kinds of transformers (and also other oil-paper insulated assets) can be simulated (Figure 5). The parameters of the simulated curve are adapted until the simulated curve fits the measured curve best. When this is the case, all parameters (moisture, oil conductivity, etc.) of the "fitting" simulated curve are identical to the parameters of the measured transformer. The whole procedure involves a high number of calculations but is performed within seconds by the measurement software.

The DFR method has been described by CIGRÉ [5] [6], and an IEEE guide is currently under development [7]. There are no other non-invasive ways to assess moisture in a transformer that can provide comparable accuracy.

3. Reduced time for DFR measurements

3.1 Traditional FDS measurement method

Traditionally, dielectric parameters are measured in frequency domain by applying different frequencies and measuring the response. This technique is called frequency domain spectroscopy (FDS) and is applicable for all frequencies, from the μHz area to the GHz area and above. It is quite simple in handling, but takes a lot of time to measure low frequencies as the duration of sine waves at, for example, 10 μHz, takes about 27 hours, not taking into consideration all the other frequencies which also have to be measured.

3.2 Conventional PDC measurement method

Another method to measure the dielectric properties is to apply a voltage step to the tested asset and to measure the resulting polarization current for some time. This time-dependent information can be transferred to frequency-dependent dielectric properties [5]. It is called polarization depolarization current measurement (PDC) as traditionally not only the polarization, but also the depolarization current, was measured and compared. Modern algorithms only require the polarization current which halves the measurement time. By using PDC instead of FDS, the measurement time can be significantly reduced as one single PDC measurement provides the information for all frequencies which should be measured.

This principle provides a way to save measurement time: conventional conversion from time domain to frequency domain uses a static correlation between the measurement time and the calculated frequency range. If, for example, the time

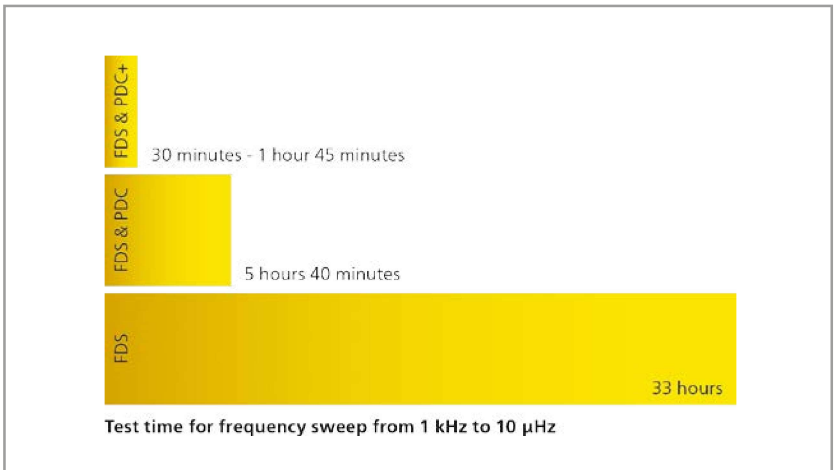

Figure 7. Test time for a frequency sweep from 1 kHz to 10 μHz

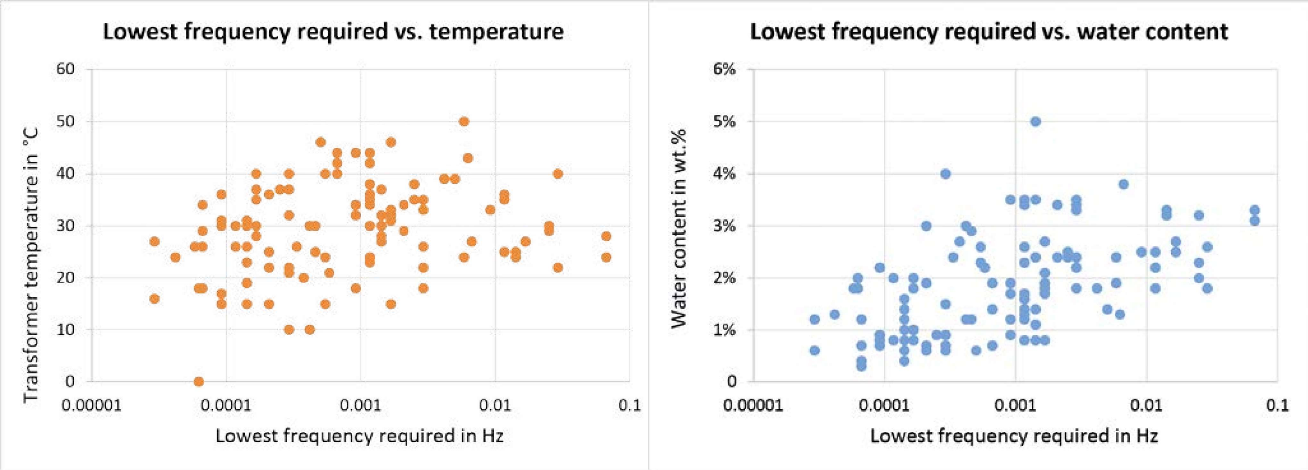

Figure 8. Correlation of transformer temperature and water content to the required lowest frequency which has to be measured. The evaluation is based on 115 dielectric measurements on power transformers.

domain measurement was performed for 1,000 seconds, the frequency response was always calculated down to the inverse frequency of 0.001 Hz.

3.3 Time-improved PDC+ measurement method

A new algorithm called PDC+ uses a dynamic approach and calculates up to 20 times more data in frequency domain from the same time domain information (Figure 6). It uses the same principle as PDC, but the lowest frequency calculated is at least three times lower than with conventional PDC.

Thus, the PDC+ technique allows much shorter measurements for the same frequency range than FDS or conventional PDC techniques (Figure 7). Modern measurement devices combine FDS for high frequencies and PDC+ for low frequencies. Where conventional FDS measurements take more than a day to measure from 1 kHz to 10 μHz, modern FDS and PDC+ devices can achieve this in 30 minutes to one hour 45 minutes.

There is also yet another way to reduce the test time. In many cases, it is not necessary to measure the whole frequency range down to 10 μHz. If the test can be stopped earlier, more time can be saved. However, shortening the measurement time too much can be critical as the important frequency range below the hump has to be measured. If the test is stopped too soon, the results would be worthless and the whole measurement would have to be repeated.

The required lowest frequency, which has to be measured in order to achieve valid results, is not showing any good correlation to the transformer temperature, so this cannot be used to determine the required frequency range (Figure 8). The required frequency range is also not directly related to the water content of the sample (Figure 8).

There is a parameter which is directly related to the hump and which is measured directly: The real part of the complex capacitance, known as C' or mostly referred to simply as "capacitance". At high frequencies, it is stable, but at the beginning of the hump it starts to increase (Figure 9). As the tan(δ) is the quotient of imaginary part C" (namely, the losses) and the real part of the capacitance C', it is obvious that a larger increase of C' than of C" leads to a lower tan(δ). The increase of C' can be used to detect the position of the hump. As the part of one to two decades left of the hump is dominated by the influence of moisture, this frequency range has to be measured. Lower frequencies are not required, so the measurement can be stopped once this frequency range has been determined.

The advantage of using C' is that its value is rarely influenced by disturbances. Also,

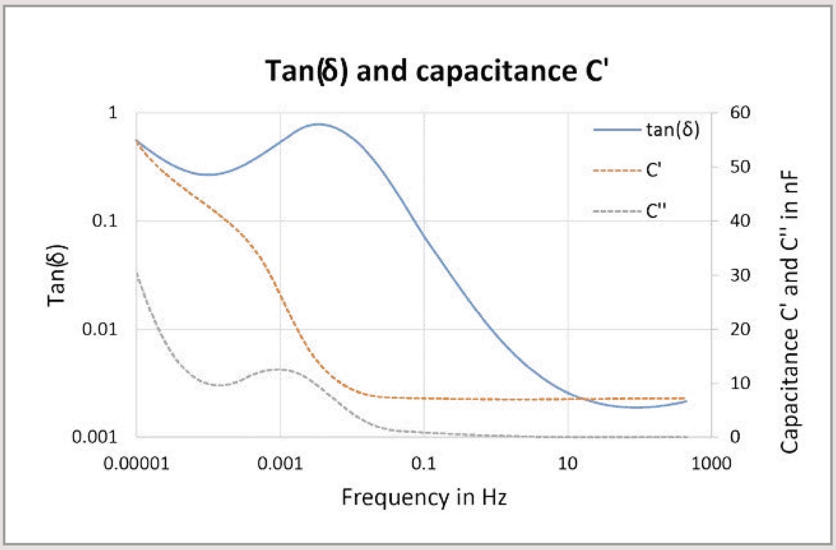

Figure 9. Correlation of the "hump" in tan(δ), the real part C' and the imaginary part C" of the capacitance for a power transformer

Modern DFR devices offer fully-automated assessment of water content and oil conductivity once the required data has been measured

for certain assets, for example, power transformers with good oil but increased moisture content, the tan(δ) curve does not show a pronounced hump, but the evaluation of the C' increase provides correct information.

The effect is not only proved empirically, but can also be derived from the dielectric behaviour: an increase of C' in this low frequency area corresponds to space charge polarization which happens in the cellulose insulation. Therefore, the frequency area where C' increases (compared to high frequencies) is influenced by the cellulose.

With the information of the required frequency range, which is available during the measurement, the frequency range can be limited to the minimum required range. This helps to reduce the test time drastically in most cases and avoids inaccurate measurements with too short frequency ranges.

4. Modern DFR measurement devices

One of the big problems of dielectric moisture determination in the past was – besides the measurement time – the high complexity of the measurement. Although the test setup itself is very easy, the determination of the correct frequency range and the assessment of the curve required background knowledge.

Modern DFR measurement software is able to automatically and individually set the frequency range for each power transformer. At first, the maximum frequency range is set and when the software has determined the increase of C', it can calculate and adjust the required remaining frequency range and the corresponding measurement time.

The increase of C' not only helps to reduce the time, but also allows a more accurate moisture assessment as the part of the curve which is dominated by moisture is reliably identified. Modern measurement software is able to perform the curve fitting and assessment of water content and oil conductivity fully automatically once the required data has been measured. It also normally includes an automated assessment function, which compensates for influences such as insulation geometry, oil conductivity and aging byproducts. The testing device should be able to conduct the automatic evaluation according to national, international or user-defined standards.

Conclusion

Water is a danger to the insulation of oil-paper insulated power transformer as it ages and decreases the mechanical strength of the insulation. If the water content is increased, counter-measures such as drying have to be applied before the insulation is severely aged. Dielectric measurements enable a reliable assessment of the water content without the drawbacks of other methods.

The new PDC+ method combined with modern software allows much shorter measurement time and easier applicability.

With the automation of the whole test, which is possible in modern software, the tester only has to set up the test set and press the start button. The only parameter which has to be entered manually is the asset temperature. Therefore, even inexperienced users can reliably assess the water content of power transformers. This information allows the user to determine if life extending actions have to be taken or if the asset is still in good shape.

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