Dielectric analysis of high voltage power transformers

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1 Introduction

Power transformers are the most expensive assets used in power transmission and distribution. Their owners expect a long working life without unplanned outages. In order to fulfill this task, the transformer has to be in healthy condition which must be verified by diagnostic means. If the results are not optimal, actions can then be taken to prevent failures. One group of diagnostic methods are dielectric measurements. Their intention is to identify the status of the insulation of the power transformer and its bushings. The integrity of their insulations is one basic requirement for their safe operation.

During the last decades, a variety of different types of dielectric measurements have been developed. The common basis of all those dielectric diagnostic measurement techniques is that they are non-invasive and identify capacitance and losses of the insulation they are applied on. Their difference is the investigated frequency range, the applied voltage and the assessment technique used to interpret the results. Collectively, these different techniques provide a variety of information about the measured insulation.

2 Dielectric properties of insulation systems

The dielectric properties of paper and pressboard are influenced by their temperature and water content. The influence of water is high especially for the tan(δ) at lower frequencies where water increases both polarization and conductivity (Figure 1) [1] [2]. Dielectric properties at line frequency and above are only slightly influenced; a significant influence is visible only where there is higher water content.

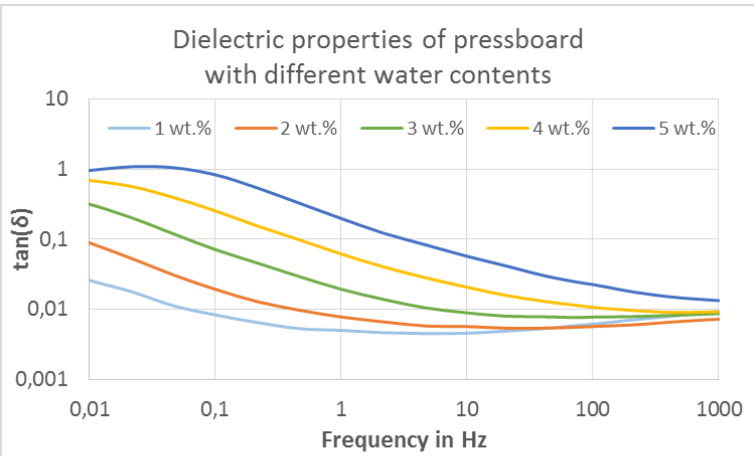

Figure 1. Dielectric properties of oil impregnated pressboard at different water contents at 20°C. (Dielectric properties of pressboard with different water contents Frequency in Hz, 1 wt. %)

The dielectric response of paper and pressboard is also dependent on temperature. Therefore, measuring the temperature is always essential when measuring dielectric properties.

The dielectric properties of mineral oil show a simpler behavior than those of pressboard and can be sufficiently modeled with a single conductivity and permittivity for low field strengths [1] [2].

The dielectric properties of a combined oil paper insulation in a power transformer are dependent on a broad range of parameters such as:

- Temperature
- Oil conductivity
- Internal geometry (amount of barriers and spacers)

- Water content in the paper and pressboard insulation

A closer look shows that these influence factors are dominant at different frequencies (Figure 2). A higher oil conductivity or temperature will cause the tan(δ) curve to shift towards higher frequencies whereas a higher water content will increase the tan(δ) at higher and lower frequencies but show very limited influence in between. For moisture assessment, the dominant part of the water content at lower frequencies provides much more reliable results. Using high frequencies for water content determination cannot be recommended as those dielectric properties are more dependent on the oil conductivity than the water content (Figure 3). A high tan(δ)/power factor value at line frequency does not provide information as to whether the reason is a high water content or a high oil conductivity (Figure 3). The latter can achieve values from 0.1 pS/m and below for new oil up to hundreds of pS/m for heavily aged oil.

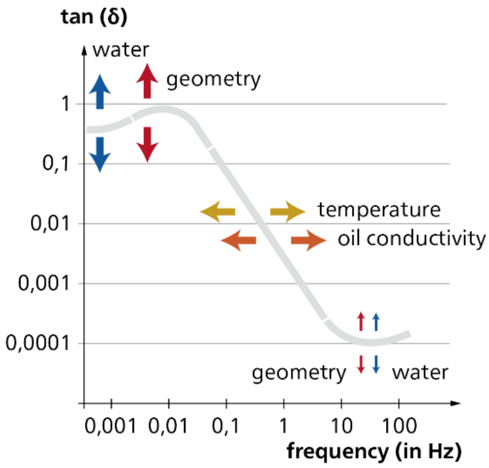

Figure 2. Dielectric properties of a power transformer oil-paper High- to the Low-voltage winding insulation (CHL)

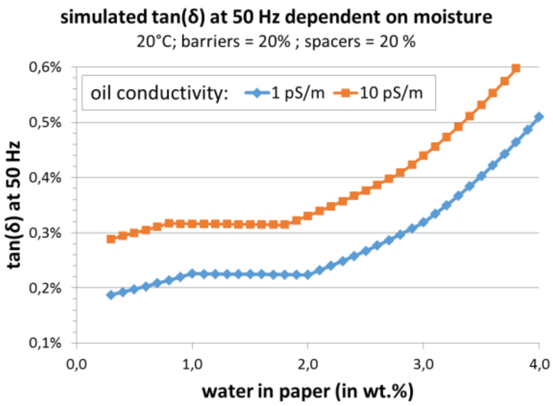

Figure 3. Simulated dependence of the dissipation factor at 50 Hz for a power transformer at two different oil conductivities (simulated tan(δ) at 50 Hz dependent on moisture; 20°C; barriers = 20 % , spacers 20 %; oil conductivity 1 pS/m, 10 pS/m; tan(δ) at 50 Hz; water in paper (in wt.%))

3 Dielectric measurement methods for field tests

Although it is theoretically possible to perform a dielectric measurement at any frequency and any voltage, several groups of measurement devices with similar test parameters are available for field test of high voltage equipment. Therefore, the following chapters will highlight the features and the practical use of each of the test methods.

Measurements at a single frequency

Dielectric measurements at a single frequency are usually performed at the line frequency of the system, usually 50 Hz or 60 Hz. As interference at the same frequency from a live system nearby has to be expected in field use, usually a high voltage source is required to achieve a suitable signal to noise ratio, making the test equipment often quite big and heavy. The advantage of testing at the line frequency of the asset is that all determined parameters (capacitance, losses…) apply also in the real use of the asset.

Measurements at a limited frequency range (15 Hz to 400 Hz)

An improved version of the measurement at line frequency is the measurement at a frequency range including line frequency. A typical frequency range is 15 Hz to 400 Hz. Due to the increased frequency range, the frequency dependency of dielectric properties can be analyzed. Although the still limited frequency range does not allow for a separation of the multiple influence factors (see Figure 2), often some further conclusions regarding the status of the asset can be drawn. Dielectric properties at line frequency can either be measured directly or they can be obtained by interpolation, thus, a comparison of measured values to reference values at line frequency is also possible.

Measurements using variable voltage ("tip up test")

The usually called "tip up test" is a measurement at a single frequency where the voltage is increased and the dielectric parameters are measured in a voltage range. Mostly line frequency is used but also a combination with a frequency range (see previous section) is possible. There are some defects which can be detected by such a test, like a bad contact at a measurement tap of a bushing (see Figure 9).

Broadband dielectric measurements (DFR)

Broadband dielectric measurements (often called "DFR" for Dielectric Frequency Response) are used to measure the dielectric properties of an asset in a very wide frequency range, usually from the lower kHz region to a few mHz or even µHz. Various principles exist, using measurements in frequency as well as time domain. Also combinations are possible and can help to combine advantages of different principles [3]. When performed in a similar and correct way, the results from one method can be converted to the other [4] [5]. The most used form of presenting the obtained data is in frequency domain, i.e. the property is displayed in a chart versus the frequency.

The big advantage of using a very broad frequency range is the high sensitivity for different influence factors (see Figure 2). This makes the method highly sensitive for detection of e.g. water and aging for example [6]. With the assistance of a PC, this method is also capable of determining the absolute amount of the water content in the paper/pressboard insulation [1] [7] [3]. This way, also the conductivity of the oil is determined.

4 Measurement setup and guarding

Depending on the connection, different parts of the power transformer insulation are measured. The two winding core type transformer is a very good example to show the different parts of insulations which can be measured in a transformer. It is also used here to explain the principle of guarding.

A two winding transformer with high and low voltage winding provides 3 different insulations which can be measured: The insulation from the high- to the low-voltage winding CHL, the insulation from the high-voltage winding to core and tank CH and the insulation from the low-voltage winding to core and tank CL.

The insulation CHL in case of core type transformers is made of barriers and spacers which give the insulation mechanical stability and enable the oil flow to cool the windings. Compared to the other insulation parts, the mayor amount of cellulose (paper and pressboard) is located in the CHL insulation so its properties are highly influenced by those of the cellulose. Therefore, when properties of the cellulose like the water content should be analyzed, CHL is of the highest importance.

The insulation CH, which is from the high voltage windings to the tank mainly consists of oil. The influence of cellulose usually comes mainly from the parts of the clamping construction. The insulation CL, which is largely from the low voltage windings to the core also consists of oil and cellulose, but usually much less cellulose is present than in the CHL insulation.

If the CHL insulation would be measured by only injecting a voltage at the HV side and measuring the current at the low voltage side (or vice versa) without a guard connection, the current via the bushings and via CH and CL would also be measured (Figure 4 a).

In order to eliminate those additional influences and to be able to measure the properties of CHL alone, the technique of guarding is used. It uses an additional “guard” connection at the measurement device via which unwanted currents can be “bypassed”. By connecting the tank to guard in the above example, only the current via the CHL insulation is measured (Figure 4 b).

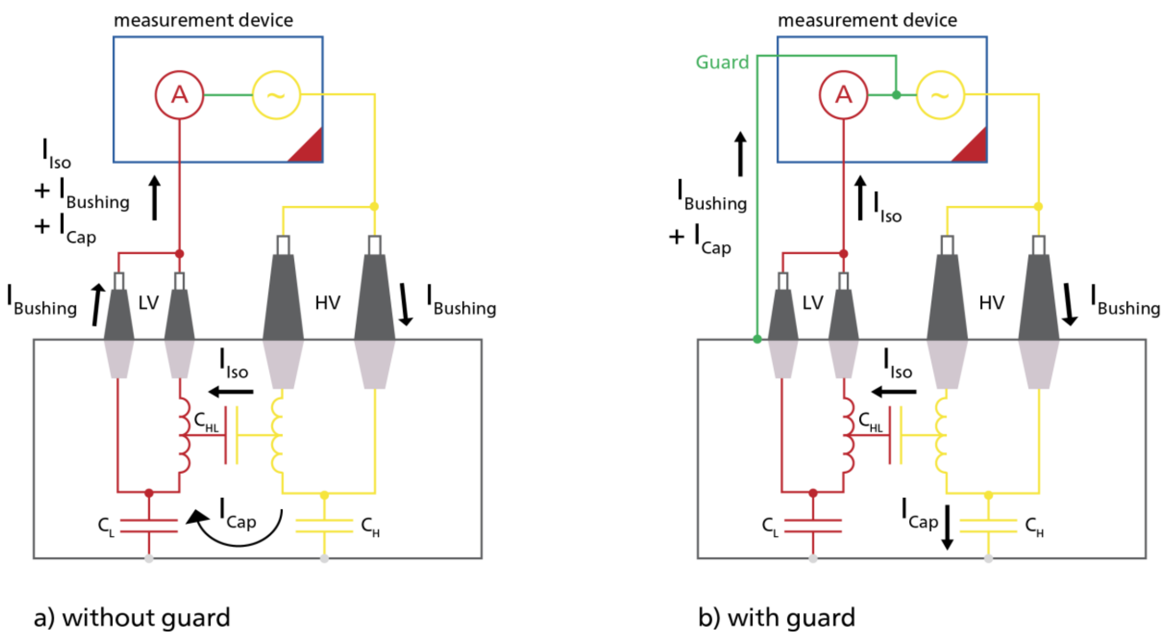

Figure 4. CHL measurement on a two-winding transformer without and with guard (measurement device; ISO; Bushing; Cap; without guard; Guard; with guard)

5 Performing dielectric measurements on power transformers

Preparations

Before any dielectric measurement is performed on a power transformer, all electrical connections to the bushings have to be disconnected completely. This is not only for safety reasons but also because dielectric measurements will measure all parts connected to the system and induced voltages can lead to disturbances of the measurement. All windings of the same group (HV, LV, TV…) are shorted before the measurement. Also the neutral bushing, if available, should be included in the shorting.

It has to be noted that for all kinds of dielectric measurement the temperature will have a significant influence on the result. Therefore, it is essential to measure and to note it.

Measurements at line frequency

Measurements at line frequency provide parameters which can be compared to reference values in order to see if any differences are visible. Whereas the capacitances are usually not significantly influenced by small temperature deviations between the actual and the reference measurement, the dissipation/power factor measurements can only be compared if they have been performed at the same temperature.

A survey performed on over 100 power transformers included the relation of the dissipation factor at 50 Hz to the water content (Figure 5). The dielectric losses tend to increase for higher water contents but it is not possible to derive a specific water content from a measured tan(δ) value. For example, a dissipation factor of 0.5 % was measured at a transformer with a low water content of 1.4 wt.% but also at a transformer with a high water content of 4 wt.%.

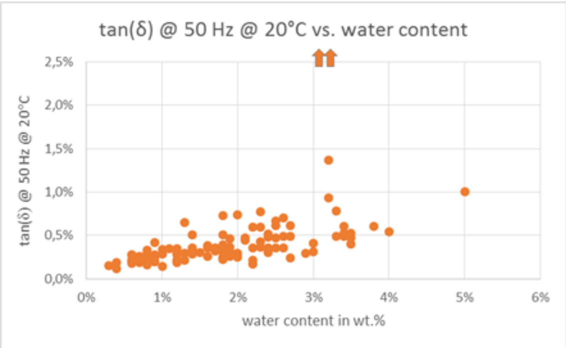

Figure 5. Ratio of tan(δ) at 50 Hz and 20 °C to the water content in the cellulose at over 100 power transformers, assessed via broadband dielectric measurement using the OMICRON DIRANA test system. (tan(δ) @ 50 Hz @ 20 °C vs. water content; water content in wt. %)

Measurements at 15 Hz to 400 Hz

Measuring the tan(δ) at a small frequency range close to power frequency, for example from 15 Hz to 400 Hz not only provides information about the dielectric losses at power frequency but also shows the slope of the tan(δ) curve. This provides additional information about the oil conductivity and can help to analyze whether the high tan(δ) is caused by the oil. Nonetheless, the information of this line frequency value is not sufficient to reliably determine the water content.

Figure 6 shows the tan(δ) of 4 power transformers in a frequency range from the µHz region up to some hundred Hz. At 50 Hz, the assets with 0.7 % and 2.3 % of water in the paper insulation show quite identical tan(δ) values (0.164% and 0.172%), but when the value is measured at different frequencies, the difference of the curves is clearly visible, even in the restricted frequency range of 15 Hz to 400 Hz. A high negative slope of the curve in this range is an indicator for a high oil conductivity as the red curve shows. Positive slopes in the whole frequency range indicate usually a very low oil conductivity.

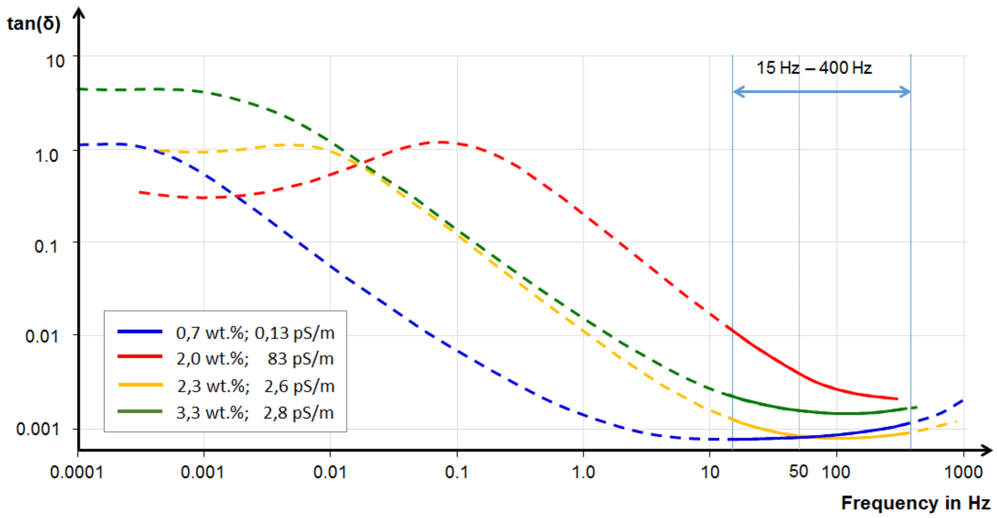

Figure 6. Broadband dielectric response of 4 different power transformers at 20°C. (Frequency in Hz)

Measurements using variable voltage ("tip up test")

Measurements with variable voltage, also called "tip up tests", are usually not performed on the power transformer itself but on the bushings where they can help to detect for example contact problems or breakdowns between grading layers [8] [9].

Broadband dielectric measurements

The dielectric properties of a large frequency range, including those at lower frequencies (mHz or µHz region) allow for the separation and identification of the properties of oil and pressboard in a power transformer.

The measured curve typically shows the characteristic shape which includes a "hump" at lower frequencies (Figure 6). The region below the "hump", around 1 - 2 decades from the "hump" peak, is highly influenced by the water content in the cellulose insulation. Determining this frequency region is essential and the measurement, typically starting at higher frequencies, must not be stopped before this frequency region has been measured. Therefore, setting a sufficiently large frequency region is very important.

A practical approach is to set the largest range which is possible and to stop the measurement once the user recognizes that all the required data has been measured. Another frequently used scheme is performing the measurement over night after the required safety measures have been established.

A survey on over 100 measurements on power transformers clearly shows the stop frequency can't be derived from the asset temperature as even quite warm power transformers can require very low stop frequencies in the µHz region (Figure 7). The stop frequency was defined as the frequency 1.5 decades below the frequency of the "hump".

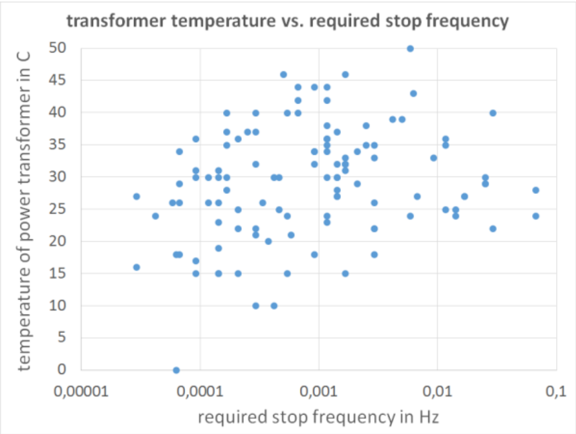

Figure 7. Required stop frequency, depending on the transformer temperature in a survey including over 100 power transformers (transformer temperature vs. required stop frequency; temperature of power transformer in C; required stop frequency in Hz)

The temperature of the insulation is of essential importance for moisture analysis and therefore should be carefully noted. Without the correct insulation temperature, a reliable moisture assessment of the solid insulation is impossible. The top oil temperature correlates best with the average insulation temperature, therefore, it is recommended to use this value for the moisture assessment.

The assessment of the curves is usually automated by the assistance of a computer and a database for oil impregnated cellulose which contains dielectric properties of pressboard at various water contents and temperatures. The result of this assessment is the water content in the cellulose insulation and the oil conductivity. The remaining life of the asset is dependent on many factors, however, the moisture content is an important parameter. Therefore, this measurement is very helpful in estimating the remaining life of the transformer insulation and shows if measures like drying or oil processing are necessary.

6 Measurements on bushings

In a power transformer, usually more than one bushing of the same type and age is installed which allows the comparison of dielectric properties between the identical units additionally to a comparison to fixed limits. Thus, if for example, three identical bushings show identical dielectric properties, the existence of a problem (which can be detected by dielectric measurements) is also unlikely in any of them.

In addition, where dielectric measurements are performed on bushings, the temperature dependence has to be considered. Investigations showed that even complex compensation techniques are not able to perform such a compensation in all cases [10]. Therefore, the best way to compare dielectric values of bushings, say to other bushings or to fixed limits, is to perform the measurements at the same or similar temperature.

Measurements at line frequency on bushings

The measurement of the capacitance and the dissipation/power factor at line frequency has been a very common procedure for many decades. Whereas a change in capacitance indicates a breakdown between capacitive layers, an increase of the dissipation/power factor can also indicate problems such as water, aging, carbonized parts or bad contacts. Both IEEE and IEC bushing standards require the measurement of the dissipation factor at room temperature as a routine test on new bushings. Table 1 shows the limits at line frequency according to IEC 60137 [11] and IEEE C57.19.01 [12] for different kinds of new bushings.

	Resin impregnated paper (RIP)	Oil impregnated paper (OIP)	Resin bonded paper (RBP)
Tan δ (source IEC 60137)	< 0.7 %	< 0.7 %	< 1.5 %
PF (source IEEE C57.10.01)	< 0.85 %	< 0.5 %	< 2 %
Typical values for new bushings	0.3 % - 0.4 %	0.2 % - 0.4 %	0.5 % - 0.6 %

Table 1. Limits and typical dissipation factor (tan(δ)) and power factor (PF) values at line frequency according to IEC 60137 and IEEE C57.19.01 at 1.05 Um√3 and 20 °C / 70 °F (Resin impregnated paper (RIP); Oil impregnated paper (OIP); Resin bonded paper (RBP); Tan(δ) (source IEC 60137); PF (source IEEE C57.10.01); Typical values for new bushings)

Measurements at 15 Hz to 400 Hz on bushings

The measurement of the dielectric properties, especially the dissipation/power factor at lower frequencies increases the sensitivity towards moisture and aging. Figure 8 shows the dissipation factor for a dry and a wet bushing between 20 Hz and 400 Hz. Although the difference is also visible at line frequency and above, it is most significant at lower frequencies.

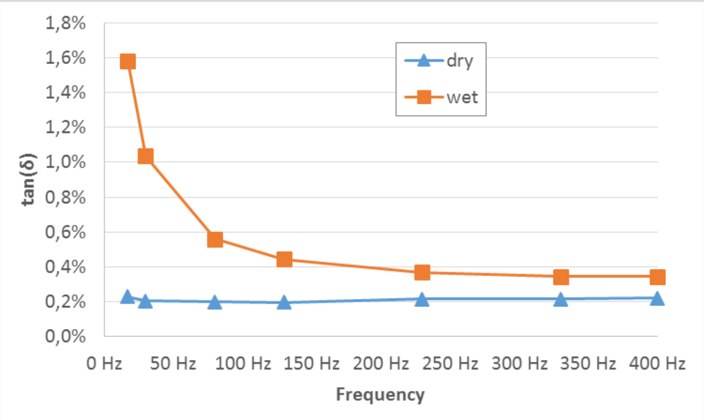

Figure 8. Frequency variable tan(δ) of a dry and a wet 33 kV OIP bushing at 30°C (data from [8]) (dry; wet)

Table 2 shows the indicative limits at different frequencies of the Cigre power transformer maintenance guide [9].

	Resin impregnated paper (RIP)		Oil impregnated paper (OIP)		Resin bonded paper (RBP)	
Frequency	**new**	**aged**	**new**	**aged**	**new**	**aged**
15 Hz	< 0.6 %	< 0.7 %	< 0.5 %	< 0.7 %	< 0.7 %	< 1.5 %
50 Hz / 60 Hz	< 0.5 %	< 0.5 %	< 0.4 %	< 0.5 %	< 0.6 %	< 1.0 %
400 Hz	< 0.6 %	< 0.7 %	< 0.5 %	< 0.7 %	< 0.7 %	< 1.5 %

Table 2. Indicative values of tan(δ) limits for bushings at 20 °C [9] (new, aged)

Measurements using variable voltage (“tip up test”) on bushings

Measurements of bushings at different voltages can reveal problems like bad contacts of measurement tabs. If such a problem exists, the dissipation/power factor decreases towards higher voltages (Figure 9).

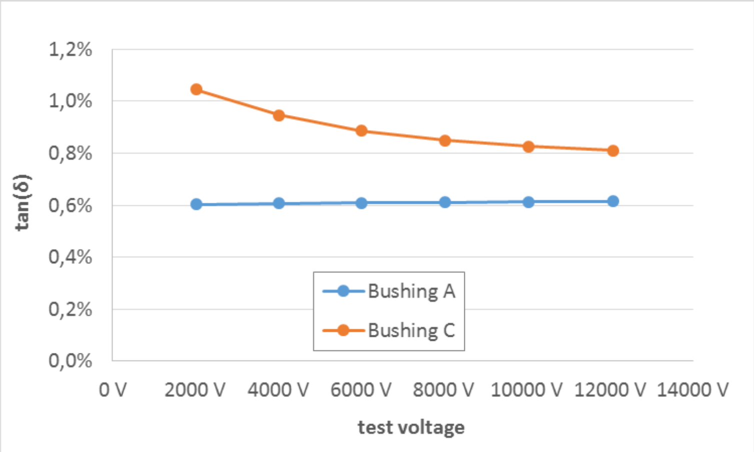

Figure 9. Tan(δ) measurements of two 123 kV RBP bushings of the same type at different voltages with contact problems at the measurement tap of bushing C (data from [8]) (Bushing A, Bushing C; test voltage)

Broadband dielectric measurements on bushings

As the low frequency area is most sensitive towards water and aging, broadband dielectric measurements can be used to detect small changes in the water content and are therefore also applicable for new bushings for example for quality control.

Broadband dielectric measurements of Oil Impregnated Paper (OIP) bushings also allow an assessment of the absolute water content with a procedure which is similar to the assessment of power transformers [13]. A determination of the absolute water content is not possible for other kinds of bushings like RIP or RBP as the database is only valid for pure oil-cellulose insulations [3]. However, the water content is also influencing the dielectric properties of those insulation systems so changes can be detected by comparing different measurements.

7 Conclusion

Dielectric measurements help to detect various problems on power transformers and bushings. The different types of dielectric measurements allow for the identification of specific problems (Table 3). For the transformer insulation for example, a broadband dielectric measurement will provide not only the absolute water content in the cellulose insulation but also the oil conductivity. On bushings, a “tip-up”-test with increasing voltage could reveal possible contact problems which can hardly be detected by other tests. By choosing the correct tests, engineers can detect issues on power transformers and bushings and propose maintenance before failures occur.

Test range	... can be applied to determine ... at power transformers	at bushings
line frequency	general condition	general condition, breakdowns between capacitive layers, detection of a high water content
15 Hz - 400 Hz	general condition, statements regarding the oil conductivity	general condition, breakdowns between capacitive layers, detection of a high water content
tip-up test (variable voltage)	problems at the bushings	contact problems, breakdowns between capacitive layers, general condition
broadband dielectric measurement	absolute water content, absolute oil conductivity, general condition	absolute water content (OIP only), detect influence of water and aging, general condition, breakdowns between capacitive layers

Table 3. Summary of detectable problems with the different types of dielectric tests (… can be applied to determine …; Test range; at power transformers; at bushings; line frequency; general condition; general condition, breakdowns between capacitive layers, detection of a high water content; 15 Hz – 400 Hz; general condition, statements regarding the oil conductivity; tip-up test ; variable voltage; problems at the bushings; contact problems; broadband dielectric measurement; absolute water content, absolute oil conductivity, general condition; absolute water content (OIP only), detect influence of water and aging)

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