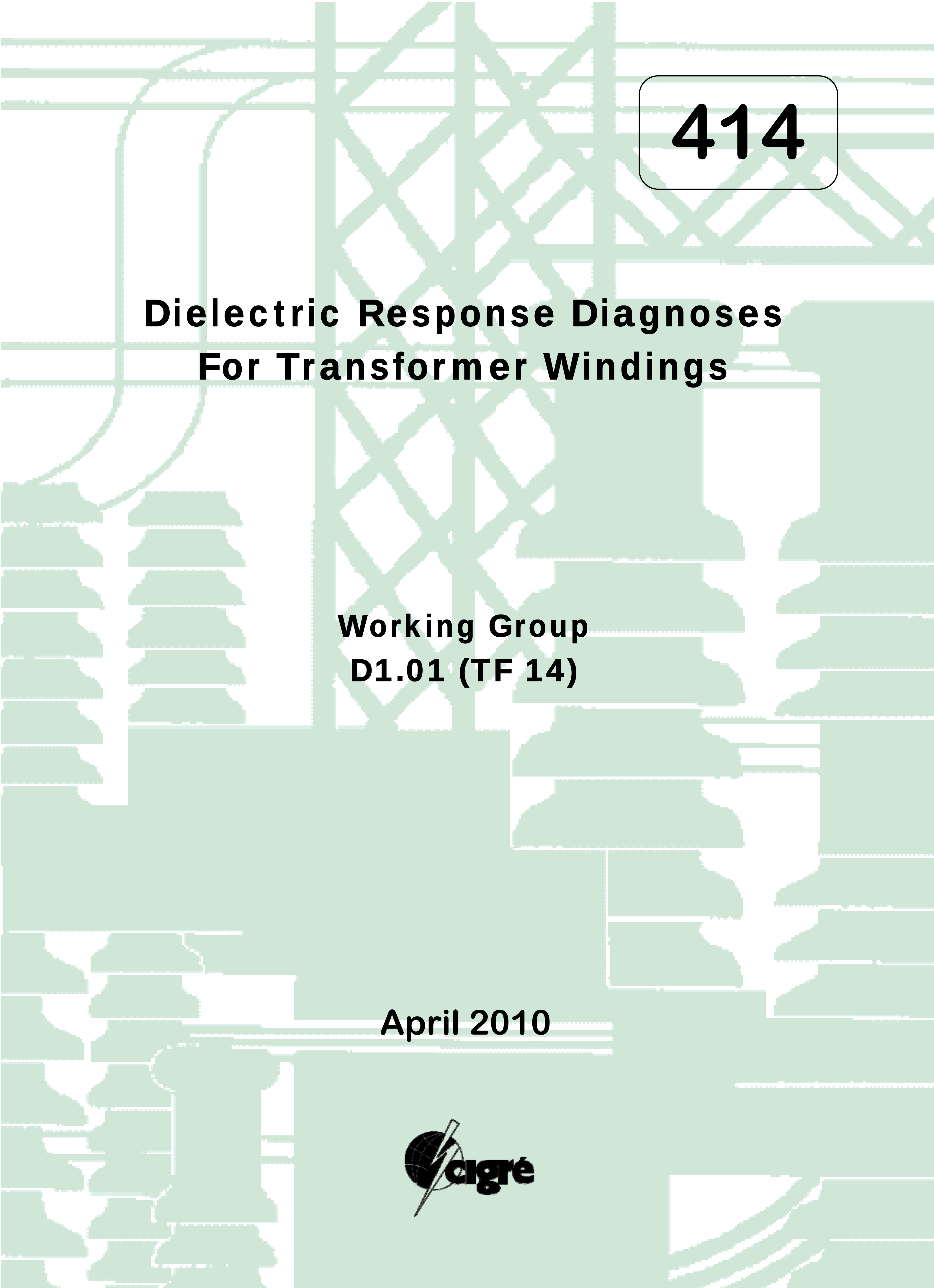

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Dielectric Response Diagnoses For Transformer Windings

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Dielectric Response Diagnoses for Transformer Windings

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Content

Executive summary

The dryness of the oil-paper insulation systems in power transformers is a key factor in both their short and long term reliability since moisture has deleterious effects on dielectric integrity and insulation ageing rates. Traditionally, moisture in oil measurements have been used to estimate the dryness of transformers, but this has not been a particularly reliable approach because of possible sampling and analysis errors and because moisture distributes unequally between cellulose and oil, the greater part residing within the solid insulation, with the water content in the oil being very dependent on temperature and also oil condition, and therefore not simply correlated to solid insulation dryness. The moisture content in the solid cellulose insulation is therefore the key parameter. Unfortunately it is impractical to determine this directly by taking paper samples. Therefore, recent attention has been directed to methods of determining moisture content by measuring the effects of the moisture on electrical properties of the insulation. Rather than traditional measurements of power frequency dissipation factor, the variation of various dielectric parameters in the time and frequency domains have been studied in an attempt to isolate the effects of moisture.

A previous CIGRE Working Group, 15.01.09 [1], evaluated the three foremost of these so-called ‘dielectric response’ techniques:

- Return voltage measurements, sometimes also called recovery voltage – (RVM)
- Polarisation and depolarisation current variation in time domain - (PDC)
- Capacitance and dissipation factor variation with frequency – (FDS)

It was concluded that all three techniques reflect the same fundamental polarisation and conduction phenomena in transformer insulation, the special feature of which is a combination of oil gaps and solid insulation, and as a consequence are influenced strongly by both solid insulation moisture content and oil condition, and also, but less strongly, by the geometry of the solid and liquid insulations. Mathematical modelling was seen as the key to determining how measured responses are affected by oil conductivity and moisture content. By contrast, the simple relationship claimed between RVM dominant time constant and solid insulation moisture content was shown to be flawed. Although these dielectric response techniques were considered promising, it was concluded that solid insulation moisture contents determined from measured responses still needed to be verified by comparison with basic chemical measurements, and also that the influences of different types of pressboard/paper and ageing products still had be to determined.

The present Working Group has investigated the influences of different types of solid insulation and ageing products, provided detailed guidance on the practicalities of making dielectric response measurements, and collected case examples illustrating the value of such measurements. The work has focussed almost exclusively on the two techniques which allow the clearest discrimination between the effects of oil condition and solid insulation moisture content: FDS and PDC. It is concluded that different types of pressboard and ageing products, in particular low molecular weight acids, can have a significant effect on measured dielectric responses. As a result, as shown by a case example, the solid insulation moisture content in aged insulations can be overestimated and improvements to interpretation schemes are desired. As regards verifying dielectric response moisture determinations by comparison with basic chemical measurements, it is concluded that there are too many uncertainties associated with the application of equilibrium diagrams based on moisture estimation

in oil obtained by Karl Fischer titration for this to be a useful reference, but relative saturation measurements are seen as a promising alternative.

Measuring configurations in time and frequency domains
When estimating the moisture content in the solid part of traditionally designed transformers, one usually focuses on the main insulation, i.e. the insulation between the coaxially arranged high voltage (HV) and low voltage (LV) windings. The capacitance of this insulation is commonly denoted as CHL. Other capacitances of interest can, for example, be winding capacitances to ground (tank, core, etc.), i.e. CL or CH.
Dielectric response measurements, independently if in time or frequency domain, can be performed within different configurations, UST (Ungrounded Specimen Test) where the ground act as natural guard or GST (Grounded Specimen Test) with or without guard. Examples of instrument connections for these configurations are shown in Figures S1 and S2.

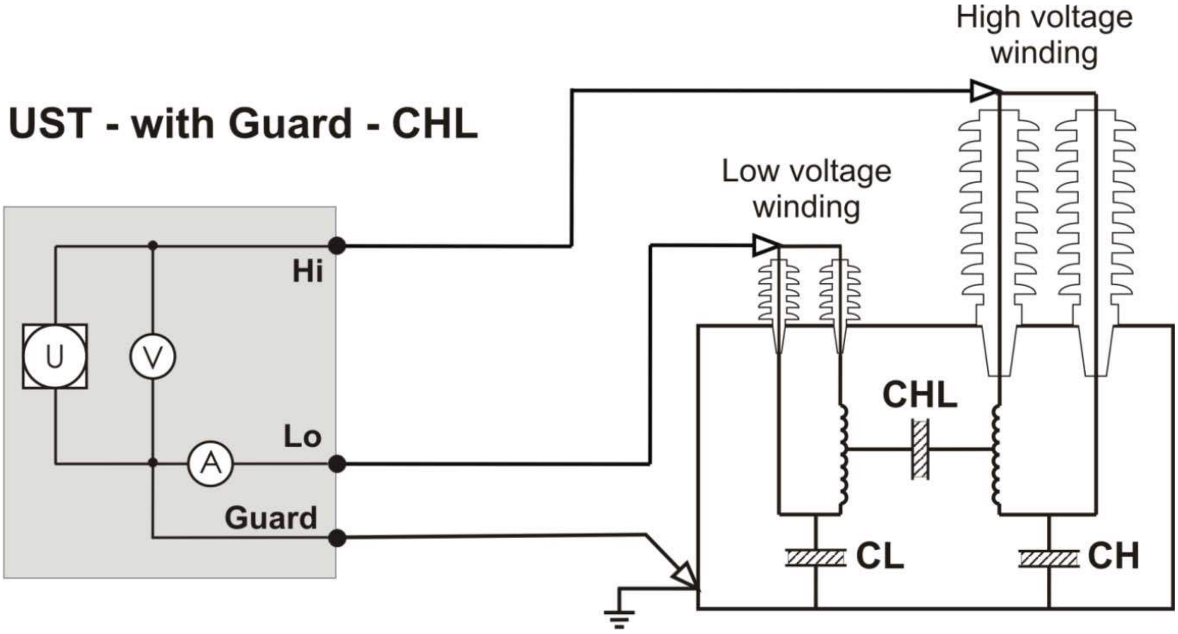


Figure S1: UST connection of dielectric response measuring system to a transformer for CHL configuration.

In case of auto-transformers having usually a tertiary winding, provided it is not internally earthed, the measurements of main to tertiary insulation, CHT, are possible and preferred, as illustrated in Figure S3.

Time domain measurements can directly be related to the polarisation and conduction phenomena in the investigated insulation system. Through measuring polarisation current $i_p(t)$ and depolarisation current $i_d(t)$ (PDC), information about its dielectric response function $f(t)$ is obtained, provided it is charged for a sufficiently long time. A rule of thumb says that the test object should be charged for at least 5 to 10 times as long as it is depolarised. It also is possible to estimate the dc conductivity, σ_{dc}, of the system from the difference between the polarisation and depolarisation currents. In an oil-barrier system most interesting information is obtained for longer times up to a few thousands seconds. The barriers are charged via the oil ducts immediately after voltage step application. Therefore the initial current values and the main time constant of the current curves are directly related to the conductivity of oil in the main ducts. The polarisation and depolarisation current and the difference between polarisation and depolarisation curves at longer times are directly related to the conductivity of the paper/pressboard part of the insulation system and its water content as indicated in Figure S4(a).

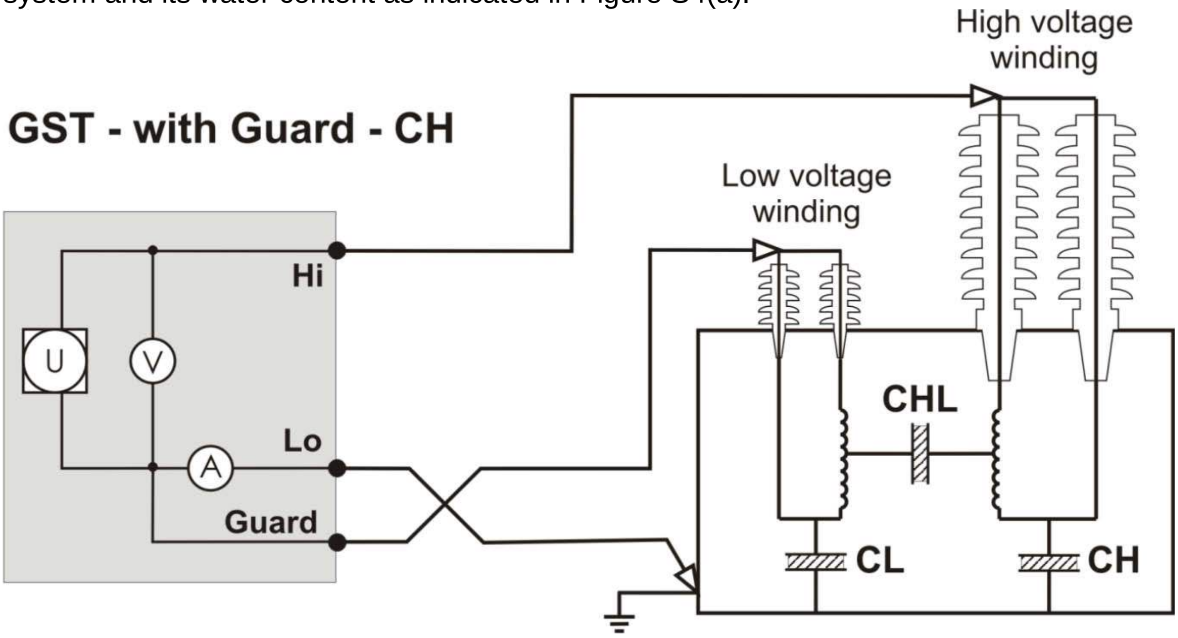


Figure S2: GST connection of dielectric response measuring system to a transformer for CH configuration.

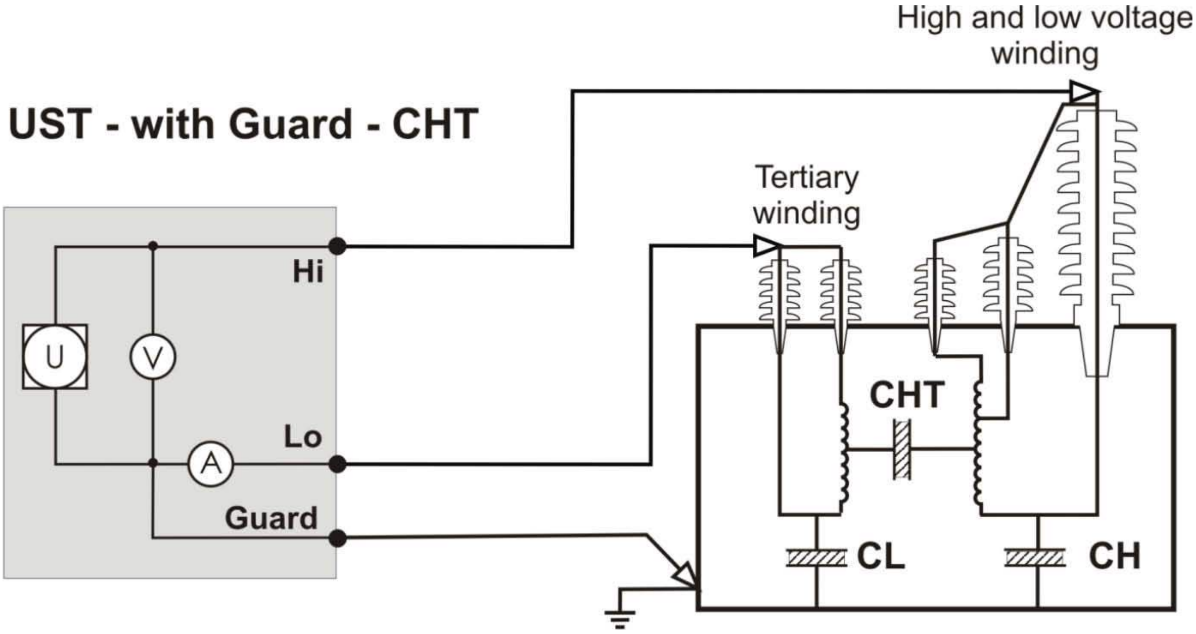
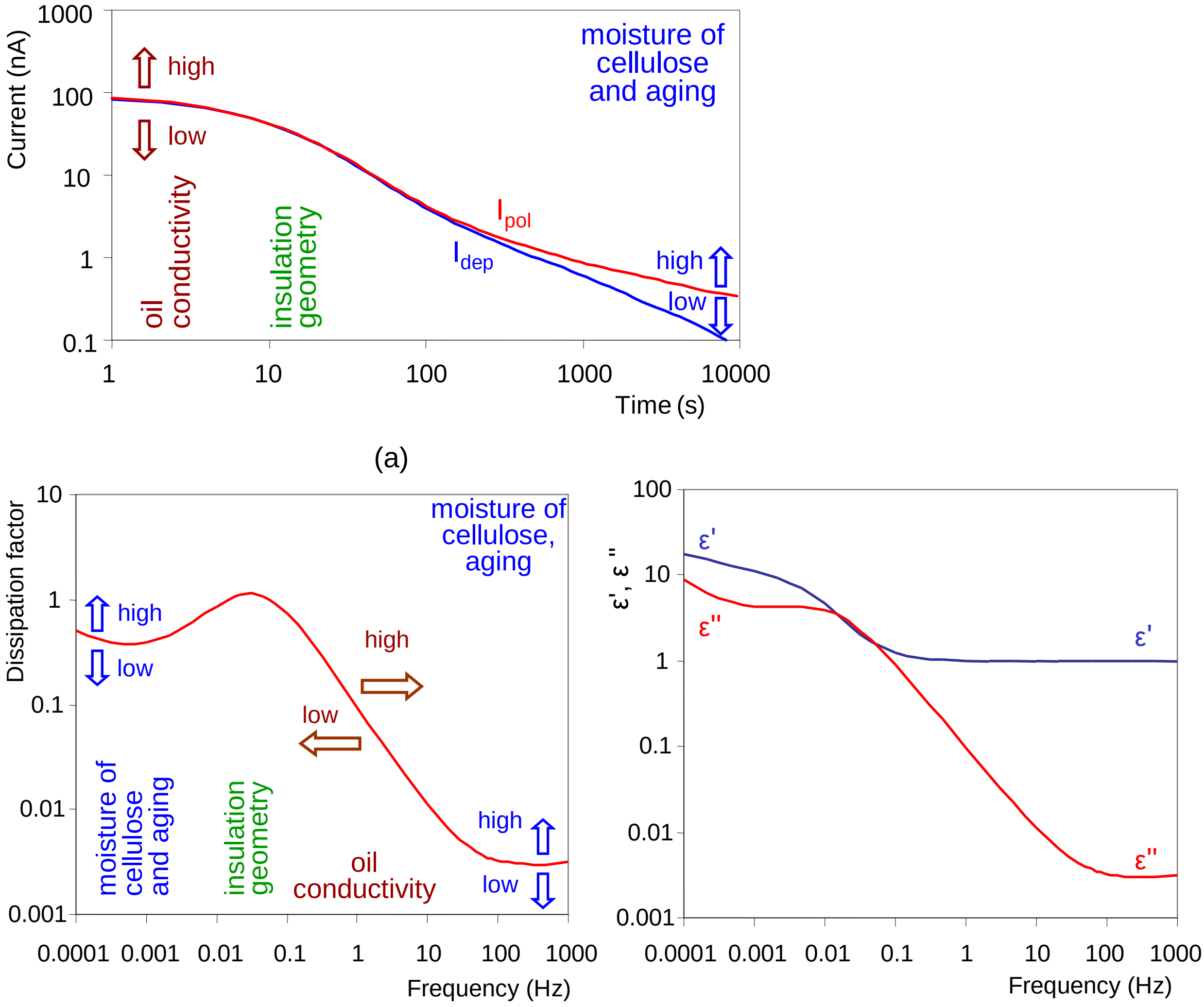


Figure S3: UST connection of dielectric response measuring system to an autotransformer with tertiary winding.

An equivalent method in the frequency domain is to measure the responses from sinusoidal excitations at different frequencies (FDS), say from 0.1 mHz to 1 kHz. On this basis the complex relative permittivity $\hat{\varepsilon}(\omega)$ at the frequency of the applied field, assuming a capacitive test object, can be found. It is important to notice that the imaginary part of the complex relative permittivity, $\varepsilon''(\omega)$, (loss part) contains both the resistive (dc conduction) losses and the dielectric (polarisation) losses. Another way of presenting the measured information of a FDS is to use the dissipation factor $\boldsymbol{tg}\delta(\omega) = \varepsilon''(\omega)/\varepsilon'(\omega)$. As shown in Figure S4(b), at the very low ($<10^{-2}$ Hz) frequency range the response is mainly influenced by the properties of the pressboard. In this range the imaginary part, $\varepsilon''(\omega)$ of the complex relative permittivity, has usually a slope similar to that of the real part $\varepsilon'(\omega)$, which represent the polarization behavior of the solid part of transformer insulation, modified by water content. The same is true for the higher frequency range (>10 Hz). The central part of the response is, on the other hand, influenced by the properties of the oil, mainly by its conductivity. Although insulation geometry is indicated to have a significant influence on responses in particular parts of the responses, it still has an effect over the entire frequency and time ranges.

The characteristic boundaries in PDC and FDS spectra differ for various moisture contents, conducting ageing by-products and temperatures.



(a)

(b)

Figure S4: Main features of PDC (a) and FDS (b) responses in oil-paper/pressboard barrier systems.

Execution of measurements

A successful dielectric response measurement on a power transformer requires adequate planning and coordination with its owner for finding information on winding geometry and on means to disconnect the unit from network. The objectives of the measurements, and thereby the resulting connection of the instrumentation to the transformer, should preferably be decided forehand.

Good understanding of the factors that may influence the measurements under field-conditions, and therefore also the interpretation of dielectric response results, is of crucial importance for the diagnosis reliability. Constant and preferably not too low temperature is advantageous for the interpretation quality – at higher temperatures the time necessary for the measurements can be shortened. It is recommended to make guarded CHL measurements between main transformer windings. In the case of CH and CL measurements, it is also important to make sure that the transformer bushings are dry and clean.

Before starting the measurements the transformer should preferably be completely disconnected from the station power connections, i.e. all connections to the bushings should be dismantled, and the station connections should be properly grounded. The bushing terminals of the individual windings should, if possible, be shortened together by conductors kept away of earthed structures. For CH and CL measurements internal leakages and creeps from bushing surfaces remain as the disturbing factors and therefore should be considered in the analyses of the results. If any of the windings has a neutral point connected either directly to ground or through impedance to ground, also this connection should be removed. The neutral bushing should preferably be interconnected with the phase bushings during the measurements. Sometimes a surge arrester is connected to the neutral point, and preferably, this connection should also be isolated.

The measurements are often affected by interference in the substation, such as parasitic leakage currents and induced electromagnetic disturbances. It is therefore important to secure proper grounding connections of the transformer tank during the measurements to minimize the ground interference. Proper placement of connecting leads can also minimize the influence of capacitive coupled or radiated noise. Use of shielded connecting cables is recommended in noise environments.

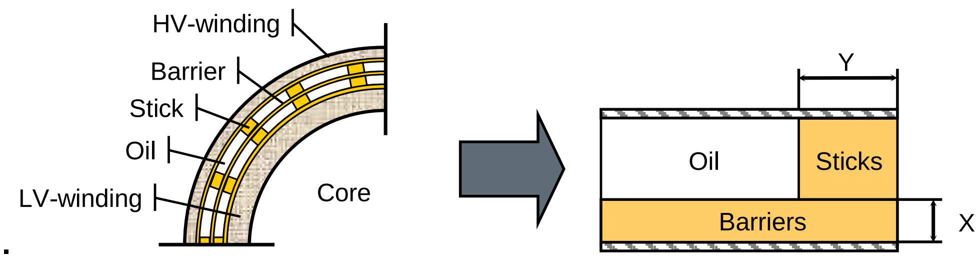
The temperature of the insulation system in transformer has a great influence on the results of dielectric response measurements. Transformer temperature often varies and it is not equal inside the tank – higher at the top than at the bottom. If the measurements are made just after taking the transformer out of operation, its temperature will be slowly decreasing. It is recommended to register the temperature of oil just before starting the dielectric response measurements. The most accurate way to determine the oil temperature is to take top and bottom oil samples and measure the temperatures directly on-site in the sampled oil. After opening the tap, cold oil flows out first, thus waiting for sufficient time is recommended in order to get a representative sample. If oil sampling involves too much effort, indications from the built-in temperature gauges may be used, though it should be bear in mind their readings depend on location of the temperature probe. Alternatively, the average winding temperature can be calculated from a comparison of the actual winding resistance to a measurement at known temperature (e.g. factory acceptance test, FAT).

It is also recommended to register the ambient temperature, relative humidity and weather conditions in the station. In addition, making photographic documentation on the transformer and the measuring setup as well as recording the transformer nameplate information is advisable.

Modelling of dielectric response

In core type transformers, the main insulation between windings consists of cylindrical pressboard barriers in series with oil ducts and sticks. Interpretation of the results of dielectric response measurements aiming at evaluating the amount of moisture contained in the solid part of transformer insulation can be obtained by means of so called X-Y model, which represents volume fractions of the insulation system components.

Figure S5 shows the basic structure of a main insulation duct in a core type power transformer and its X-Y representation, where X and Y often vary between 0.2 - 0.5 and 0.15 - 0.25, respectively. For proper modelling, the configuration of the measured insulation system of the transformer should be taken into account. For core type transformers the geometrical capacitance between windings can be estimated, based on construction drawings, as the capacitance of concentric cylinders. For shell type transformers the calculation is more complex, but still can be done assuming the construction details are known. Further, information on dielectric response of pressboard at different humidity contents and of oil is also necessary. The total response of X-Y model at particular temperature, given moisture content in pressboard and the conductivity of oil is in detail described in [1].



(a) (b)

Figure S5: Basic structure of the insulation duct seen from above (a) and its X-Y representation (b).

Error analysis

Since the analysis and interpretation of dielectric response data is based on a comparison between measured dielectric properties and a library of model data obtained in laboratory on pressboard and paper samples, the quality of the latter determines the accuracy of moisture analyses.

It is shown that different factors influence the quality of result interpretation. The type of pressboard material (density) and origin as well as oil conductivity and acid content in cellulose have an impact on the response. The resulting errors have been estimated and are illustrated in Table A below. The errors found are “absolute”, i.e. independent of the actual moisture level in the insulation. For example, for a dry transformer the relative errors will end up being high. Both over and under estimates of moisture are possible. It is important to be aware of these errors and take them into account in the assessment of the transformer insulation quality. Certainly the influence of the different errors will be judged differently from situation to situation dependent on transformer vintage, type, service conditions, service record, measurement conditions etc.

Table A: Error sources and their maximum magnitudes in estimation of moisture in cellulose (given in percent water by weight of cellulose)

Error source	Approx. error	Comment
Type of pressboard HD => LD or v.v.	0.7 %	Assuming all insulation changed. Assuming HD board when actual board is LD causes underestimation of moisture.
Type of HD pressboard	0.5 %	
Low molecular weight (hydrophilic) acids	0.08 -0.15 % per NV = 1 mgKOH/g ***in pressboard*** For heavily acidic field aged transformers the error range is believed to be up to 1%	1 mgKOH/g pressboard corresponds to about 0.01 mgKOH/g oil for this type of acids. Corresponding total NV of oil cannot be specified as the percentage of low molecular weight acids vary very much between transformers. The presence of acids causes overestimation of moisture.
Incorrect insulation geometry parameters X and Y	Up to 0.6%	
Temperature	0.07 %/K	Calculated at a temperature of 310 K, but does not seem to be significantly different over a temperature range of 273 – 353 K. Real temp higher than assumed temp causes moisture overestimation.

[1] S.M. Gubanski, P. Boss, G. Csepes, V.D. Houhanessian, J. Filippini, P. Guuinic, U. Gäfvert, V. Karius, J. Lapworth, G. Urbani, P. Werelius and W.S. Zaengl - "Dielectric Response Methods for Diagnostics of Power Transformers", ***CIGRE Technical Brochure***, No. 254, Paris 2004.

1 INTRODUCTION

1.1 Basics

The insulation system of power transformers consists of oil and cellulose. Both materials generally change their dielectric properties during the life of the transformer and among factors contributing mostly to the degradation of transformer insulation moisture plays an important role. Presence of water in solid part of the insulation, even in small concentrations, increases its aging rate, lowers the admissible hot spot temperature and increases the risk of bubble formation. In addition, moisture reduces the dielectric strength of transformer oil as well as the inception level of partial discharge activity.

Methods for evaluating moisture content and ageing in pressboard and paper are thus of great interest to transformer owners. Over the recent years, attempts have been undertaken to replace the traditional way for determining moisture content in pressboard and paper in insulation of power transformers, based on chemical analyses of oil according to IEC 60422, by new methods utilising dielectric response measurements. One of the main reasons driving ahead the development of the new techniques is related to the inferior accuracy of the former methodology, especially at lower temperatures. In addition, the electrical measurements are simpler and it is possible to perform them on-site.

CIGRE Task Force D1.01.09 – Dielectric Response Methods for Diagnostics of Power Transformers - presented in 2004 [1] conclusions regarding the state of the knowledge on the applicability of the dielectric response techniques. The techniques compared were:

- Dielectric spectroscopy in time domain, i.e. measurements of polarisation and depolarisation currents (PDC) and recovery (or return) voltage (RVM),
- Dielectric frequency domain spectroscopy (FDS), i.e. measurements of electric capacitance C and dissipation factor $tg\delta$ in dependency of frequency.

This work confirmed that the dielectric response measurements can provide valuable information on the state of oil-paper insulation in power transformers, in particular the moisture content. All the dielectric response methods compared (RVM, PDC and FDS) reflect the same fundamental polarisation and conduction phenomena in transformer insulation, the special feature of a combination of oil gaps and solid insulation. The oil-paper insulation system as a composite of two different dielectric media, where an insulating liquid with ionic conduction is mixed with a less conducting impregnated solid (pressboard or paper), has its own dielectric response which not only reflects properties of each material but also the way they are combined. Therefore the influence of oil gaps, the condition of the oil, specifically its conductivity, has a significant impact on dielectric response, and this must be taken into account when attempting to estimate moisture contents in the solid insulation from the results of all three methods.

To further validate the indications of the dielectric response techniques the work of CIGRE has continued. Related research activities were conducted at various industrial and academic centres. Among them, an extensive investigation program was carried out within a European research project REDIATOOL – “Reliable Diagnostics of HV Transformer Insulation for Safety Assurance of Power Transmission System” [2]. Particular attention has concentrated on verifying the estimates of water content determined by the dielectric response techniques in comparison with basic chemical measurements. The influences of different types of pressboard and paper and ageing products on dielectric response have also been addressed and demonstrated for improving interpretation scheme of the dielectric response measurements [3, 4, 5].

In this report the continuation of the work performed by CIGRE Task Force D1.01.14 – Dielectric Response Diagnoses for Transformer Windings – is summarized by presenting hands-on guidelines for performing meaningful dielectric response measurements on power transformers. The work described concentrates on diagnosing the moisture content in transformer insulation system. The attempts to differentiate between the influence of moisture and aging products in pressboard and paper on the dielectric response still remains under consideration and the issue is not further discussed here. A number of study cases are also reported in order to exemplify different practical situations that should be considered when performing diagnostic measurements of dielectric response on power transformers.

1.2 Objective

The following objectives were considered when preparing this report:

- reporting on the present knowledge how the dielectric responses of the materials in transformer insulation system depend on type, manufacturer, moisture, contamination, aging, temperature, etc.,
- advising how practical measurements should be arranged to provide best possible data for conclusive diagnosis,
- illustrating, by description of different study cases, difficulties and possibilities arising from the applications of dielectric response measurements.
- providing guidelines on correct interpretation of results of dielectric response measurements.

1.3 Scope

The work reported in this document has limited its interest to investigations of the influences of different types of solid insulation and ageing products on interpretation of dielectric response measurements in terms of moisture content in solid parts of transformer insulation. Detailed guidance on the practicalities of making dielectric response measurements are provided and collected case examples illustrate the value of such measurements. Although some companies claim they are able to detect by means of dielectric response measurements other types of defects in transformers, such for example bad shield contacts, the possibilities are not presented in this report since relevant documentation has not yet been available and openly evaluated.

Two dielectric response techniques (PDC and FDS) for which well developed interpretation schemes based on mathematical models are available and which take into account the separate influences of insulation system geometry, oil conductivity and moisture.

Most of the work reported has been based on measurements between windings, for which a guarded measurement setup is applicable, but considerations on measurements of winding insulation to ground are included.

The results presented in this report were performed by means of commercially available instruments, but this does not exclude the possibility of using other dielectric response measuring systems, provided these are suitable for application in a field environment and designed to follow conditions formulated below.

1.4 Dielectric response

The purpose of this chapter is to formulate the basic relations for the dielectric response characterization of electrical insulation. For more details on this subject the readers are advised to reference literature [1, 6, 7, 8].

Under assumption that the considered insulation material behaves linearly and is homogeneous and isotropic, the information obtained by performing dielectric response measurements in either the time or the frequency domains is the same. The results of measurements can therefore be transformed from time to frequency domain and vice versa.

In time domain, the conductivity σ_{dc}, the instantaneous (high frequency) component of the relative permittivity, ε_∞, and the dielectric response function, $f(t)$ characterise the behaviour of a dielectric material [6]. The response function, $f(t)$ is the response to a delta pulse. From this, the response - or polarization, P can be calculated for any excitation shape, $E(t)$ through the convolution, $P = \int_0^\infty f(t)E(t-\tau)d\tau$. It is also worth of notifying that current measurements in time domain can directly lead to quantification or at least estimation of $f(t)$.

The Fourier transform of the response function $f(t)$ allows for the transformation to frequency domain. It yields the complex susceptibility, $\tilde{\chi}(\omega) = \chi'(\omega) - i\chi''(\omega)$. The relation between the susceptibility and the permittivity is $\varepsilon'(\omega) = \varepsilon_\infty + \chi'(\omega)$, $\varepsilon''(\omega) = \frac{\sigma_{dc}}{\varepsilon_0\omega} + \chi''(\omega)$ and the dissipation factor is defined as $tg\delta = \varepsilon''(\omega)/\varepsilon'(\omega)$. Therefore, in the frequency domain, the dc conductivity, σ_{dc}, the high frequency component of the relative permittivity,

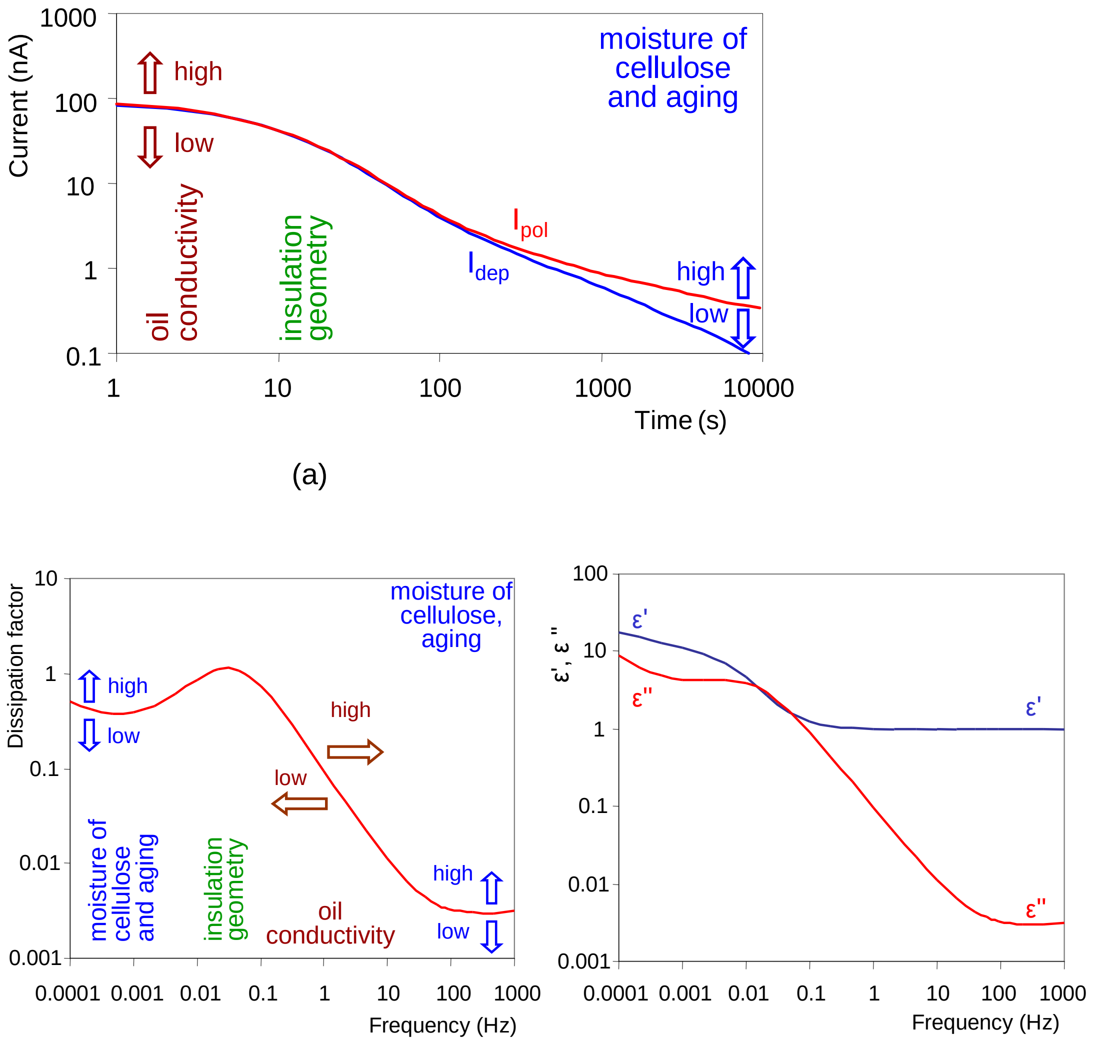
ε_∞, and the complex dielectric susceptibility, $\widehat{\chi}(\omega)$, characterise the dielectric material, and as for the time domain, it is possible to find these parameters by the measurements.

The oil-paper insulation system is a composite of two different dielectric media, where an insulating liquid with ionic conduction is mixed with a lower conducting impregnated solid (pressboard or paper). It is important to realise that each has its own dielectric response and when putting them together the total response will not only reflect properties of each material but also the way they are combined. When these two media are put into contact (forming interfaces), charge accumulation occurs at the interfaces due to the differences between their electrical properties. This kind of polarisation is called Maxwell-Wagner or interfacial polarisation [see for example 9, 10].

1.5 Measuring methods

Time domain measurements can directly be related to the polarisation and conduction phenomena. Trough measuring polarisation current $\boldsymbol{i_p(t)}$ and depolarisation current $\boldsymbol{i_d(t)}$ (PDC) [7, 8], information about the dielectric response function $\boldsymbol{f(t)}$ is obtained, provided the test object is charged for a sufficiently long time. To determine the response function $\boldsymbol{f(t)}$, it is easier to use the depolarisation current $\boldsymbol{i_d(t)}$ where there is no dc current present. Many solid dielectric materials have dielectric response functions that decrease slowly with time. A rule of thumb says that the test object should be charged for at least 5 to 10 times as long as it is depolarised in order to get a depolarisation current, which is proportional to the dielectric response function. It also is possible to estimate the dc conductivity, σ_{dc}, of the test object from the difference between the polarisation and depolarisation currents.

In an oil-barrier system most interesting information is obtained for longer times up to a few thousands seconds. The barriers are charged via the oil ducts immediately after voltage step application. Therefore the initial current values and the main time constant of the current curves are directly related to the conductivity of oil in the main ducts. The polarisation and depolarisation current and the difference between polarisation and depolarisation curves at longer times are directly related to the conductivity of the paper/pressboard part of the insulation system and its water content. These features are indicated in Figure 1(a).



(a)

(b)

Figure 1: Main features of PDC (a) and FDS (b) responses in oil-paper/pressboard barrier systems.

An equivalent method in the frequency domain is to measure the responses from sinusoidal excitations at different frequencies (FDS), which is practically an extension of the common C-Tan-Delta measurement at power frequency and the measurements can be done from 0.1 mHz to 1 kHz. On this basis the complex relative permittivity $\hat{\varepsilon}(\omega)$ at the frequency of the applied voltage, assuming a capacitive test object, can be found. It is important to notice that the imaginary part of the complex relative permittivity, $\varepsilon''(\omega)$, (loss part) contains both the resistive (dc conduction) losses and the dielectric (polarisation) losses. Another way of presenting the measured information of a FDS is to use the dissipation factor $\boldsymbol{tg}\delta(\omega)=\varepsilon''(\omega)/\varepsilon'(\omega)$.

As shown in Figure 1(b), at the very low (<10^{-2} Hz) frequency range the response is mainly influenced by the properties of the pressboard. In this range the imaginary part, $\varepsilon''(\omega)$ of the complex relative permittivity, has usually a slope similar to that of the real part $\varepsilon'(\omega)$, which represent the polarization behavior of the solid part of transformer insulation, modified by water content. The same is true for the higher frequency range (>10 Hz). The central part of the response is, on the other hand, influenced by the properties of the oil, mainly by its conductivity [1]. Although insulation geometry is indicated to have a significant influence on responses in particular parts of the responses, it still has an effect over the entire frequency and time ranges.

The characteristic boundaries in PDC and FDS spectra differ for various moisture contents, conducting ageing by-products and temperatures.

2 MODELLING DIELECTRIC RESPONSE OF POWER TRANSFORMER

2.1 X-Y model

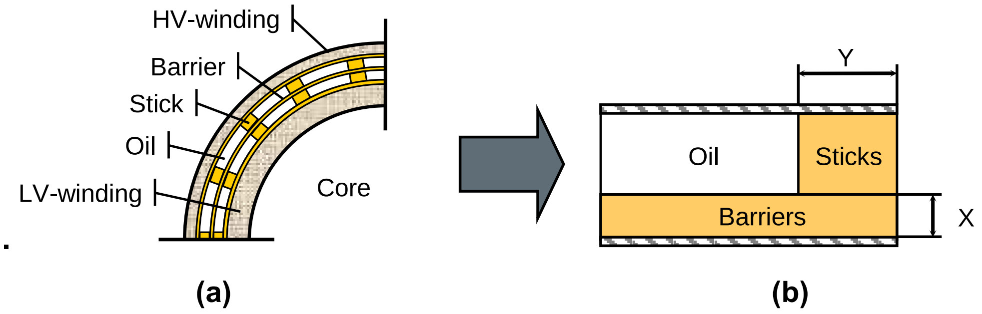
In core type transformers, the main insulation between windings consists of cylindrical pressboard barriers in series with oil ducts and sticks. Interpretation of the results of dielectric response measurements aiming at evaluating the amount of moisture contained in the solid part of transformer insulation can be obtained by means of so called X-Y model [1, 11], which represents volume fractions of the insulation system components.

Figure 2 shows the basic structure of a main insulation duct in a core type power transformer. The insulation consists of concentric cylinders made of oil impregnated pressboard and axial sticks. The complex geometrical arrangement shown in this figure can be simplified by separately combining its components, i.e. barriers and spacers and oil ducts, into single material blocks representing the components of the composite duct insulation, where:

$$\boldsymbol{X} = \frac{\text{total thickness of barriers}}{\text{width of the duct}}$$

$$\boldsymbol{Y} = \frac{\text{total width of the spacers}}{\text{periphery of the duct}}$$

In power transformers, ***X*** and ***Y*** often vary between 0.2 - 0.5 and 0.15 - 0.25, respectively. The total response of X-Y model at particular temperature, given moisture content in pressboard and the conductivity of oil is in detail described in [1].



(a) (b)

Figure 2: Basic structure of the insulation duct seen from above (a) and its X-Y representation (b).

For proper modelling, the configuration of the measured insulation system of the transformer should be taken into account. For core type transformers the geometrical capacitance between windings can be estimated, based on construction drawings, as the capacitance of concentric cylinders. For shell type transformers the calculation is more complex, but still can be done assuming the construction details are known. Further, information on dielectric response of pressboard at different humidity contents and of oil is also necessary.

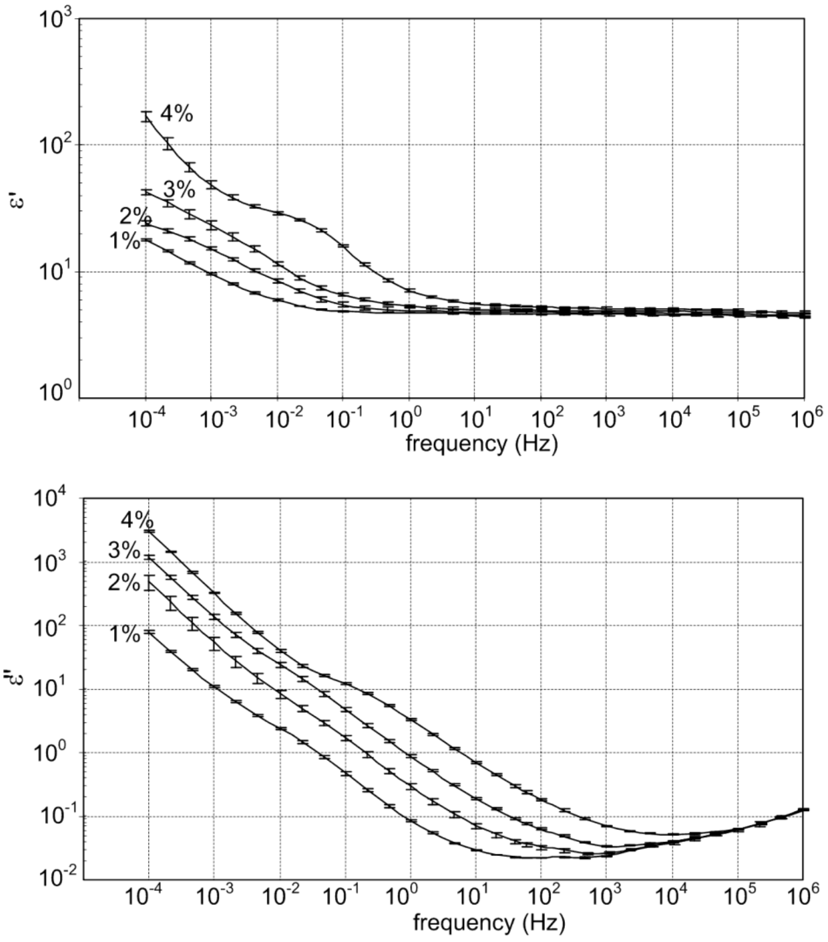


Figure 3: Dielectric permittivity of pressboard containing different amount of moisture (1%, 2%, 3% and 4%) at 50 ºC [3].

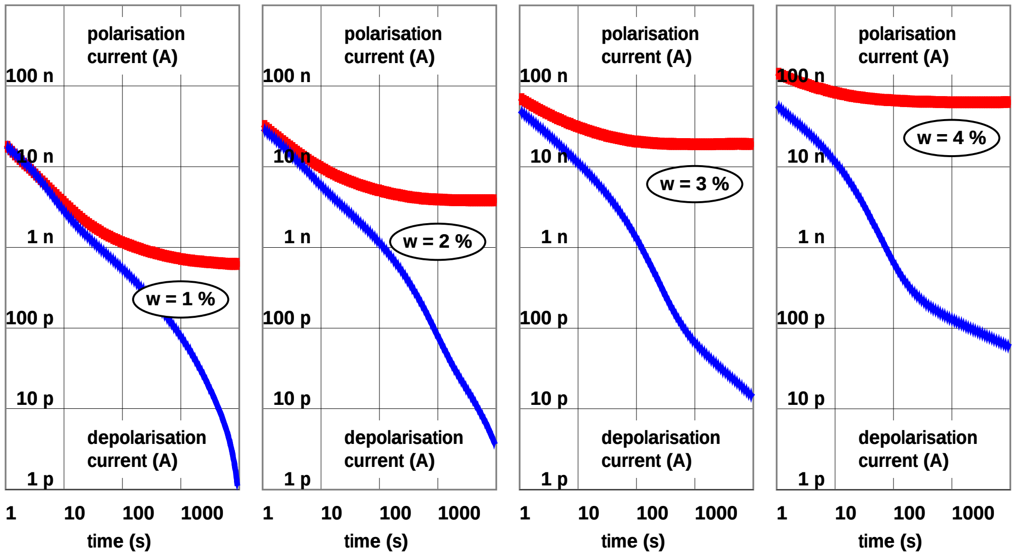


Figure 4: Example of relaxation currents (polarisation and depolarisation currents) measured on samples with different moisture contents [14].

The dielectric response of mineral oil is quite simple and can be characterised by its essentially frequency independent permittivity, $\hat{\varepsilon}(\omega) = \boldsymbol{const} = 2.2$, and volume conductivity, σ_{dc}, whereas its dielectric response, $\boldsymbol{f}(\boldsymbol{t})$, can be neglected [11]. Pressboard and paper are, on the other hand, characterised by a strong dielectric response, $\boldsymbol{f}(\boldsymbol{t})$. This response is, in addition, dependent on moisture content and ageing products. Results of measurements on well-defined pressboard samples with different moisture content are used as a database [3,12, 13, 14]. Examples of the model responses in frequency and time domains are respectively illustrated in Figure 3 and in Figure 4. The temperature dependence of dielectric properties of pressboard/paper and oil are characterised by the activation energies, typically 0.9 eV and 0.4 eV for pressboard and oil, respectively [3]. If both components, i.e. oil and paper, are sandwiched, it is possible to calculate the resultant behaviour for the composite insulation if the geometrical arrangement is known.

For modelling FDS response from the information on the dielectric properties of cellulose and oil, the frequency and temperature dependent permittivity and dissipation factor of the composite insulation is calculated and compared with results of measurements on real transformers.

For modelling PDC response similar procedure is followed. If the geometry of the main insulation (i.e. the relative portions of oil ducts, barriers and spacers) and a mean temperature are known, polarisation and depolarisation currents can be calculated from the model and compared with measured currents.

By use of curve fitting procedure material parameters (oil conductivity, moisture content in pressboard) and other variables (insulation geometry, temperature) can be estimated.

2.2 Influence of pressboard type, oil quality on the dielectric response of laboratory pressboard models

Since the analysis and interpretation of dielectric response data is based on a comparison between measured dielectric properties and a library of model data obtained in laboratory on pressboard and paper samples, the quality of the latter determine the accuracy of moisture analysis. This section presents recently acquired information [4, 5, 15, 16, 17] on the influence of pressboard material, oil conductivity and its acidic content on dielectric response spectra, which in addition to the earlier gathered knowledge are complementary and ought to be considered for improving common interpretation schemes. The influence of the type of pressboard material is discussed in section 2.2.1, the effect of the conductivity of the oil used for pressboard impregnation in section 2.2.2, and in section 2.2.3 it is demonstrated that different constituents contributing to the conductivity of oil may have very different influence on the response of pressboard.

2.2.1 Influence of pressboard

Two high density (HD1 and HD2) and two low density (LD1 and LD2) pressboard types made by three manufacturers were compared through measuring dielectric properties of pressboard discs in frequency range of 0.1 mHz to 1 kHz in a shielded measurement cell. The moisture content of the four samples, determined by means of Karl Fischer titration, was 2.5 %; all the samples were impregnated with new mineral oil. A coulometric titration cell was used to determine the water content by heating the samples in an external oven at 160°C [21].

Figure 5 shows the complex permittivity of the four pressboard samples. The high density materials (1.1-1.3 g/cm^3) exhibit higher permittivity of ε' ~ 4.6 compared to the low density materials (0.9 g/cm^3) having ε' ~ 3.0. The high density materials contain more cellulose fibres per volume, thus are more polarisable. The losses, the imaginary part ε'' of permittivity, are higher for the high density materials as well.

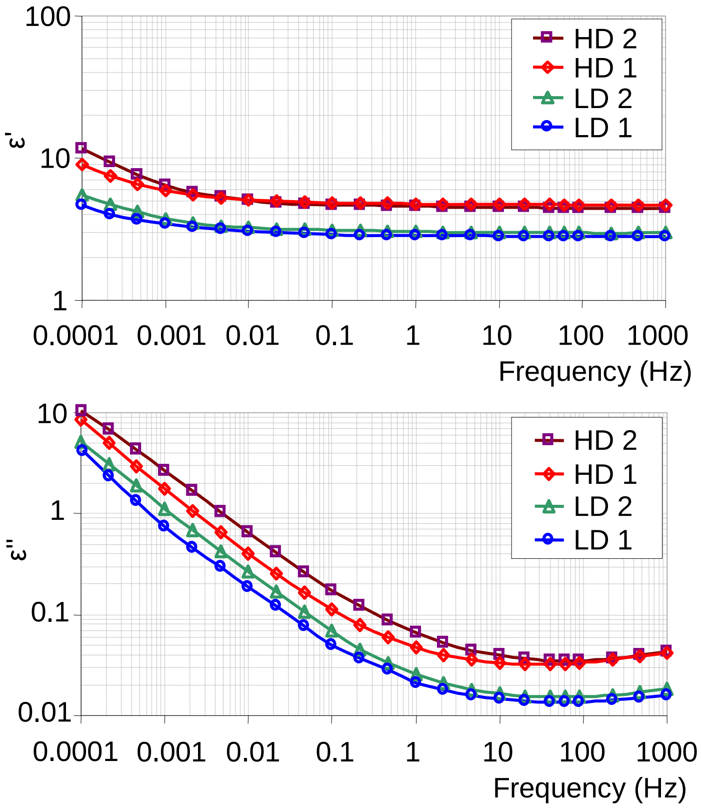


Figure 5: Dielectric permittivity of four pressboard types of different origin having 2.5% moisture content measured at 23°C [5].

Moisture contents for the four materials LD1, LD2, HD1 and HD2 were determined by means of analysis software [3] and were respectively 1.3; 1.5; 1.5 and 2.0 %. The difference between these results and the estimation of water content of 2.5 % determined by Karl Fischer titration is probably caused by use of different titration procedures when scaling the database of the software.

When analysing results of measurements on a real transformer, the origin of the pressboard is usually unknown. Therefore the observed variation of pressboard dielectric properties may, to a certain extent, influence the accuracy of moisture content estimates. Similar conclusion was drawn in [18], where two types of high density pressboard from various manufacturers were compared – the difference between moisture contents derived from titration analyses and results of moisture determination by the software was 0.4-0.5 %.

High density pressboard is typically used as a component of the main insulation between low and high voltage windings and low density pressboard in end insulations. Therefore, if possible, one should use the respective data when modeling and interpreting measurement results.

2.2.2 Influence of oil quality

New pressboard samples having 0.7 and 2.6% moisture content were impregnated with different types of oils (one new and thee service aged, the latter sampled from different transformers). Table 1 shows parameters of the oils (neutralization number, conductivity and resistivity) as measured before impregnating the pressboard samples. Typically the oil conductivity at room temperature ranges from 0.05 pS/m for new oils to about 20 pS/m for aged oils, in extreme cases it may raise up even to 1000 pS/m.

Table 1: Neutralization number, conductivity and resistivity of the four oils used to impregnate the pressboard samples

	NN (mg KOH / g oil)	Conductivity (pS/m)		Resitivity (GOhm·m)	
		20°C	90°C	20°C	90°C
Oil 1	0.054	0.05	2.3	20'000	430
Oil 2	0.29	3.5	66,5	290	15
Oil 3	0.3	21	320	48	3.1
Oil 4	0.32	148	1945	6.8	0.51

Figure 6 depicts how the conductivity of impregnating oil influences the dissipation factor of the new pressboard samples. Although the moisture content of all samples was identical (2.6 %), the losses increase with the conductivity of the oil used for impregnation. Analyses of these data by means of modelling software [3] resulted in different estimates of the moisture content, namely 2.1; 2.7; 3.0 and 3.8% for the respective oil conductivities, meaning that a presence of conductive aging by-products in the oil may yield an overestimation of moisture content in pressboard. An approach to compensate for the influence of conductive aging products in oil and paper insulation is illustrated in [17].

Figure 7 shows the behaviour of dielectric response for pressboard containing only 0.7 % of moisture. In such a case the influence of conductive aging by-products dissolved in oil becomes weaker.

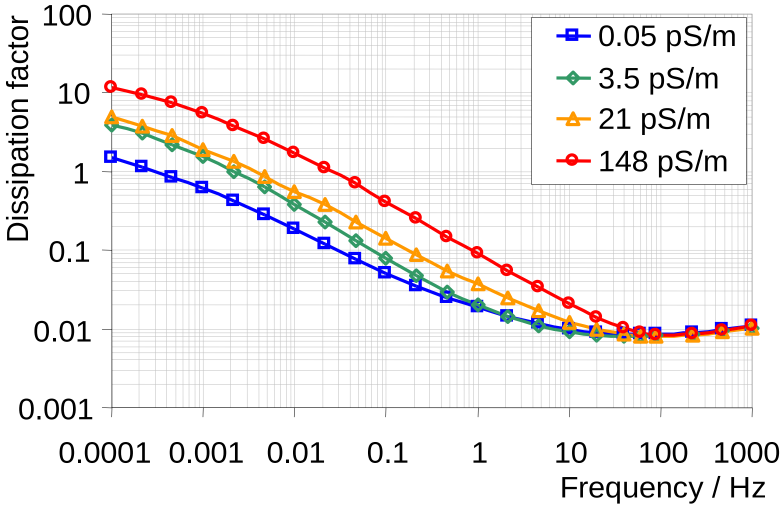


Figure 6: Dissipation factor of new pressboard having 2.6% moisture content impregnated with oils of various conductivities: 0.05; 3.5; 21 and 148 pS/m [5].

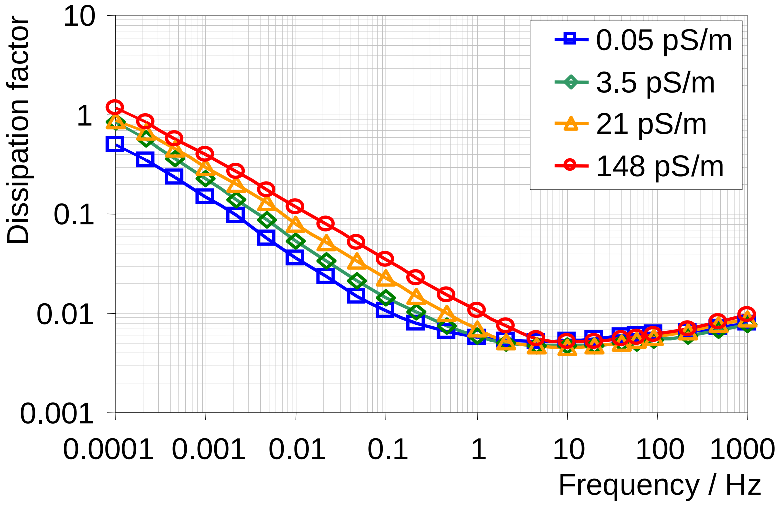


Figure 7: Dissipation factor of new pressboard having 0.7 % moisture content impregnated with oils of various conductivities: 0.05; 3.5; 21 and 148 pS/m [5].

The influence of oil quality on the conductivity of model samples of paper and pressboard, as measured in time domain, was also reported in [15, 16]. The results show that structure and kind of the solid material, its water content and the conductivity of the impregnating oil have an influence on the dielectric properties.

2.2.3 Influence of acids

Various carboxylic acids are produced in the ageing of cellulose and oil. Cellulose ageing mainly produces lower molecular weight acids being water soluble, while oil ageing produces higher molecular weight acids predominantly oil soluble. When modelling FDS response, the effect of acids should be taken into account for both oil and cellulose. The effect of acids in the oil is primarily to increase its conductivity. The effect of acids in cellulose represents the addition of polar molecules which should have an effect upon the dielectric response of both paper and pressboard. Experiments were performed on high density pressboard to find this effect and its dependence upon the humidity level [4].

The pressboard had apparent density (i.e. before drying) of 1.2 g/cm^3 and thickness 1 mm, and moisture contents 0.2 % and 3.9 %. The samples were impregnated with dried and degassed naphtenic transformer oil containing either none added acids, a mix of short-chained carboxylic acids (modelling cellulose ageing), or a mix of long-chained carboxylic acids (modelling oil ageing). Each acid mix consisted of two acids contributing equally to the overall neutralisation value of 0.4 mgKOH/g. The short-chained acids were formic and acetic acid (1 and 2 carbon atoms) and the long-chained acids were naphtenic acid (an ill-defined mix with an average number of carbon atoms of 15) and stearic acid with 18 carbon atoms. As diffusion through pressboard can take long time, the pressboard was stored in the oil for at least 5 months before experiments started. The results are illustrated in Figure 8 and show “master curves” [1, 6] for use at 20 °C, obtained for a very wide frequency range by combining records from tests at several temperatures.

Humidity alone causes a shift of the response curves towards higher frequency, and for the loss ε” there is also a somewhat upward shift, as can be observed in Figure 3, which also shows a humidity-dependent “hump” to the left of the minimum, seen in many but not all studies on FDS of pressboard.

Like moisture, also short-chained acids shift the response curves towards higher frequencies, and for ε” there is a somewhat upward shift as well. The effect of short-chained acids is fairly but not entirely equal to the effect of moisture. The acids cause a change in the shape of ε” near the minimum.

This change is different from the moisture-dependent “hump” of Figure 3. The shape change pushes the minimum further towards higher frequencies than is the case at the lowest frequencies of the low-frequency branch. But overall, in practical transformer diagnosis, it will probably be difficult to see a difference between the effect of short-chained acids and moisture. Long-chained acids possibly show a little contribution in pressboard of low humidity, but none whatsoever when the paper or pressboard is moist.

So why is there such a big difference between long-chained and short-chained acids? The answer is that short-chained acids, which are also water soluble, diffuse into the cellulose with very little amount remaining in the oil [19], while long-chained acids, which are fat-soluble, stay in the oil and hardly enter the cellulose. In the dielectric response experiment, this was also reflected in the conductivity and the remaining neutralisation value of the oil ***after*** impregnation. Both the oil without acids and the oil originally containing short-chained acids had a conductivity at 20 °C of 0.04 – 0.09 pS/m depending on humidity, and the neutralisation value was reduced from the original 0.4 to about 0.02 mgKOH/g, both indicating that hardly any acid remained in the oil. Note that this also means that if an oil-analysis shows significant amounts of short-chained carboxylic acids in the oil, the solid

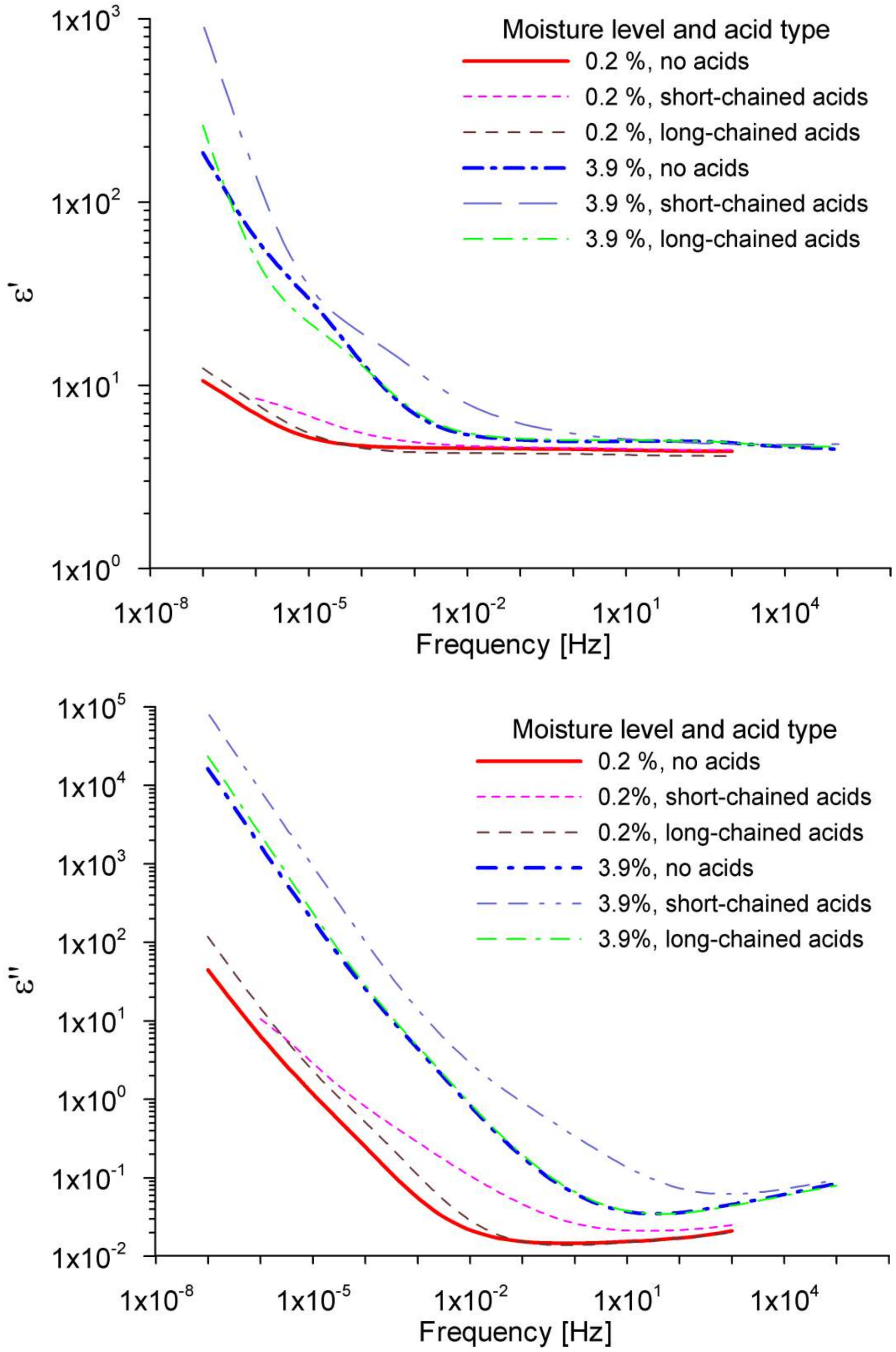


Figure 8: Dielectric response of pressboard with varying moisture and acid content [4].

insulation will be full of them. With long-chained acids, the neutralisation value ended up at 0.37, and the conductivity of the oil was 0.5 – 10 pS/m, i.e. a factor 10 higher than for the oil which originally contained short-chained acids.

In summary, in a transformer, the majority of the short-chained acids formed by cellulose ageing remain inside the pressboard. They contribute a little to the conductivity of the oil, whereas their contribution to the response of the solid insulation is similar to the contribution from moisture. In contrary, long-chained acids stay in the oil and contribute heavily to its conductivity, but hardly enter the pressboard or paper and therefore contribute very little if anything at all to the response of the solid insulation.

2.2.4 Practical aspects and error estimates

Previous sections have shown that certain parameters will have an impact on the measured dielectric response and consequently affect the estimated moisture content of the cellulose insulation. Practical aspects of these parameters and error estimates are presented in this section.

The analyses presented in this section are based on FDS, but as one (at least in principle) can calculate PDC from FDS and vice versa, the error estimates should be valid both for FDS and PDC measurements.

Assume that an FDS measurement has been done on a transformer in order to establish the moisture content of the solid cellulose dielectric (which is usually mainly pressboard). Also assume that measurements on the oil have determined its dielectric properties very well. Using modelling of the transformer, it should then be possible to calculate the overall response of the solid cellulose dielectric from the measured response of the transformer. Assume that this has been done in a way which gives the entirely correct response of the solid dielectric. This response should in principle reveal the (average) moisture content of the solid insulation when using the known influence of moisture on the shape and frequency shift of the response. But as seen in sections 2.2.1 to 2.2.3, there are other influences that are hard to distinguish from the influence of moisture.

In chapter 2.2.1 it was shown that the type of pressboard material (density) has an impact on the response, but also that there were differences between different materials of fairly similar density. Thus, if the pressboard material used in the transformer is different from the material used in modelling, the difference will cause an error in the moisture estimate. In particular, if assuming the solid insulation is HD pressboard when a significant part of it is LD, the moisture content will be underestimated. Changing from HD to LD pressboard shifts the responses towards lower frequencies and lower values, which is exactly the opposite of what moisture does. However, in power transformers barriers and spacers in the main ducts are typically made of HD pressboard while formable parts such as end insulation (angle rings) are made of LD pressboard.

As seen in 2.2.2 and 2.2.3 the presence of low molecular weight acids and possibly some of the other ageing products causing increased oil conductivity will shift the curves towards higher frequencies and higher values, which is the same as water does although some minor details differ. An overestimation of the moisture content will therefore be the result. However, as both moisture and acids are unwanted agents accelerating degradation, especially in combination, the considerable curve shift should cause the transformer operator to consider refurbishment of the transformer. Still, detailed knowledge of the reason for a shift would be preferable in order to select the most appropriate refurbishment method.

The insulation geometry parameters X and Y affect the shape of the modelled response that to a certain degree reassembles the impact of moisture. Therefore, use of incorrect X and Y parameters will influence the estimated moisture content. Too large an amount of cellulose in the model will underestimate the moisture content and vice versa.

Another factor which can cause erroneous moisture estimate is temperature. The response shifts upwards in frequency with an increase in temperature. The insulation activation energy is a measure of this shift. If the pressboard temperature is higher than assumed in the moisture estimation analysis, an overestimation of the moisture content will be the result.

Following is an attempt to put numbers on these errors, still assuming that a “perfect” response curve for the solid dielectric alone has been obtained from the overall response of a transformer. This must only be considered as a rough estimate of the errors, as the range of materials and the range and concentration of possible ageing products tested so far is very limited. Most of the error analyses shown below, and also most practical moisture analyses, are based on what is probably the safest marker for moisture content in the solid cellulose: the frequency shift of the low frequency branch of the obtained solid cellulose response, i.e. the branch mainly dominated by DC conductivity. Since the “hump” seen in this part of the response in some but not all experiments may be an experiment-dependent artefact, the following analyses are based on the response at frequencies lower than where the “hump” occurs. In one case, analysis software has also been used.

Error estimates based on the conductivity of the surrounding oil have not been included, because the precise influence on the cellulose depends on to what degree the constituents of the particular mix causing that conductivity are absorbed by the cellulose. Estimates based on the presence of the particular constituent low molecular weight carboxylic acids are included, however, since it is largely absorbed by the cellulose, as opposed to for instance high molecular weight acids.

The impact of LD or HD pressboard, in this case all with a moisture content of 2.5 %, is shown in Figure 5. The HD response is shifted up in frequency approximately a factor 5 compared to LD pressboard. In one experiment it is estimated that the frequency shift depends upon moisture as e^{BM} where M is the moisture content of the pressboard in per cent weight and B is 1.6 $\%^{-1}$, which is within the 1 – 2 $\%^{-1}$ range suggested by Figure 3. In this analysis, the response change caused by the difference in pressboard types corresponds roughly to a moisture difference of 1 %. Analysis software, both one commercial and one made for use at a laboratory, indicate 0.7 %. This is if the entire solid insulation is made from the “wrong” type of pressboard, and scales down according to the actual percentage if only part of the insulation is of the “wrong” type.

The difference between the two HD pressboards studied corresponds to an error in the moisture estimation of 0.3 % according to the exponential model above and 0.5 % according to the analysis software.

A similar very crude analysis for low molecular weight acids indicates that the presence of such acids in the pressboard to a neutralisation value of 1 mgKOH/g corresponds to 0.08 - 0.15 % moisture (depending on actual moisture). Note that the specified neutralisation value is in the pressboard, not in the oil. The corresponding equilibrium neutralisation value of the oil due to the low molecular weight acids alone is about 0.01 mgKOH/g, but note that this is valid for the particular acid mix used in the experiments, only formic and acetic acid which have the lowest molecular weight of any carboxylic acids. The equilibrium shifts more towards the oil the higher the molecular weight of the acids are.   An example from real life was a service aged oil having an overall neutralisation value of 0.3 mgKOH/g, of which about 25 % could be due to hydrophilic carboxylic acids [20], which is very much the same as low molecular weight acids. That would correspond to a neutralisation value of the pressboard of somewhere in the range 4 – 7, corresponding to an error in moisture estimation of 0.6 – 1 % by weight, which is significant. The few service aged oils analysed for the relative content of low molecular weight acids have shown that 1 – 27 % of the acids were of low molecular type, with 12 – 16 % being the most typical range. The latter would have corresponded to an error in the moisture estimate of roughly 0.5 %.

A sensitivity analysis of the insulation geometry parameters impact on estimated moisture content was performed on a dry and wet transformer. For these transformers the moisture content in the cellulose and geometrical parameters, X and Y were known. In the modelling the geometrical parameters were systematically varied and the error in the estimated moisture content recorded. With a deviation in the geometrical parameters up to ±0.1 a reasonable fit of the model to measured data could be achieved. For larger deviations the fit became poor. Within the ±0.1 range of the geometrical parameters the maximum error in estimated moisture content was up to 0.6%.

The temperature dependence of the positioning of the entire response curve along the frequency axis is proportional to $\boldsymbol{e}^{-\boldsymbol{E_a}/\boldsymbol{kT}}$ where the activation energy $\boldsymbol{E_a}$ is about 1 eV, $\boldsymbol{k}$ is Boltzmann's constant and $\boldsymbol{T}$ is the absolute temperature. For $\boldsymbol{T} \approx 310$ K (or 37 °C) this gives a shift of a factor about 1.12 in frequency for each degree K of temperature difference. This corresponds to an error of 0.07 % moisture. Thus an error of a few K in the estimate of the temperature does not mean much, but 10 K gives 0.7 % which is a significant error.

Pressboard reference responses for the determination of moisture are most likely to be available at a given temperature, typically 20 °C. In addition there should be information about the shift with temperature, where $\boldsymbol{E_a}$ is central. This information is supposed to be used for compensating for a transformer measurement temperature being different from the reference temperature. Uncertainty about $\boldsymbol{E_a}$ value will give an uncertainty in the final moisture determination. While one experiment has found $\boldsymbol{E_a}$ to be 1.02 ± 0.3 eV for both paper and pressboard, independently of the moisture and acid content, a wider range has been found in other experiments. For instance, one such experiment found the range 0.90 – 1.15 eV with some moisture dependence, where the higher values typically belonged to the moistest samples [14]. For each 0.1 eV error in $\boldsymbol{E_a}$, the error in estimated moisture is 0.008 %/K, calculated around room temperature. Thus as an example, with reference temperature 293 K and measurement temperature 333 K, the error in the moisture estimate will be 0.3 % by weight for 0.1 eV error in $\boldsymbol{E_a}$. This is moderate compared to the other possible error sources.

The results are summarized in Table 2.

Table 2: Error sources and their maximum magnitudes in estimation of moisture in cellulose (given in percent water by weight of cellulose)

Error source	Approx. error	Comment
Type of pressboard HD => LD or v.v.	0.7 %	Assuming all insulation changed. Assuming HD board when actual board is LD causes underestimation of moisture.
Type of HD pressboard	0.5 %	
Low molecular weight (hydrophilic) acids	0.08 -0.15 % per NV = 1 mgKOH/g ***in pressboard*** For heavily acidic field aged transformers the error range is believed to be up to 1%	1 mgKOH/g pressboard corresponds to about 0.01 mgKOH/g oil for this type of acids. Corresponding total NV of oil cannot be specified as the percentage of low molecular weight acids vary very much between transformers. The presence of acids causes overestimation of moisture.
Incorrect insulation geometry parameters X and Y	Up to 0.6%	
Temperature	0.07 %/K	Calculated at a temperature of 310 K, but does not seem to be significantly different over a temperature range of 273 – 353 K. Real temp higher than assumed temp causes moisture overestimation.

The errors found above are “absolute”, i.e. independent of the actual moisture level in the insulation. For a dry transformer the relative errors will end up being extremely high. Also, for a fairly dry transformer, the errors may in principle even shift the response curves further to the left of the curves for dry HD pressboard, yielding an essential underestimation of moisture level.

Both over and under estimates of moisture is possible as seen above. It is important to be aware of these errors and take them into account in the assessment of the transformer. Certainly the influence of the different errors will be judged differently from situation to situation dependent on transformer vintage, type, service conditions, service record, measurement conditions etc.

In the experiments described above (section 2.2.3) the oil conductivity was increased by adding various carboxylic acids. In contrast to this, the increased oil conductivity, as presented in section 2.2.2, was caused by presence of aging by-products developed in service-aged power transformers. These by-products are not necessarily of acidic nature. There seem to be service-aged oils where only a minor part of the oil conductivity can be attributed to acids, but only influence of acids have so far been tested for their effect on the dielectric response.

3 MEASURING SYSTEM CONFIGURATIONS

When estimating the moisture content in the solid part of traditionally designed transformers, one usually focuses on the main insulation, i.e. the insulation between the coaxially arranged high voltage (HV) and low voltage (LV) windings. The capacitance of this insulation is commonly denoted as CHL. Other capacitances of interest can, for example, be winding capacitances to ground (tank, core, etc.), i.e. CL or CH.

Dielectric response measurements can be performed within different configurations, UST (Ungrounded Specimen Test) where the ground act as natural guard or GST (Grounded Specimen Test) with or without guard. Basic circuit connections for the test configurations are presented below.

3.1 UST configuration

Ungrounded Specimen Test (UST) measurement is performed between two object terminals that are not connected directly to ground. Examples are the main insulation between high and low voltage windings in power transformers CHL or bushing insulation between the high voltage electrode and capacitive tap.

There may also be one or more other terminals available, both grounded and ungrounded, as for example tertiary winding of the transformer and transformer tank. In case of one such terminal there are three capacitances present. These are, in general, the capacitance of the insulation part to be measured, Cx and two stray capacitances, Cs1 and Cs2 between the terminals of Cx, as schematically indicated in Figure 9 below. Without guard both stray capacitances are measured together with Cx. By connecting the stray capacitances to ground, which acts as a guard, their influence is eliminated.

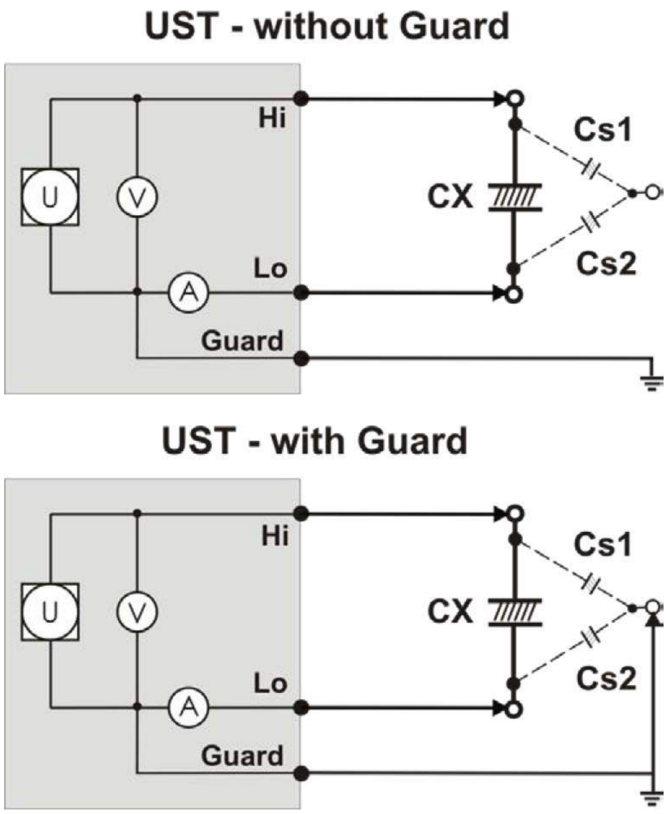


Figure 9: UST measurement configurations.

A connection diagram for a UST measurement on a power transformer is shown in Figure 10 and indicates how the measurement leads should be attached. The capacitance to be measured is the main inter-winding insulation CHL, where the voltage electrode (Hi) is connected to high voltage bushings and the measuring electrode (Lo) to low voltage bushings. The ground electrode can, in this case, be connected to the third available terminal - grounded transformer tank, thus eliminating the influence of capacitances between windings and tank.

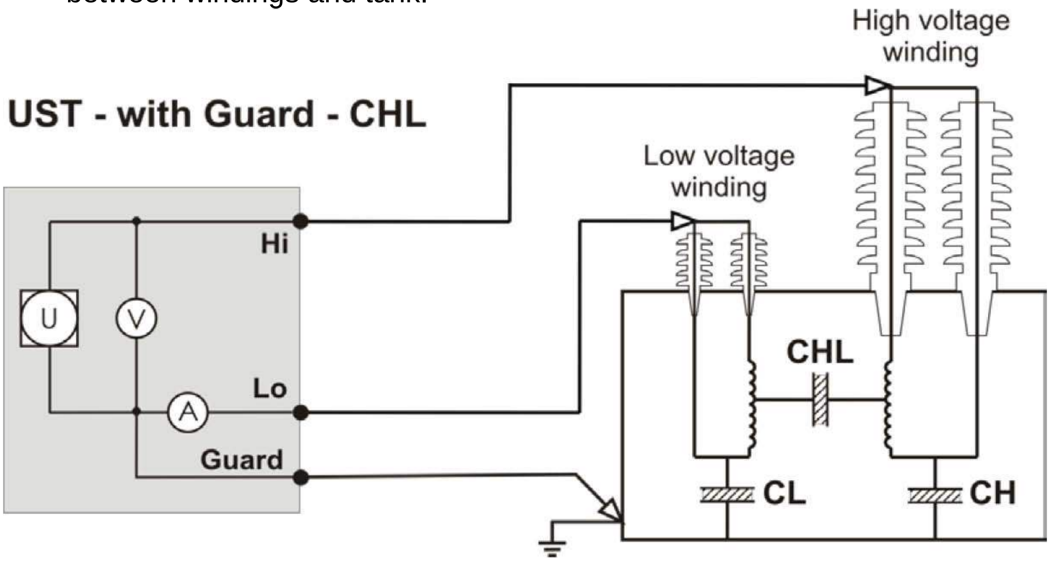


Figure 10: UST connection of dielectric response measuring system to a transformer for CHL configuration.

3.2 GST configuration

Grounded Specimen Test (GST) measurement is performed between two of the object terminals, of which one is directly connected to ground. Examples are the insulation between high or low voltage windings and tank or core, CH or CL, and bushing insulation between capacitive tap and flange. There may be one or more other terminals available, both grounded and ungrounded, as, for example, low-voltage and/or tertiary winding of the transformer and transformer tank. Similarly, as for UST configuration, the presence of one such terminal results in additional stray capacitances, Cs1 and Cs2**,** as shown in Figure 11 below. Without guarding these capacitances are measured together with Cx (Figure 11 upper graph), whereas by guarding, their influence is eliminated (Figure 11 lower graph).

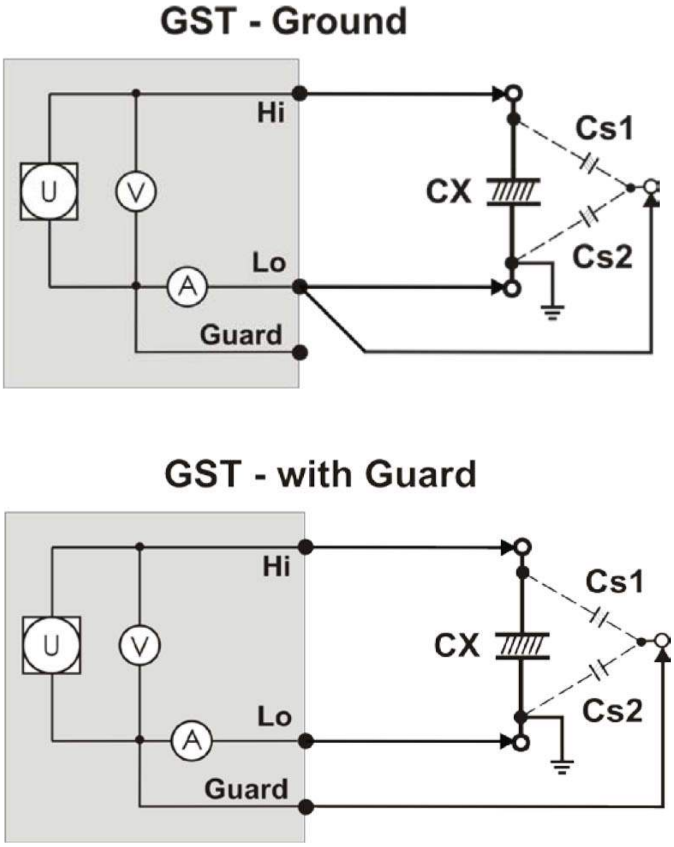


Figure 11: GST measurement configurations.

A connection diagram for a GST measurement on a power transformer is shown in Figure 12.

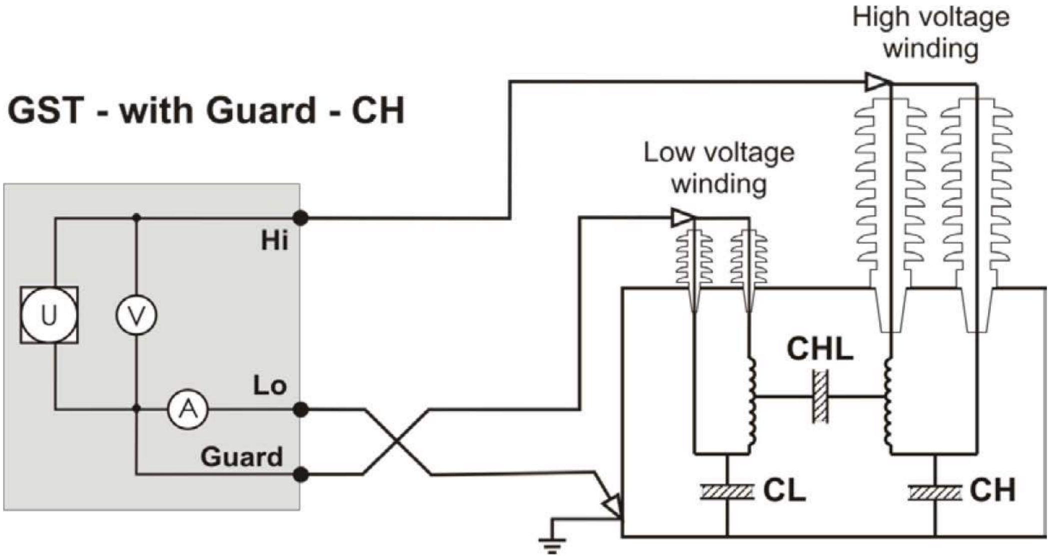


Figure 12: GST connection of dielectric response measuring system to a transformer for CH configuration.

3.3 Contribution of different parts of the insulation to the response

In a transformer different insulation segments form capacitive couplings between each other as well as to the transformer tank and core. The measured dielectric response therefore depends on which terminal the measurement leads are attached to, on the test equipment configuration (UST, GST) and on the winding arrangement in the specific transformer. For that reason it is important to connect the measuring instrument in a proper way and be aware which segments of the transformer insulation that is included in the measurement.

Figure 13 schematically shows the windings of phase A of a two winding transformer. In the figure the capacitive coupling between insulation segments and tank/core are symbolically depicted forming the three main capacitances:

- between HV winding and LV winding (CHL)
- between HV winding to tank and to core (CH)
- between LV winding to tank and to core (CL)

The other two phases have similar couplings.

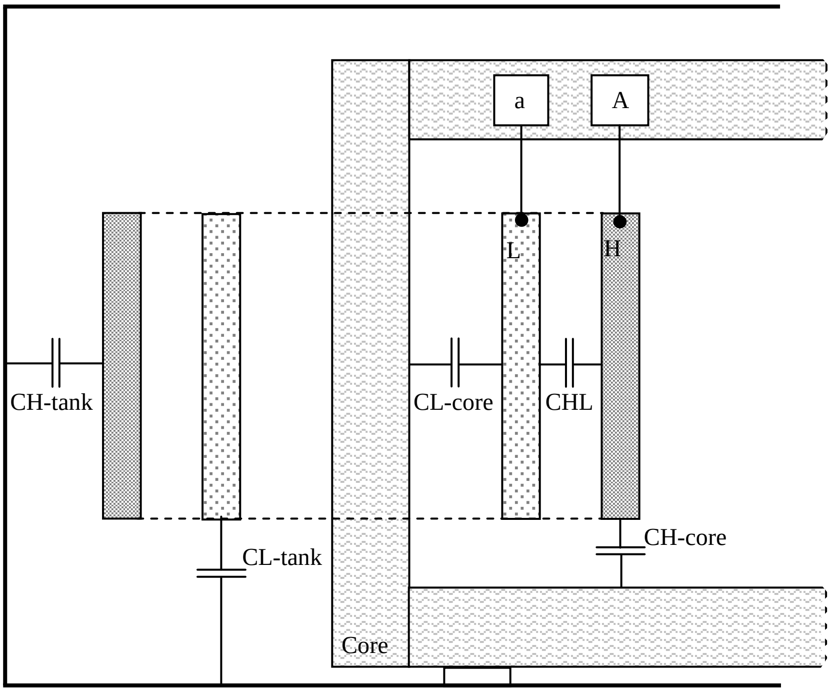


Figure 13: Schematic drawing of phase A windings in a transformer. The capacitive couplings between insulation segments and tank/core are symbolically represented by respective capacitances.

3.3.1 Ungrounded measurement CHL

If possible one should measure one capacitance segment at a time with help of guarded measurement configuration in order to assess that specific part of the insulation system. An example of such a measurement is the CHL measurement.

In this configuration voltage is applied to the high voltage winding and current is measured at the low voltage winding (UST measurement configuration). All other terminals are grounded. This measurement is similar for all types of transformers except for auto transformers where the series and common windings are galvanic-connected. The insulation assessed is the insulation between high and low voltage winding, CHL in Figure 13 This is the preferred configuration for moisture estimation, for which the interpretation schemes based on the modelling of the response data [1] work most reliably.

Most auto-transformers have a tertiary winding, so, provided this is not internally earthed, measurements of main to tertiary insulation, CHT, are possible and preferred, as illustrated in Figure 14.

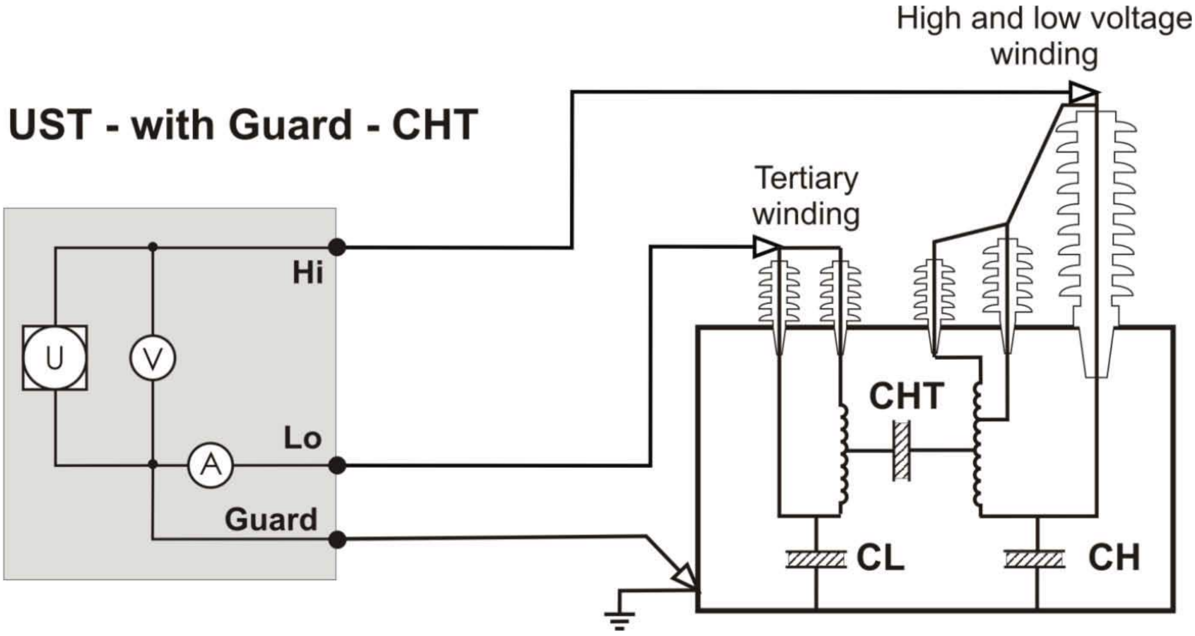


Figure 14: UST connection of dielectric response measuring system to an autotransformer with tertiary winding.

3.3.2 Measurements to ground CH and CL

In these configurations the voltage is applied to one of the windings and all other winding terminals are connected to guard. All currents flowing to the tank (ground) are measured. These are GST guard measurements and include additionally contributions from bushings and creep to ground.

In the CH measurement voltage is applied to the high voltage winding and current is measured at all parts connected to ground (GST guard measurement). The insulation measured is primarily the insulation between the high voltage winding and the tank, but it also includes the end insulation between high voltage winding and core, see

Figure 13. This configuration is less suitable for moisture assessment using the modelling of the response data [1] but is however important for diagnosing insulation to ground.

In a CL measurement voltage is applied to the low voltage winding and current is measured at all parts connected to ground (GST guard measurement). The insulation measured is primarily the insulation between the low voltage winding and the core but it also includes the end insulation between low voltage winding and winding leads and tank, see Figure 13.

When measurements between high and low voltage windings are for any reason difficult or impossible, an acceptable alternative is created through measurements between the innermost winding and the core.

3.3.3 Influence of winding arrangement

The winding arrangement is also important when performing diagnostic measurements. In some transformers the high voltage winding is split, as schematically illustrated in Figure 15. The two parts of high voltage winding HV surround the low voltage winding LV. For such an arrangement the measurement between HV winding and LV winding is applicable but one should be aware that in this case two insulation segments are assessed in parallel, i.e. CH1L and CH2L, see Figure 15.

The CL measurement will in this particular case be different from the previously discussed CL measurement. The surrounding high voltage windings, which are connected to guard, will shield away most of the current from the low voltage winding to tank and to core. The response is dominated by the end insulation of the low voltage winding, the bushings, and creep currents to ground. It is therefore advised to check the capacitance value of the configuration measured. For power transformers, values below 1 nF usually indicate that the loss is dominated by end insulation and higher dissipation factors can be accepted.

The CH measurement will also, for this winding arrangement, assess several insulation segments. In this case the contribution comes from the insulation between inner high voltage winding and core/tank in parallel with the insulation between outer high voltage winding and core/tank, see Figure 15.

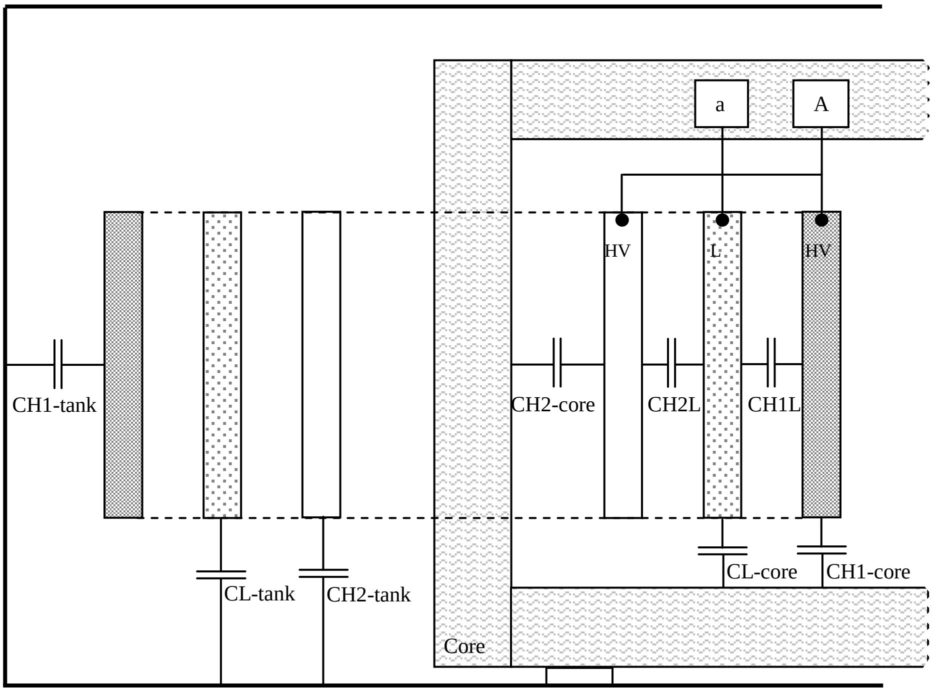


Figure 15: Schematic drawing of phase A windings for a transformer in which the high voltage winding is split into two parts. The capacitive coupling between insulation segments and tank/core are symbolically represented by capacitances. For this winding arrangement the low voltage winding is surrounded by the high voltage main and regulation windings.

There may exist in practice transformers with more complicated winding configurations than the case described above. The general principle is still that guarded measurements between windings are preferred.

4 EXECUTION OF MEASUREMENTS

4.1 General instructions

A successful dielectric response measurement on a power transformer requires adequate planning and coordination with its owner for finding information on winding geometry and on means to disconnect the unit from network. The objectives of the measurements, and thereby the resulting connection of the instrumentation to the transformer, should preferably be decided forehand.

Good understanding of the factors that may influence the measurements under field-conditions, and therefore also the interpretation of dielectric response results, is of crucial importance for the diagnosis reliability. Constant and preferably not too low temperature is advantageous for the interpretation quality – at higher temperatures the time necessary for the measurements can be shortened. It is recommended to make guarded CHL measurements between main transformer windings. In the case of CH and CL measurements, it is also important to make sure that the transformer bushings are dry and clean.

Before starting the measurements the transformer should preferably be completely disconnected from the station power connections, i.e. all connections to the bushings should be dismantled, and the station connections should be properly grounded. The bushing terminals of the individual windings should, if possible, be shortened together by conductors kept away of earthed structures. For CH and CL measurements internal leakages and creeps from bushing surfaces remain as the disturbing factors and therefore should be considered in the analyses of the results.

If any of the windings has a neutral point connected either directly to ground or through impedance to ground, also this connection should be removed. The neutral bushing should preferably be interconnected with the phase bushings during the measurements. Sometimes a surge arrester is connected to the neutral point, and preferably, this connection should also be isolated.

In exceptional cases CHL measurements can be performed with only disconnectors opened. In such a case all the equipment representing direct galvanic connections to ground, such as voltage instrument transformers and neutral point impedances, must be disconnected. In such cases, special safety precautions must also be observed, so that the measurement procedures do not violate national regulations and company instructions. Description of such procedures is not included in this guide.

The measurements are often affected by interference in the substation, such as parasitic leakage currents and induced electromagnetic disturbances. It is therefore important to secure proper grounding connections of the transformer tank during the measurements to minimize the ground interference. Proper placement of connecting leads can also minimize the influence of capacitive coupled or radiated noise. Use of shielded connecting cables is recommended in noise environments.

The temperature of the insulation system in transformer has a great influence on the results of dielectric response measurements. Transformer temperature often varies and it is not equal inside the tank – higher at the top than at the bottom. If the measurements are made just after taking the transformer out of operation, its temperature will be slowly decreasing. It is recommended to register the temperature of oil just before starting the dielectric response measurements. The most accurate way to determine the oil temperature is to take top and bottom oil samples and measure the temperatures directly on-site in the sampled oil. After opening the tap, cold oil flows out first, thus waiting for sufficient time is recommended in order to get a representative sample. If oil sampling involves too much effort, indications from the built-in temperature gauges may be used, though it should be bear in mind their readings depend on location of the temperature probe. Alternatively, the average winding temperature can be calculated from a comparison of the actual winding resistance to a measurement at ambient temperature.

It is also recommended to register the ambient temperature, relative humidity and weather conditions in the station. In addition, making photographic documentation on the transformer and the measuring setup as well as recording the transformer nameplate information is advisable.

The following specific recommendations are advised to be considered before commencing the measurement procedure:

- Check functionality of the measuring instruments before going to the measuring site - this can be done by performing check measurements on a capacitance box.
- Upon arrival to the substation the measuring team should report to the site supervisor for discussing the activity plan, for getting a briefing on safety regulations and a summary on all earlier performed operations (disconnections, etc.). Always follow local safety instructions.
- Check whether parallel work is or will be carried out on the transformer that might restrict its availability.
- Inspect if all disconnecting/dismantling operations were performed in accordance to earlier agreements. In case of discovered discrepancies, obtain permission to have the complementary operations performed. Typical example is remaining connections of the neutral point impedance.
- Request availability of uninterrupted 1–Φ power supply suitable for supplying the measurement instruments.
- Obtain formal permission to start working on the transformer. Usually the transformer is at this stage grounded for safety reasons.
- Check for availability of a reliable grounding point; if ground grid is out of reach install ground rod.
- Plan methods and means to secure reliable connection of the measuring instruments to transformer terminals,

- If winding arrangement is not known, it should be identified by capacitance measurements.
- Protect measuring instrumentation from possible undesired influences by weather conditions.
- After completing the measurement, get assistance in re-establishing the protective ground connections on to the transformer before attempting to make any further disconnections/reconnections on the transformer top.
- Restore external transformer couplings to the initial state and report to the supervisor that the measurements are finished and that the transformer is restored to the state in which it was approached.

4.1.1 Suggested check-list of transformer data to be registered for tested transformer from its nameplate and other sources (instruction manual, construction drawings, etc.)

- Rated voltages, MVA, 1-Φ or 3–Φ, manufacturer and year and serial number. Take a photo of the nameplate.
- Number of windings and winding arrangement, presence of tertiary or split winding and if it has one point of delta internally earthed,
- Sealed type or free breathing type,
- Type(s) of cooling and the type most frequently used,
- Presence of oil duct between windings, if possible dimension of windings and of main oil duct,
- On-load and/or de-energized tap changer on HV or LV side - record tap changers positions,
- Core, frame and yoke internally connected to tank or brought out externally through a bushing on tank cover. Are they directly grounded or grounded via any resistor?

4.1.2 Supporting information about the transformer state

- Filled with oil or without oil, any vacuum/pressure applied,
- New, in-service, out-of-service or faulty,
- Rewound or modified in the past,
- Past records on DGA and furans for trouble checking or e.g. thermal ageing,
- Past records of oil analyses (moisture, conductivity, breakdown strength, dissipation factor, acidity, etc…),
- Records of oil and winding temperatures in service, e.g. from oil sampling records,
- Details on fault or tripping events, if the transformer is tripped from operation,

- Dielectric response measurement is to be performed before or after refurbishment; if after has it been done before?
- Request oil sampling from tank and tap changer before switching off from service (test oil conductivity and moisture in oil by KF titration)

4.1.3 Suggested check-list for execution of dielectric response measurements on power transformers

- The transformer must be disconnected from the net, which means that any connection to the transformer bushings including neutral(s) must be disconnected. There are procedures measuring UST-configurations, e.g. CHL with e.g. limited length of cables still connected to the bushings. These procedures will not be included in this guide, please contact the instrument manufacturer for instructions.
- Short the high voltage windings including their neutral point if present and available. Short other interconnected windings and their neutral, if existing, together. Use copper wire or similar connectors.
- For accuracy in GST measurements, inspect severity of pollution on bushing surfaces. Pollution in combination with rain and/or high air humidity during the measurements may cause relatively large leakage currents flow to the ground. This problem can however be reduced if the bushings are cleaned or by placing protective conductor rings on the external bushing surfaces and connecting them to the guard terminal of the instrument, thus reducing the creep currents.
- The transformer tank must be properly grounded.
- If the transformer is equipped with a Load Tap Changer (LTC) put the tap in a position away from neutral (some load tap changers have an over-voltage protection that is not correctly short-circuited if the tap is in neutral position). Record LTC position and DETC (De-Energized Tap Changer) positions.
- Make sure to record serial number, estimate of insulation temperature (top oil temperature, winding temperature), ambient temperature and weather conditions including relative humidly and temperature. See also earlier sections.
- Before connecting the main cable to mains outlet, connect the instrument protective earth/ground (PE) cable to PE at or in connection to the transformer tank. The PE cable is first connection made and last removed.
- Connect the instrument to a mains outlet that fulfil local safety requirements (usually PE of the transformer and the outlet must be metallically connected); otherwise use an isolating transformer.
- Power on the instrument.
- The measurement used for moisture assessment is preferably a UST measurement, e.g. CHL, with a reasonable capacitance usually above 1 nF. The capacitance depends on winding arrangement and possible

electrostatic shields, and if the capacitance is too low, choose another configuration, e.g. CHT (or if no UST configurations are possible, CL).

- Connect the instrument cables first to the instrument and thereafter to the interconnected bushings, as planned forehand. Usually the voltage cable should be connected to the winding that is believed to be exposed most to electromagnetic disturbances, which usually is the HV winding. Thus, the current cable should be connected to the less exposed winding, i.e. the LV winding. No winding should be left on floating potential, i.e. windings should either be connected to guard or to ground. It is essential to keep detailed records of the connections made.
- Get permission and assistance for removing transformer protective ground connections.
- Execute measurements.
- Possibly rearrange test leads and perform more measurements.
- After completing the measuring series disconnect the instrument cables first from the interconnected bushings and thereafter from the instrument.
- Backup test data.
- Switch off test equipment and disconnect the instrument from mains outlet.
- As the last operation, disconnect the PE-cable.

4.2 Supplementary recommendations and comments for FDS measurements

As regards FDS measurements, the following recommendations are to be obeyed:

- Tests are normally performed with voltage levels up to 200 V peak, but it is advisable to choose as low voltage as possible with respect to background noise level. A wide frequency test should be performed with at least one configuration, preferably UST; usually the range 1 mHz – 1 kHz is used but lowest frequency can be omitted for measurement at elevated temperatures. In case of low temperature or dry transformers, the lowest frequency should preferably be 0.1 mHz. Other configurations are either omitted or measured in a shorter frequency range, e.g. 10 mHz – 1 kHz. Avoid including the power frequency or it first harmonics (e.g. 50, 100, 150 Hz…) in the list of measuring frequencies.
- Initial control tests for checking the object capacitance may include measuring it at highest frequencies, a few tests to ensure that the instrument is properly connected and winding that should be floating is not grounded or faulty (similar to depolarization current test).
- If the instrument allows for viewing the wave forms of both the applied voltage and the current measured, they should be observed for contents of harmonics. A high offset level or dominating power frequency component may lead to (i) difficulties with carrying out the measurements, (ii) prolonged measuring times or (iii) inaccuracies of the results.

- Instrument output current is limited, often to about 50 mA peak, which, depending on measuring voltage and load capacitance, sets the maximum frequency of the measurements to f_{max}= 0.05/(2*pi*U*C). In such case, it is usually advisable to perform the measurement at both 200V peak and at a lower voltage for comparing the results afterwards.
- As long as UST (winding to winding) measurements are possible to perform, results of these should be used for interpretation in terms of water content in solid part of transformer insulation system. UST measurements minimize the influences from loading capacitances to ground as well as from internal and external leakage currents to ground.
- GST measurements (winding to ground) are less useful for the estimation of moisture content, since the measurements between winding and ground involve more complicated configuration of insulation geometries (i.e. bushings, windings to core, tap changer components, etc.). The frequency range for GST measurement can therefore be reduced to 10 mHz to 1 kHz.

4.3 Supplementary recommendations and comments for PDC measurements

A three-step measurement procedure is advised in order to obtain best accuracy:

- Initial reconnaissance measurement to assess remaining charge without any voltage applied.
- Ground all bushing terminals after shutdown for discharging - it is required that the test object is de-polarized prior to the measurements,
- Control measurement of short duration (e.g. 5 s) and with low charging voltage (e.g. 100 V) to verify the amplitude of measured current. The next step can be started after the depolarisation current decreases to minimum. The depolarisation duration before the main measurement (during control measurement) shall be long enough to achieve a current significantly lower than the lowest current to be expected. A good grounding system is essential in obtaining very low remaining currents. This is sometimes difficult when the test is carried out in the area without ground grid e.g. in workshop or storage. Then an installation of a ground rod for testing is essential.
- Any fault in the winding under test increases the depolarization current during initial measurement. The quite-constant pattern with the current magnitude of several hundreds nA to μA range is the symptom. The test shall finish in this first step. Further investigation can be done by means of the initial measurement of different connection, e.g. insulation of winding to ground.
- Main measurement with charging voltage of 100 – 500 V for the insulation between windings (CHL) and duration of 10^4 s/ 10^4 s for polarisation/depolarisation currents. Test duration may be reduced at elevated temperatures.

5 CASE STUDIES

A number of study cases are reported below in order to exemplify different practical situations that should be considered when performing diagnostic measurements of dielectric response on power transformers. Each of the study cases is preceded by indicating the aim for which it was selected.

5.1 Karl Fischer Titration as a scale for dielectric response methods

Aim:

To illustrate difficulties arising when evaluating moisture content by means of KFT analyses of transformer oil and further consequences for scaling the results of dielectric response measurements.

To evaluate the moisture content in the solid insulation of transformers based on results of dielectric response measurements, the titration according to Karl Fischer (KFT) served in this report as a conventional and direct measurement method allowing for benchmarking of the estimates. KFT measures water content in oil and in cellulose. Though the method is considered as representing the state of the art in the measurements of water mass in the solid and liquid parts of impregnated insulation, there exist a number of concerns regarding its accuracy. This chapter introduces the measurement principle and points to the conditions necessary to be obeyed for obtaining accurate results.

5.1.1 The KFT technique

Karl Fischer titration allows for determining trace amounts of water in a sample using volumetric or coulometric titration. Its principle is to add a reagent (titre iodine) to a solution containing an unknown mass of water until all water reacts with the reagent. From the amount of reagent the mass of water can be calculated. In volumetric titration the added volume of the reagent iodine is measured and the water content calculated. The sensitivity of volumetric titration is limited to some 10 µg of water so that it is hardly applicable for dry transformer oils. In coulometric titration an electrode generates the reagent iodine and the water mass is calculated using the electrically generated iodine. The moisture can enter the electrolysis vessel either by direct injection or through transfer from an external oven. The detection limit of coulometric titration reaches a few µg of water.

5.1.2 Reliability and comparability of KFT analyses - Round Robin Test

Several factors may affect the results of KFT analyses:

- There is always ingress of moisture from the atmosphere during sampling, transportation and sample preparation. This happens particularly during paper sampling from open transformers.

- Cellulose binds water with chemical bonds of different strengths. It is uncertain whether the thermal energy supplied releases all the water. Heating temperature and time certainly changes the released water.
- Laboratories differently treat constraints that are not covered by standards, such for example as the type of solvent used for oil extraction.
- Sometimes the direct injection and the heating methods yield different results of moisture in oil analyses. This might result as an influence of additives and aging by-products in oil.

To elucidate this influences and to evaluate the discrepancies that may result from KFT analyses, a round robin test (RRT) was carried out among seven laboratories from four European countries. It concentrated on analysing the water content in paper relative to weight and the water content in oil relative to weight in three oil and paper samples according to the respective laboratory's standard procedures. The obtained results revealed an unsatisfactory comparability between the laboratories [21], as shown below.

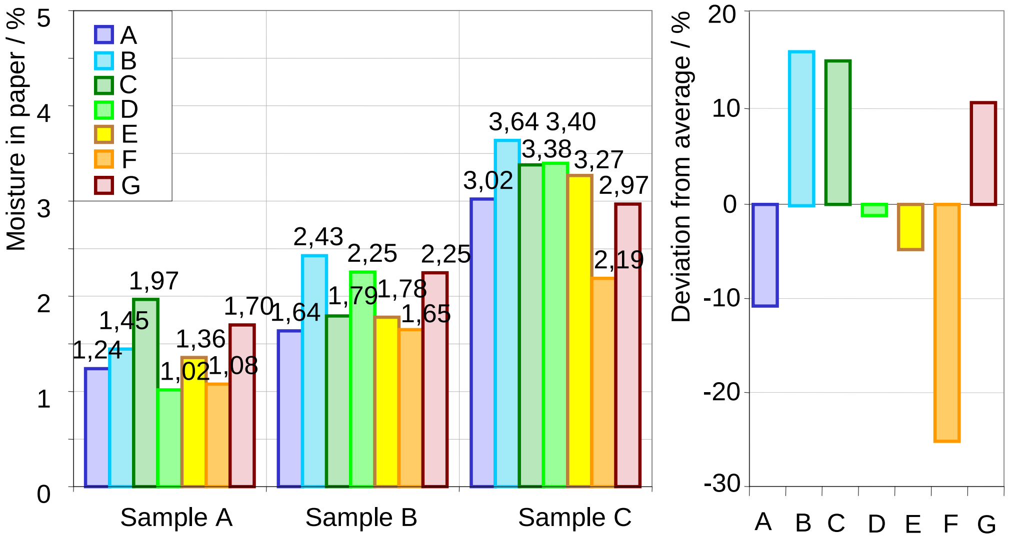


Figure 16: Moisture content in paper in % relative to weight as measured by the laboratories (left) and deviation of each laboratory from the average (right).

The results of moisture in paper analyses are depicted in Figure 16. For example, for sample A the moisture estimates varied between 1.0 and 2.0 %. The laboratories used different oven temperatures during the titration of paper samples. One systematic influence is therefore obvious - the heating temperature of paper in the oven increases the released mass of water. This is due to existence of chemical bonds of different strengths, which hold water molecules in paper. On the other hand, the heating temperature must remain below the threshold for decomposition of cellulose by pyrolysis, which if exceeded will result in additional water production. Beside this, other differences could only be explained by stochastic influences. For sample A, containing little water, the comparability was worst and hardly acceptable.

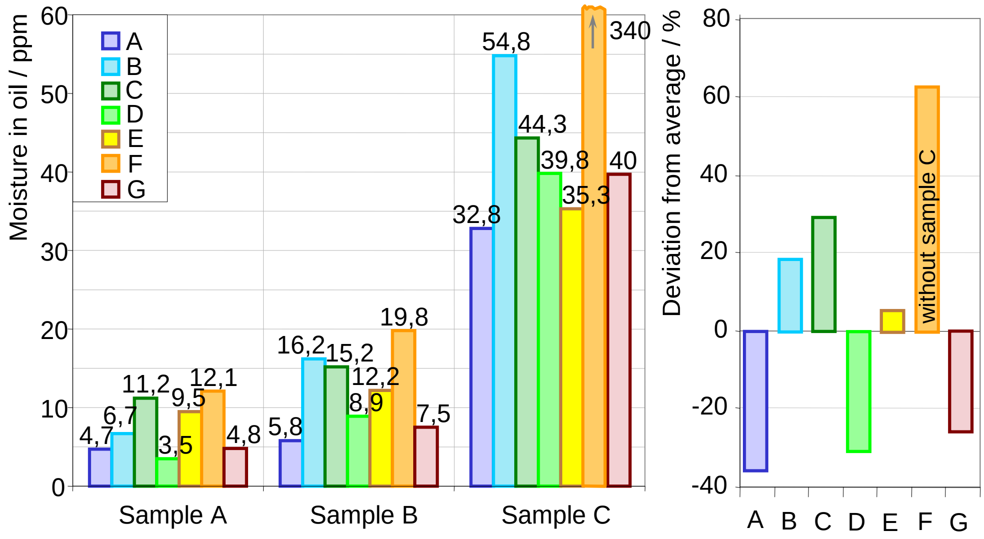


Figure 17: Moisture content in oil in ppm relative to weight as measured by the laboratories (left) and deviation of each laboratory from the average (right)

On the other hand, the results of moisture in oil analyses, shown in Figure 17, provided a reasonable conformance only for the wet oil sample C, although unexpected discrepancies could also be observed. For the drier samples A and B only a trend was recognizable; the results varied from 3.5 to 12.1 ppm for sample A and from 5.8 to 19.8 ppm for sample B. Systematic differences were obvious. It has to be mentioned that for the dry oils, the results also varied within one single laboratory and a standard deviation of 20% is not unusual.

5.1.3 Consequences for interpretation of dielectric response measurements

Water content determination by means of dielectric response methods is often calibrated by comparing them with evaluations based on KFT. However, as shown above, KFT results also suffer from a poor comparability between different laboratories. The user must therefore be aware of this fact, and understand that a deviation in the comparison does not necessarily point out weaknesses of the dielectric methods. The sampling procedure and the titration parameters used by specific chemical laboratory determine comparability to dielectric response based results.

This also applies while comparing the moisture evaluation result of various dielectric response methods between each other. The moisture analyses are based on comparison to results obtained on model samples. If different titration techniques were used to scale the models, the dielectric response methods stringently will come to different results as well.

In recent years new moisture sensors have become available for continuous on-line monitoring. A technical brochure provided by the CIGRÈ WG A2.30 represents the practical application of these sensors especially in comparison to the traditional approach of oil sampling, Karl Fischer titration and subsequent application of an equilibrium diagram [22].

5.2 Dielectric response diagnostics

Aim:

To present possibilities and challenges arising under application and interpretation of dielectric response measurements. Comparisons between different moisture determination approaches (dielectric response, KFT and moisture equilibrium) are demonstrated, including illustration of the influence of aging of insulation components on estimation of moisture content.

5.2.1 Comparison of moisture determination by means of dielectric response measurements and KFT

The main aim of the work presented in this section aimed at calibrating the estimated moisture content in paper obtained from FDS measurements against results of KFT analyses of oil and paper samples taken from the investigated transformer. Generally, the possibilities to obtain paper or pressboard samples from power transformers that are temporarily taken out of operation are very limited. Such studies can thus be performed on defective units, undergoing repair or scrapping, where the solid insulation can readily be accessed. However, the number of units available for this type of investigations is anyhow fairly low. Therefore, an offered opportunity to perform measurements on a defective transformer that had to be opened and repaired was appreciated.

The transformer studied was a three-phase unit, manufactured in 1967, rated 50 kV/10 kV and 40 MVA. It had Y0y0 phase configuration and OFAF cooling. Indications for a presence of fault in the tap-changer, previously also experienced in other two identical units, initiated broader investigations, which aim was to judge whether the unit could be repaired or should be scrapped. Insulation condition was assessed and it was found that the solid insulation was significantly aged with DP values around 350 and possibly even down to 300. Further, the oil was severely degraded, showing high level of acidity. It was however concluded that the transformer could still be shipped for repair and the oil should be replaced by new oil or refurbished one.

The unit was out of operation for a period of 4.5 months and the FDS measurements and other analyses were performed at several occasions during this period, i.e. before, during, and after the repair. KFT analyses, performed on oil samples and on samples of paper and pressboard, allowed for comparison of moisture content estimations obtained by different techniques. Samples of the paper were taken when the transformer was opened in workshop, whereas the oil samples were taken at several occasions throughout the disconnection period.

Figure 18 shows in detail the positions and when the samples of solid insulation were taken together with the respective moisture content values obtained from KFT analyses.

The analyses of results from dielectric spectroscopy measurements showed that the estimated moisture contents varied and were in the range of 1.4-2.4%. These estimates were in good agreement with the results from KFT analyses performed directly on paper and pressboard samples, 1.0-2.5%. Also estimates based on oil samples gave similar results, about 2.4%, if the in-service temperature was used as the reference. Since the time constant for moisture migration between oil and paper in large power transformers is extremely long, especially at lower temperatures, the in-service temperature is the proper selection for the KFT analyses, even if the transformer has been taken out of operation and was allowed to cool for a few days.

The general conclusion is that moisture level in solid part of the insulation in the investigated transformer is at the level of about 2%, which indicate a fairly dry condition. More details on the analyses of this and other study cases can be found in [23, 24, 25].

5.2.2 Moisture determination in a heavily aged transformer

A heavily aged transformer was designated for scrapping. Such a case provides a good opportunity for comparing different methods of moisture assessment in paper samples. The transformer, built in 1950, and rated 104/23,4 kV, 30 MVA, had an ONAF cooling. Mineral oil type Shell Diala 6KX from 1954 and having neutralization number of 0,49 mg KOH/g filled the transformer. Paper and oil samples were taken out after measuring the dielectric properties (polarization and depolarization currents in time domain as well as complex capacitance in frequency domain). The insulation temperature was 24°C during the measurements.

Figure 19(a) displays the polarisation and depolarisation currents measured through the main transformer insulation CHL as a superposition of conductivity and polarisation phenomena. As seen in the figure, the polarisation current approached its saturated value quite early, at around 300 s, and almost no decrease occurred afterwards. Further decay of polarisation was solely dominated by the conductive component of the current. Since the final current value could be estimated at 300 s, the measurement might have been stopped at that time, which indicated an unusually high conductivity of insulation system in this transformer.

Figure 19(b) displays the dissipation factor as measured between HV- and LV-winding. The losses in the insulation are very high even at power frequency, e.g. 0.13 at 50 Hz. Conductivity of the oil influences the dielectric response of this transformer only down to 0.1 Hz, below this frequency the properties of cellulose dominate. Because of the highly conductive nature of this insulation the measurements might have been stopped at 0.01 Hz since sufficient amount of information for the analysis was gathered.

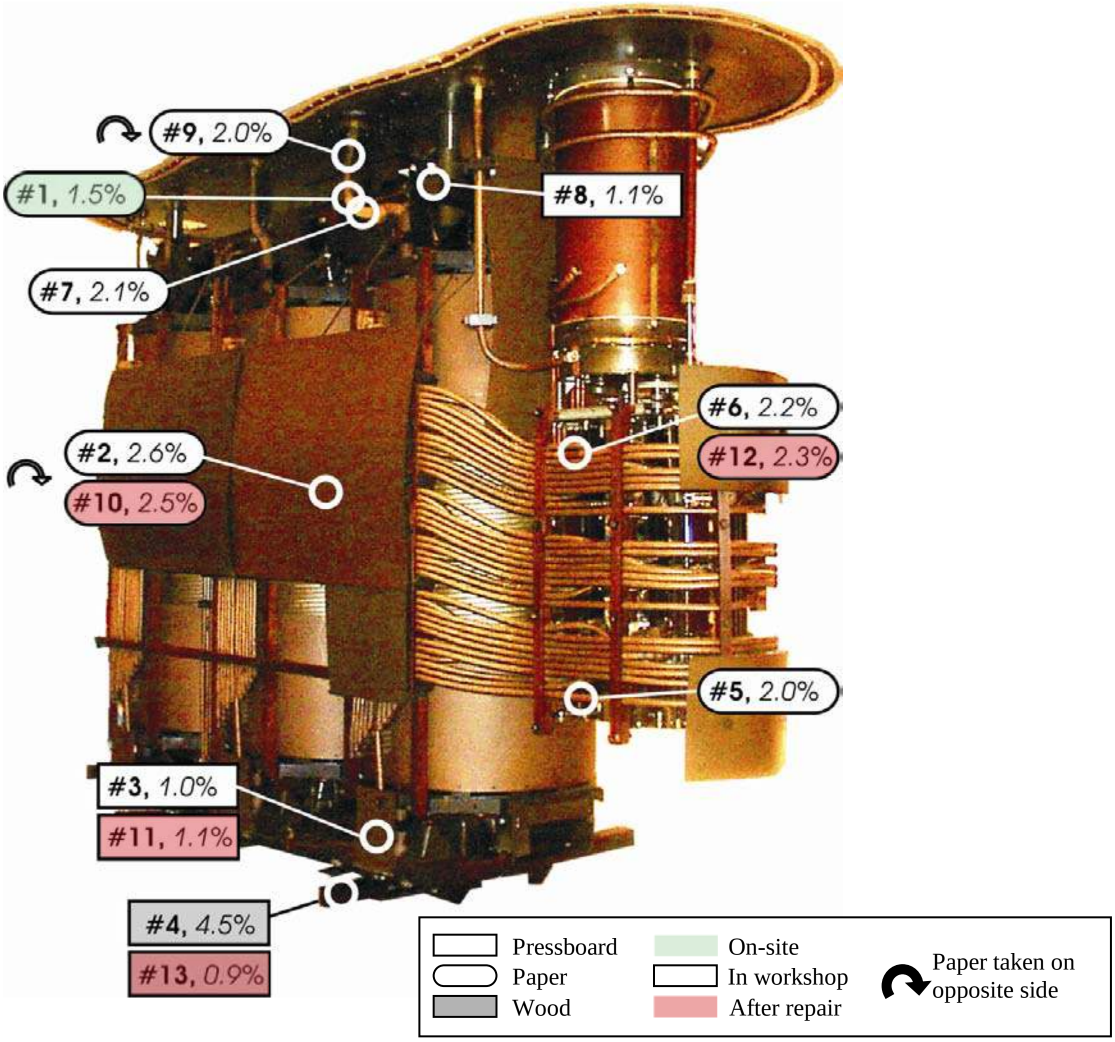
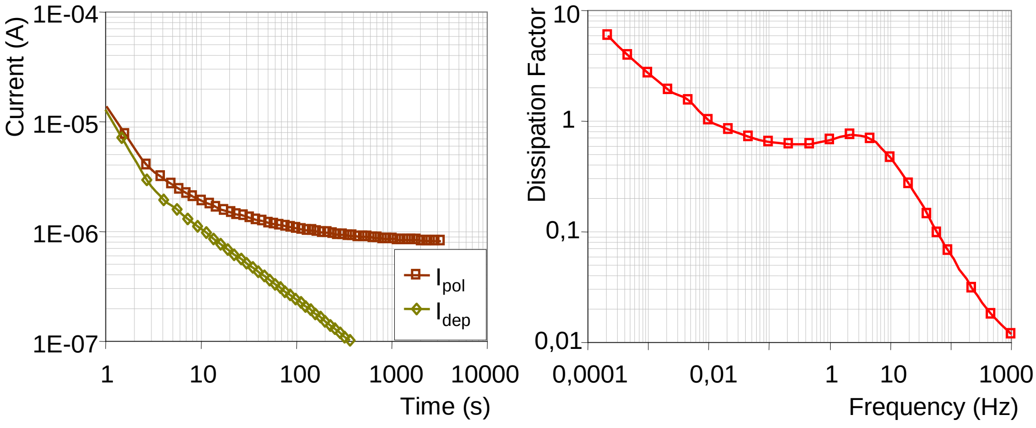


Figure 18: Moisture content estimated by means of KFT in samples of transformer solid insulation at different locations and sampling events.



(a) (b)

Figure 19: Polarisation currents (a) and dissipation factor (b) measured between HV- and LV-winding of the studied transformer.

The oil conductivity of this transformer was both measured and estimated based on the dielectric response model, yielding respectively σ_{meas} = 0.9 nS/m at 22°C and σ_{mod} = 1.3 nS/m at 24°C. Both the results agree well, as observed for all comparisons of measured to modelled oil conductivities. The oil conductivity likewise the neutralisation number value of 0.49 g KOH/kg oil were here unusually high (normally, at room temperature, the oil conductivity is within the range of 0.05-20 pS/m), which indicate a high content of conductive aging products.

Figure 20compares the results of the analyses of the time domain measurements performed. Karl Fischer titration of the paper samples yielded 2,6 % moisture by weight (KFT). Results of the modelling of the dielectric response measurements by means of different software differ from each other: Two algorithms (DA1, DA2) had no compensation for the influence of conductive aging products and came to 3.8 and 4 % moisture by weight. Another algorithm (DA3) with build-in compensation for conductive aging products [17] indicates 2.9 % moisture relative to weight.

In the oil sample the moisture saturation was measured directly onsite and the moisture content in ppm by Karl Fischer titration in a laboratory. When using moisture sorption isotherm [22], the relative saturation reading led to 2,5 % of moisture in cellulose (RS), which well agrees with the KFT analysis of the paper samples and the dielectric response analysis with compensation for conductive aging products. At the same time, direct application of equilibrium curves, based on moisture content in oil in ppm [26], yielded much too high content of moisture in paper - 6,0 %.

This study case indicates that when analysing the moisture content in a strongly aged transformer the methods and algorithms not adopted for taking into account the aging state and moisture adsorption capacity of transformer insulation may overestimate the moisture content.

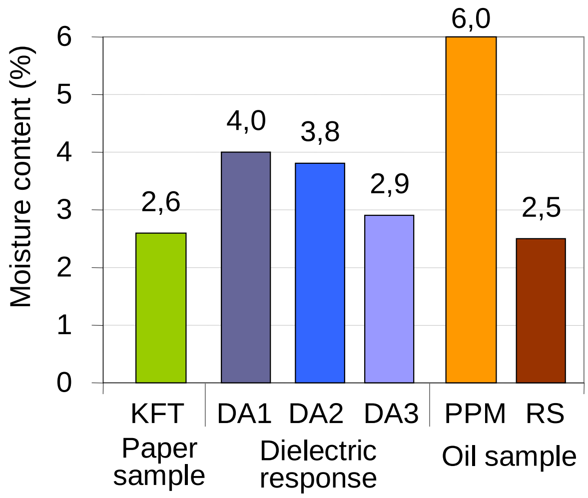


Figure 20: Moisture content in the solid insulation obtained from Karl Fischer titration of paper samples (KFT), dielectric response analyses (DA1, DA2, DA3) and from use of equilibrium diagrams for moisture by weight in oil (PPM) and from the relative saturation of oil (RS).

5.2.3 Oil exchange and drying of power transformers

The following study case is presented to exemplify the effects of oil exchange and drying of transformer insulation on the results of dielectric response measurements.

A large amount of sludge was found in the oil of a 300 MVA transformer after 23 years of uninterrupted operation. The owner of the transformer decided to exchange the oil. Prior and after this operation, measurements of PDC, RVM and tan δ (at 0.1 Hz) were performed [27] and the results are shown in Figure 21 and summarised in Table 3. Furthermore, a paper sample was shaved at a lead of a tap winding and analysed. The degree of depolymerisation was DP = 352, which indicated a normal thermal ageing of the paper.

Table 3: Results of diagnostic measurements carried on a 300 MVA transformer prior and after oil exchange

Measurements	**Prior to oil change**	**After oil change**
tan δ at 0.1 Hz, directly measured	0.894	0.187
tan δ at 0.1 Hz, from PDC analysis	0.901	0.191
conductivity σ_{oil} of the oil, from PDC analysis in 1/Ωm	$\approx 4.5\cdot10^{-11}$	$\approx 3.5\cdot10^{-12}$
Moisture in the solid insulation material, from PDC analysis	3 %	2.7 %
Moisture in the solid insulation material, from RVM measurements	3.45 %	2.48 %
Depolymerisation degree	352	

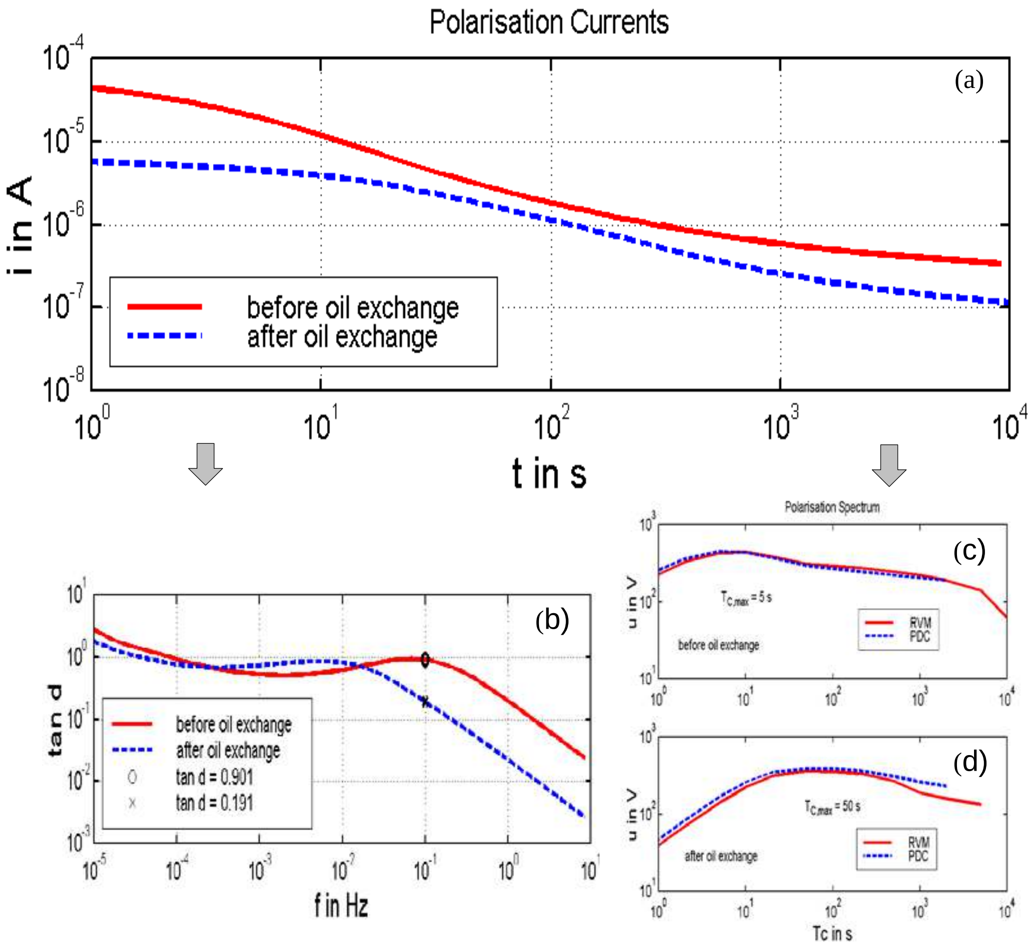


Figure 21: Polarisation currents measured between HV and LV windings in 300 MVA transformer before and after oil exchange (a) with calculated tanδ spectrum in frequency domain (b); RVM polarisation spectra before (c) and after (d) oil exchange compared with spectra calculated from PDC results [27].

The PDC analysis showed clearly that the oil exchange reduced oil conductivity by about one order of magnitude, which can directly be seen from the current values at t = 1 s, Figure 21(a). This was also confirmed by separate oil conductivity measurements. Furthermore it is concluded that the water content in the barriers was not changed significantly. Respective estimates of water contents, 3% before and 2.7% after the oil exchange, were estimated by comparing PDC curves with calculated ones, as shown in Figure 22 (a) and (b). The estimates were obtained by taking into account the insulation geometry. Pressboard conductivity, which is related to the water content, could also be calculated based on the long term current values. Figure 21 also shows frequency dependence of tan δ and RVM spectra, which were calculated from the time domain data of PDC measurements. As it can be seen from the figure, these agree well with the measured data.

Due to the low moisture absorption capability of oil, it is not possible to decrease significantly the moisture in the solid insulation by exchanging the oil of a transformer. Assuming a weight of the solid insulation of 10000 kg and a moisture content of 3 %, we have a total water content of 300 kg. Assuming further an oil weight of 50000 kg and water in oil content of 30 ppm, which is a high value, we get a water mass of only 1.5 kg stored in the oil. Thus, the water content in the transformer prior and after the oil exchange remains almost the same. This can clearly be seen from the PDC measurement and from its frequency domain transformation, but not from the so called RVM spectra [27]. The differences between the RVM spectra seen in Figure 21 (before (c) and after (d) the oil exchange) are obviously caused by the difference in oil conductivity but not by different properties of the solid insulation.

Because the operation of oil exchange did not significantly reduced wetness of the solid insulation, it was decided to dry the transformer [14]. Results of PDC measurements that accompanied this operation showed a significant reduction of water content, which remained in agreement with the amount of extracted water, Figure 22 (c) and (d),

Figure 22 also illustrates the evaluation procedure of PDC results. Based on XY insulation model, PDC curves are simulated assuming material properties at different water contents. The best fit with the measured curves indicates the water content in the cellulose barriers.

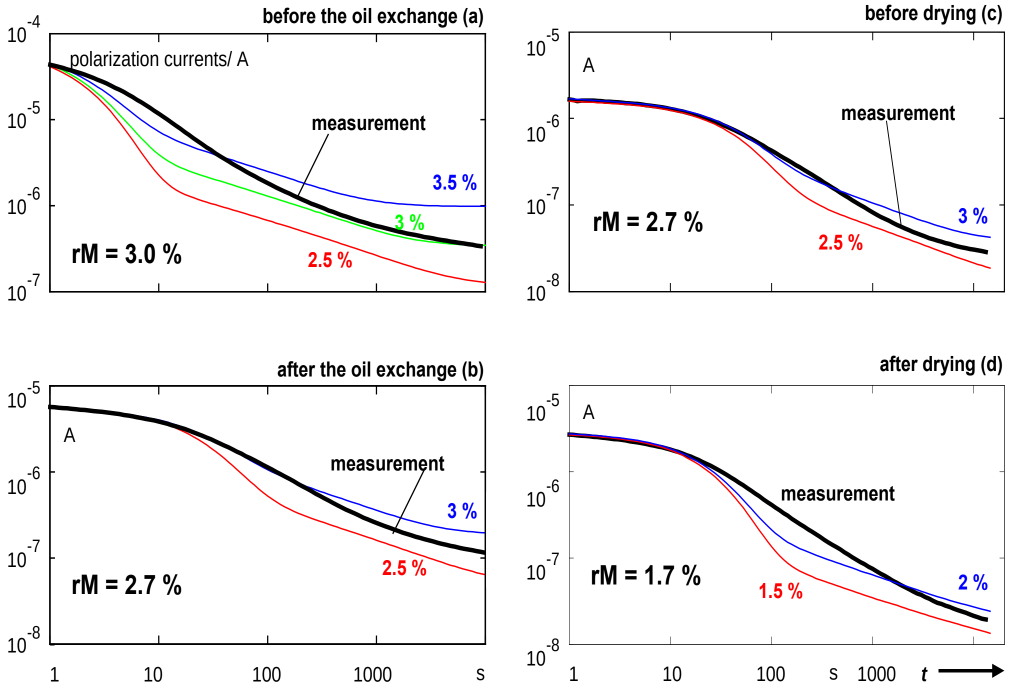


Figure 22: Polarization current measured on 300 MVA power transformer before and after oil exchange (a and b) as well as before and after drying (c and d). Moisture content rM, as marked in the graphs, is determined by curve fitting.

5.3 Influence of external environment

Aim:

Pointing to different factors that may influence results of dielectric response measurements in field conditions

5.3.1 Presence of different leakage paths

Although the determination of moisture content in power transformer insulation is nowadays rather straight forward, there may appear situations where results of dielectric response measurements become influenced by local conditions in substation. Some selected cases are therefore presented below to secure a better insight to possibilities and limitations of the techniques.

Leakage paths in CHL measurements

In CHL measurements, the voltage usually is applied to the transformer HV side and the resulting current is measured on the LV side. If the guard cable is connected to the grounded transformer tank and no other elements are connected to the bushings, the whole current flows across the main insulation between windings, following the desired current path illustrated in Figure 23. The capacitance (C') and the losses (C") of the insulation between the HV and LV windings can be characterized well. If, on the other hand, the measurements are done when only opening the disconnectors on both sides, letting in this way some elements remain connected to transformer bushings (cables, arrestors, string and post insulators, etc.), the current required to load these element capacitances loads the HV terminal of the measuring instrument. Although the capacitance of these elements can sometimes be quite high, the additional current does not severely affect the measurement. However, this situation can create a problem in case when the instrument gets into its current limit and decreases subsequently the supply voltage or a parasitic frequency dependent impedance is present, for example a voltage transformer (VT) on the LV side. Another error source is when the voltage drop in the Hi measuring cable becomes significant due to the high current caused by the additional load and thereby introduces an error in the measured impedance. This error is larger at higher frequencies since the load current increases with frequency.

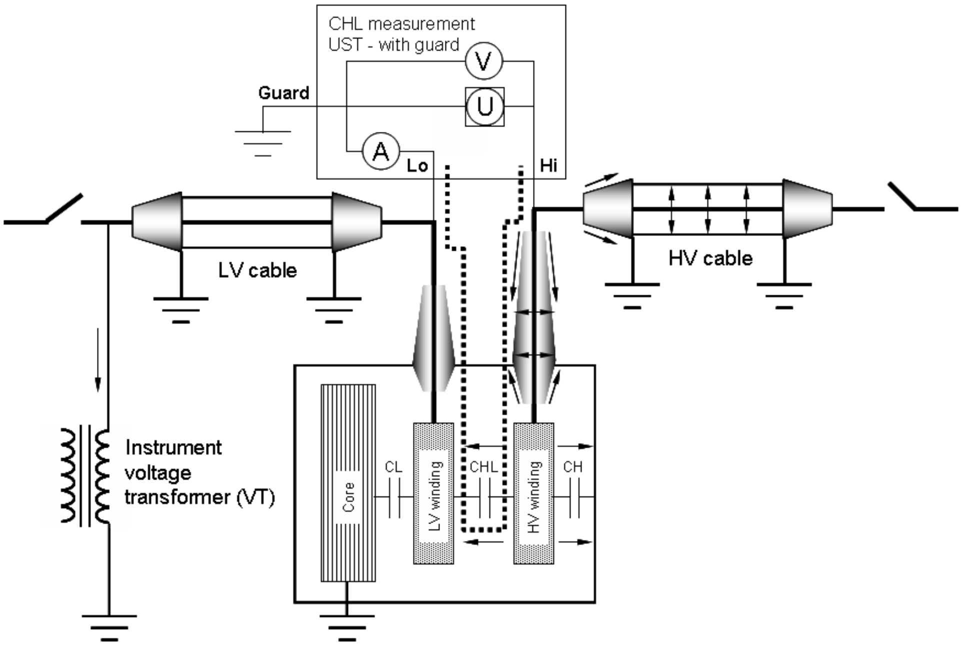


Figure 23: Main and parasitic current paths in CHL measurement with opened disconnectors.

Leakage paths in CH and CL measurements

In CH measurements the capacitance C' and the losses C'' of the insulation between the HV winding and the tank are measured by applying voltage to the transformer HV side and measuring the current returning to the ground. As Figure 24 shows, the guard should be connected to LV winding in order to avoid measuring the inter-winding capacitance (CHL) together with HV-to-tank one (CH).

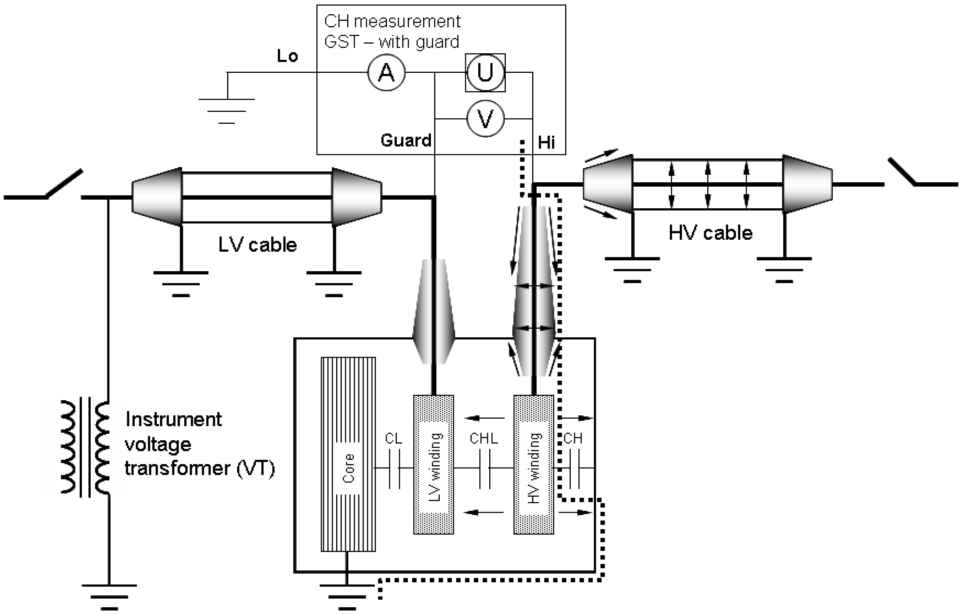


Figure 24: Main and parasitic current paths in CH measurement with opened disconnectors.

Even in case all the shunt elements are dismantled from the transformer, bushing capacitance and internal creeps are measured in parallel with the CH, as they cannot be guarded. This means that the addition of the bushing capacitance and the internal creep in CH measurements can yield deviations of the dielectric response measured.

The influence may also be strong if the measurements are performed with some circuit elements connected to the bushings. In this case the capacitances of these elements (insulators, surge arrestors, cables, etc.) are measured in parallel with the CH. The cables connected to the transformer HV side have sometimes a length of a few hundred meters and are insulated with oil-impregnated paper. Thus their capacitance is often larger than and having similar properties to the transformer internal insulation. In such a case the CH measurements are more representing the behavior of the cable insulation than that of the transformer insulation.

In CL measurements the insulation between the LV winding and the core is mainly measured. A similar situation to that analyzed in CH measurements appears. In this case also the effect of the instrument VT should be considered, if applicable, in addition to the effect of LV cables. More detail explanations and analyses on the above described cases can be found in [24].

Leakage paths along transformer bushings

Appearance of parasitic current paths along the surfaces of transformer bushings can further influence dielectric response measurements [24]. The risk of creep from bushings increases when their surfaces are contaminated, and especially in conditions of high humidity or rain.

As indicated above, the bushing creep has not much effect on CHL (UST – with guard) measurements, as the surface leakage currents are flowing to the tank, which is guarded. Major effects can, on the other hand, be experienced during CH or CL (GST – with guard) measurements. The latter effect is illustrated below as observed during FDS measurements in field conditions. Surfaces of bushings in the tested transformer were covered with old, dried and polluted silicone grease. CH measurements were performed during a rainy day and then compared with results of measurements performed on a sunny day. In Figure 25 the results of measurements (C´ and C´´), performed on a sunny day are compared with measurements made while it rained (C' rainy and C'' rainy). Large discrepancies were found between the results, caused by creep current flow along the bushings surfaces under the rain. The interpretation of the two measurements under dry and wet conditions yielded 2.7% and 5% moisture content in paper, respectively. Thus, the presence of the leakage current resulted in a strong over-estimation of the moisture content in the tested transformer.

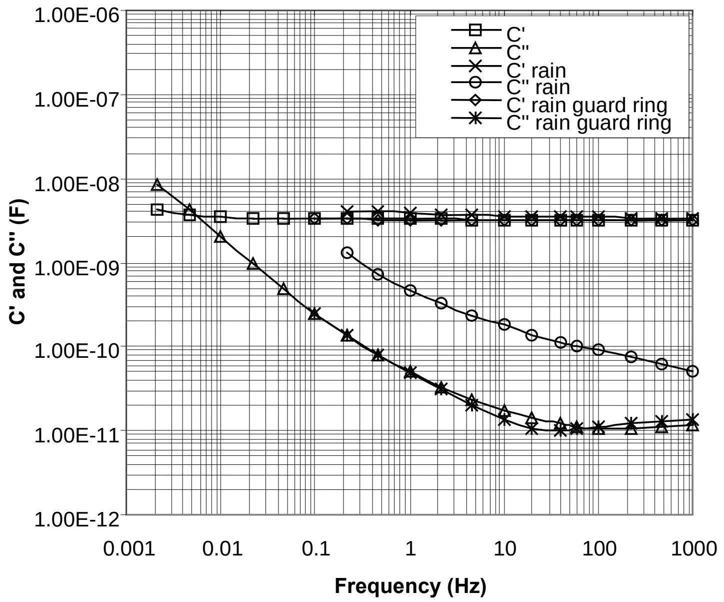


Figure 25: Effect of bushing surface creep during CH measurements in field conditions.

To avoid the effect of surface creep, soft copper straps were fixed around the bushing’s porcelain body and were connected to guard terminal of the measuring device together with the LV winding, as illustrated in Figure 26. In this way, even though the measurements were performed during rain, the influence of the currents flowing along the bushing surfaces was eliminated. This can be seen in Figure 25, where the results marked as C’ rain guard ring and C’’ rain guard ring, are very similar to the ones obtained under dry conditions, thus strongly damping the creep effect.

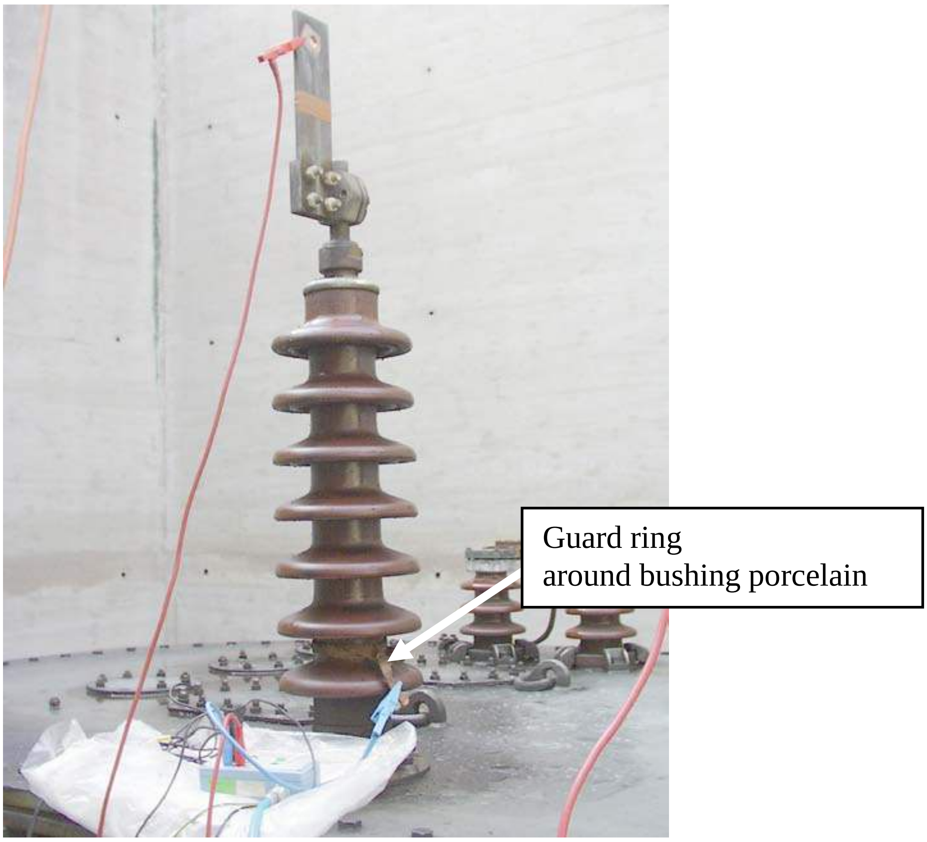


Figure 26: Guard applied around bushing for avoiding influence of surface leakage currents on results of GST - with guard measurements under strongly polluted conditions.

Electromagnetic disturbances

When disconnecting a transformer for performing dielectric measurements, other circuits in the substation usually remain energized, representing a potential source of electromagnetic disturbances. A transformer under test is most prone to pick-up the disturbances through the air if the measurements are performed with only opened disconnectors and long conducting lines, acting as antennas, remain connected to the bushings. Disturbances can also be conductively coupled through galvanic paths to the substation's ground system, for example via connected voltage instrument transformers. Measurements of voltages induced at tested transformer terminals in one such a substation were at a level of a few hundred volts when lines with a length of some tenths of meters remained connected. Under these conditions it was not possible to carry out any dielectric measurements at all.

The influence of electromagnetic disturbances, their limits and the measures to be adopted for reducing their influence on the dielectric measurements are still under investigations.

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