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Reliable Diagnostics of HV Transformer Insulation for Safety Assurance of Power Transmission System
REDIATOOL - a European Research Project

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SUMMARY

Interest is increasing in replacing the traditional way for determining moisture content in pressboard and paper in insulation of power transformers, based on chemical analyses of oil, 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 response to the conclusions of CIGRE TF 15.01.09 – Dielectric Response Methods for Diagnostics of Power Transformers [1], a European project, named REDIATOOL (Contract no. NNE5/2001/472), was initiated in 2003. The project involved collaborations among researchers and engineers from Sweden, Poland and Germany. The project in its part related to the evaluation of dielectric response methods concentrated on (i) investigations using laboratory models to improve calibration (interpretation of results) of the methods based on dielectric response measurements, on (ii) verifications performed on different types of the transformers sent for repairs, and finally, on (iii) gathering experiences from investigations of transformer insulation on-site.

REDIATOOL combines theory and laboratory methods, computer and physical modeling as well as testing real units in field conditions. This paper presents and summarises the project results, to be used by operators, manufacturers, service providers and scientists in their further work towards standardization of diagnostic methods for transformers. Results of the investigations performed allow believing that the dielectric response measurements, when properly performed and interpreted, providing more accurate information on moisture content in paper and pressboard in transformers that the use of conventional equilibrium curves.

KEYWORDS

Power transformer – diagnostic method – dielectric response - measurements - moisture - evaluation

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1. INTRODUCTION

Evaluation of moisture content in oil-paper insulated power transformers is of vital importance since water significantly accelerates ageing of cellulose. Numerous owners consider moisture content above 3% as a warning level. Oil analyses by means of Karl Fischer titration (KFT) have traditionally been used for the evaluation, assuming existence of equilibrium in distribution of moisture between oil and paper/pressboard and subsequent use of so called equilibrium curves [2]. Unfortunately, the equilibrium state is rather rare for a transformer in operation and this is one of the reasons for which the estimates are not always very accurate. In addition, for oil sampled at low temperature, the equilibrium curves are not very accurate, which additionally introduces uncertainty in the estimates of moisture content.

Several new techniques, based on dielectric response measurements of transformer insulation system, have been pointed out by CIGRE for estimating the moisture content [1]. The three main techniques are Polarisation and Depolarisation Current (PDC) measurements, Recovery Voltage measurements (RVM) and Frequency Domain Spectroscopy (FDS) measurements. The first two techniques operate in time domain whereas the latter one in frequency domain. They respectively allow for obtaining either the response function $f(t)$ of the transformer insulation system or its frequency dependent complex permittivity $\bar{\varepsilon}(\omega) = \varepsilon'(\omega) - j\varepsilon''(\omega)$, both interrelated via Fourier transformation. However, the dielectric response of the whole insulation system in transformer depends on different factors i.e. on the properties of impregnated paper and pressboard, on the properties of oil, and on the geometrical arrangement of the system components [1] and a correct evaluation of the measured data involves mathematical modelling [2], which requires knowledge on variation of the oil and paper/pressboard properties with temperature and moisture. In addition information is required about design of insulation system, i.e. the relative amounts of pressboard barriers and spacers in relation to the amount of oil.

One of the project aims was therefore to obtain the dielectric response data for new and aged samples of paper and pressboard characterised by different wetness in a broad frequency or time ranges. Based on these data computer programs for interpretation of measurement results from real transformers were developed. Another task was dedicated to comparing results of measurements and interpretations obtained by means of the three techniques on identical objects, including a transformer model with different geometrical arrangements of oil-paper barriers. Similar comparisons were also done on transformers sent for repair, from which paper/pressboard samples could be taken for direct estimates of moisture content. This way calibrations of the estimates based on the dielectric response measurements were possible.

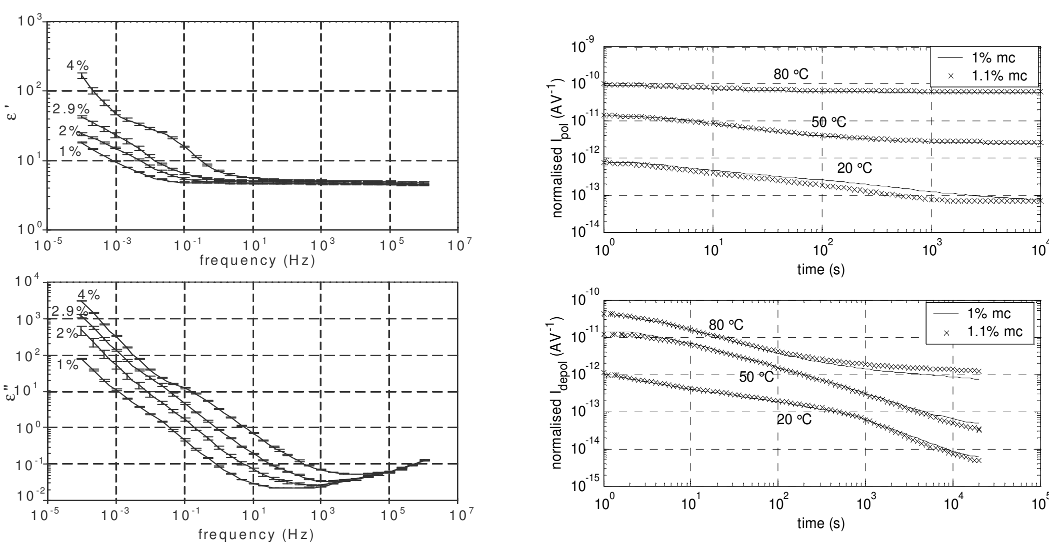
In field conditions the dielectric response measurements on transformers can be performed between high (H) and low (L) voltage windings (so called CHL measurements) or between windings and the ground (CH or CL measurements), providing possibility to evaluate different parts of the insulation. However, there exists a risk that undesired internal and external factors might influence the measurements, yielding errors in the estimates of insulation wetness. It is mostly desired that during the measurements the transformer remains completely separated and only internal leakages and eventually creep along bushing surfaces may influence the current flow. Other factors are time-varying and internally distributed temperature in the transformer, undesired weather conditions, as for example rain and high level of electromagnetic disturbances. It is also sometimes impossible, for different reasons, to dismantle bushing connections, thus the measurements have to be performed with open disconnectors only. Leakages present in parallel-connected equipment, from cables, arrestors, support insulators, etc., can affect the measurement results as well. Some of the project activities concentrated on elucidating these influences.

2. MODEL INVESTIGATIONS

2.1. Dielectric response measurements on model samples

Precise and reliable data from well-controlled oil impregnated samples of pressboard and paper are necessary for performing the modeling to correctly evaluate moisture content in real transformer insulation systems. Therefore one of the aims of this project was obtaining dielectric response data in a broad frequency range for new and aged samples of paper and pressboard. The pressboard samples, which were used for the measurements had thickness of 1.5 mm and diameter of 160 mm. Diameter of the paper discs was also 160 mm, while their thickness was 60 µm. Five groups of samples were prepared with moisture intake equal to 0.6%, 1%, 2%, 3% and 4%. All the samples were impregnated in Nynas Nytro 10GBN oil and stored in special containers. The paper and pressboard samples with moisture intake of 0.6%, 2% and 4% were also aged at 130 °C for 800 hours.

A three-electrode test cell, filled with similar oil as the one used for the impregnation, was used for measurements of dielectric responses in frequency and time domains in temperature range 20 - 80 °C. The dielectric response in frequency domain (FDS) was investigated in frequency range from 0.1 mHz to 1 MHz [3]. Figure 1a shows average dielectric responses of pressboard with different moisture contents at 50 ºC, calculated from measurements on three similar samples. The error bars indicate the deviation of the measured responses from the average. At low frequencies, at which each response corresponding to certain moisture content shows its unique shape and magnitude, error bars do not overlap. The dielectric losses in impregnated pressboard increase significantly with increasing moisture content when the frequency is lower than 100 Hz. At the same time, there is no much difference between the loss characteristics at frequencies higher than 10 kHz. Furthermore, a more rapid increase of permittivity ε' can be seen at low frequencies (below 0.01 Hz) in the samples with higher moisture intake (>2%). The same behaviour was observed at other temperature levels. This indicates clearly that the use of average responses for modelling is fully justified.



(a) (b)

Figure 1. *(a) Average dielectric responses in frequency domain of pressboard containing different amounnts of moisture (1% - 4% moisture intake) at 50 ºC with error bars representing the maximum deviation of the measured responses from the average and (b) polarisation and depolarisation currents of two samples of unaged pressboard (1% moisture intake) at different temperatures.*

Similar sets of curves were obtained for the unaged paper samples as well as for the aged samples of paper and pressboard. As regards the aged samples, a significant increment and change in spectral shape of both the real and the imaginary parts of the complex permittivity could be observed at frequencies between 0.1 mHz and 100 Hz. It is not clear yet if these changes are caused by reducing

DP or by appearence of ageing by-products, such as acids or additional water formed during the aging. Details on the data can be found in [4].

All the average measured responses allowed to derived master curves [5] of the dielectric responses in frequency range 10^{-6} Hz – 10^{8} for pressboard and paper containing different amount of moisture. The data were also analysed and fit to the known formulas describing the polarisation and conduction mechanisms operating in the considered frequency range. Parameters describing the changes introduced by temperature variation and by different levels of moisture content were defined. Similarly, the conductive behaviour of transformer oil was investigated and described in terms of temperature and wetness related parameters. Special computer programs were developed for further use in the modelling of results obtained from measurements on real transformers [4]. Simultaneously to the FDS investigations, time domain measurements of polarisation and depolarisation curtrents (PDC) were carried out. Example results are shown in Figure 1b. Analyses that followed revealed a good correlation between the results of measurements in time and frequency domains [4].

2.2. Measurements on model transformer

A model of transformer insulation [1] was used to compare evaluations provided by three different commercialised instruments, i.e. by (i) Recovery Voltage Meter RVM 5462 by Haefely Tettex with analysis software SWRVM 2 V.3.0, (ii) Polarisation/Depolarisation Currents Analyser MOD1 by Alff Engineering with analysis software PDC Evaluation Software V.3.0 and (iii) Insulation Diagnostics System IDA 200 by GE Energy Services with analysis software MODS V.1.5 (FDS). The influences imposed by insulation geometry, insulation temperature and oil conductivity were investigated. In an ideal situation, the procedures used for the analyses should be able to compensate for these three parameters [6] since during the investigations the moisture content in cellulose remained constant at about 1,1 %, as estimated by means of coulometric Karl Fischer titration of oil in the model.

The model contained eight pancake shaped coils separated by pressboard barriers and oil ducts between them. The ratio of pressboard to oil ranged from 15 to 100 %. This simulated the main insulation of different transformers. First, the dielectric responses were measured four times, at 21°C, 50°C and 78°C and once again at 21°C. During these investigations the model tank was filled with new transformer oil of type Shell Diala D (conductivity 1,6 pS/m). Afterwards the oil was replaced by a 25 years-old service aged transformer oil (conductivity 16,5 pS/m) and the measurements were repeated again at 21°C.

Figures 2 - 4 show, to the left of each figure, the basics of the interpretation schemes of the dielectric response methods RVM, PDC and FDS, whereas the diagrams to the right side display the results of analyses of moisture content for different arrangements of insulation geometry at different temperatures by the corresponding software programs. The dotted lines mark the moisture content level estimated by Karl Fischer titration. The results od RVM analysis differed strongly, although the moisture content of paper was constant during all the measurements. Dependences on the oil conductivity as well as on the temperature and the insulation geometry appeared. Hence the RVM software used could not evaluate moisture in oil-paper-insulation systems well since the interpretation scheme used was inaccurate without taking into account the geometry and oil parameters. Results of PDC analysis showed much smaller influence of insulation geometry and weaker temperature dependence [7]. These influences were already compensated by the interpretation software used. With increasing oil conductivity the evaluated moisture content increased, although in reality it remained constant. Nevertheless, the simulation results were close to the level evaluated by Karl Fischer titration. The FDS analysis provided the best compensation for insulation geometry. At the same time, the paper seemed to become drier with increasing temperature. This actually happens in reality because of moisture diffusing out of the paper, but not to indicated extent [8]. The observed tendency rather reveals imperfect compensation for temperature variations. Similarly as for the other methods, the increased oil conductivity results in a slight increased of the estimated moisture content.

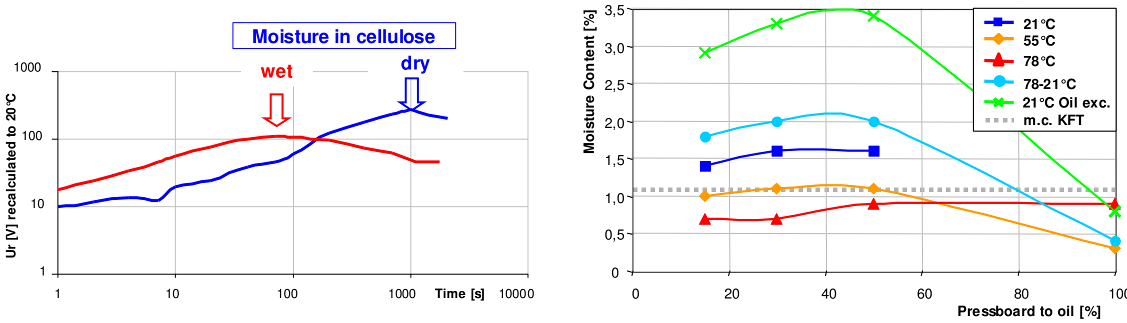


Figure 2. *Basis for interpretation of RVM results using the so called "polarisation spectrum" (left) and results of analyses by means of SWRVM 2 V.3.0 software (right).*

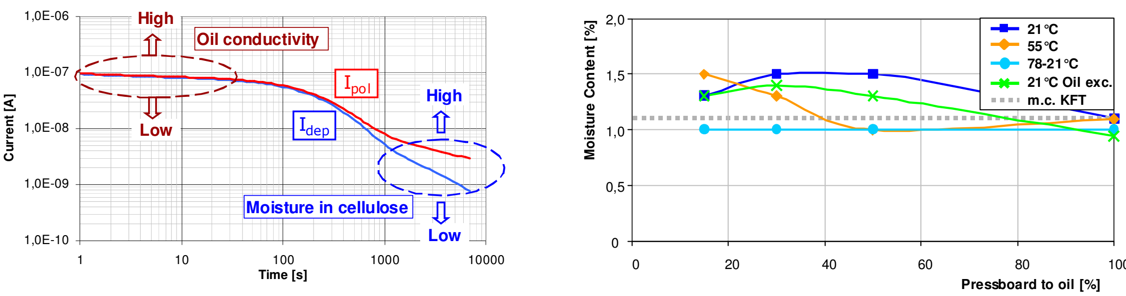


Figure 3. *Basis for interpretation of PDC results (left) and analyses PDC results by means of Evaluation Software V.3.0 (right).*

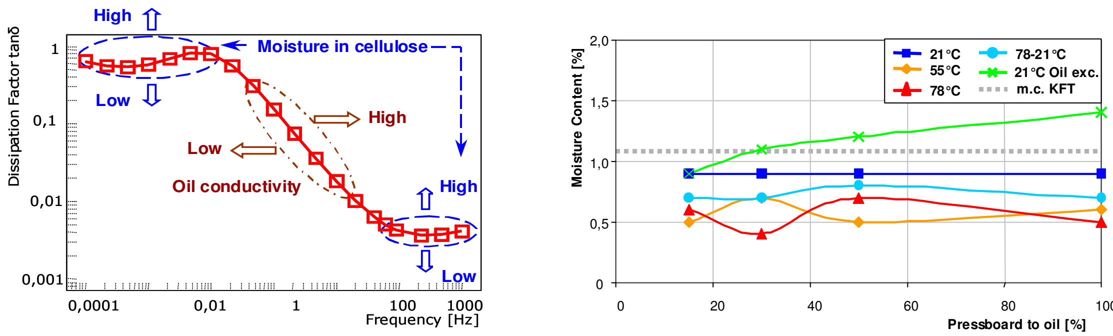


Figure 4. *Basis for interpretation of the FDS results (left) and analyses of FDS results with MODS V.1.5 software (right).*

3. FIELD MEASUREMENTS

An extensive access to power transformers operating in power networks have been provided by the cooperating utilities. This allowed performing measurements on 80 units altogether in Sweden, in Germany and in Poland. In addition 17 transformers were investigated in Sri Lanka within a parallel project sponsored by SIDA of Sweden. Attention has concentrated on gathering experiences from the use of dielectric response measurements in field conditions and on calibrating the interpretation of results against other methods.

3.1. Influence of external factors on dielectric measurements

The measurements of dielectric response have, so far, to be made off-line. Measuring devices available today on the market are quite robust in field conditions and they can be connected to a transformer in a number of different ways. Measurements can be performed between high and low voltage windings (so called CHL measurements where indexes H and L indicate high voltage and low voltage windings respectively) or between windings and the ground (CH and CL), providing possibility to evaluate different parts of the insulation. However, there is also a risk that undesired internal and external factors might influence the measurements, yielding, as a result, mistaken interpretation of insulation wetness. Operators should therefore be aware of the risks appearing at different measuring conditions and of the precautions that can be taken to minimize their effects.

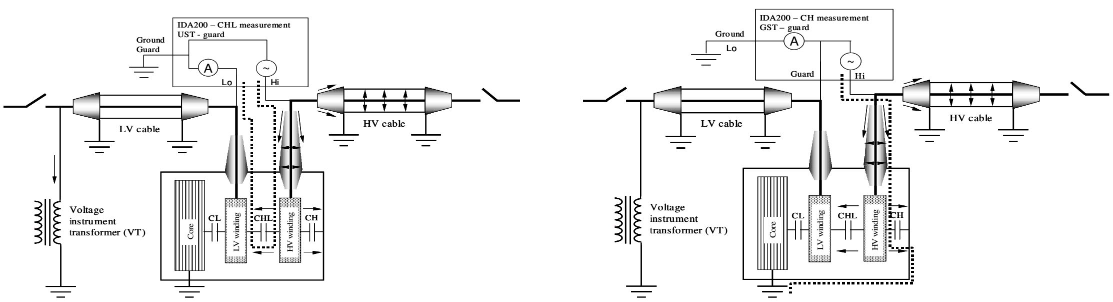
Systematic investigation on the influence of different factors on the results of dielectric response measurements in field conditions were performed. The work concentrated on FDS measurements, though PDC measurements were performed for comparison. The errors that could be committed during the measurements were analysed, with different equipment connected in parallel. The influences of rain and electromagnetic disturbances were also investigated proposing solutions to attenuate their effects. Finally, the influence of temperature distribution was considered.

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 4a. The capacitance (C') and the losses (C") of the insulation between the HV and LV windings can be characterised well. If, on the other hand, the measurements are done when only opening the disconnectors on both sides, letting this way some elements to remain connected to transformer bushings (cables, string and post insulators…), 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 affect the measurement. This situation can only 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.

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 4b shows the guard should be connected to LV winding in order to avoid measuring the inter-winding capacitance together with HV-to-tank capacitance. Even in case all the shunt elements are dismantled from the transformer, bushing capacitance and internal creeps are measured in parallel with the HV-to-tank capacitance, 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. Major influences may also appear 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 HV-to-tank capacitance. The cables connected to the transformer HV side have sometimes a length of a few hundreds meters and are insulated with oil-impregnated paper. Thus their capacitance is often larger and having similar properties that that of the transformer internal insulation. In such a case the CH measurements are more representing the behaviour of 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.

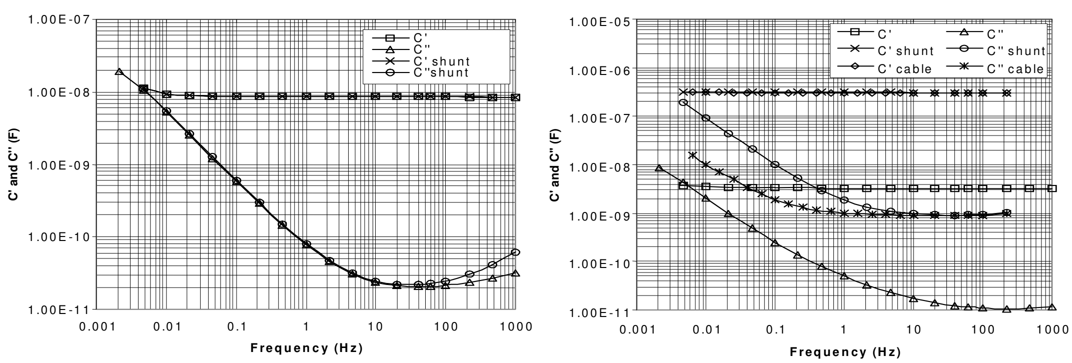
The measurements were performed on 18 transformers. More details can be found in [9, 10] The results shown below refer to one type, 50/20 kV, 40 MVA three-phase transformer. A reference CHL measurement was made with all the connections dismantled from the bushings. Other CHL measurements were made when just opening the disconnectors, leaving all the cables connected to the transformer. Figure 5 shows the results of the measurements performed under CHL and CH conditions.

Results similar to the reference ones were obtained when leaving the HV and LV cables and the other elements (surge arrestors, supports etc) connected to the transformer under CHL configuration (Figure 5a). The interpretation of the results was performed to quantify the influence of the different leakage paths in the estimation of the water content in the solid part of transformer insulation. To make that interpretation, the real conductivity of oil (1.24 pS/m) and the temperature measured directly when sampling the oil (14 °C), were used as input parameters. As no information was available about transformer geometry, 20% of barriers and 20 % of spacers were considered in all cases taking into account the typical amounts barriers and spacers in real power transformers [3]. In the CHL case, the resulting humidity values for the reference measurement and the measurements with all the shunts were respectively 1.2 % and 1.4 %.



(a) (b)

Figure 4. *Flow of current through transformer insulation system during dielectric response (FDS) measurements in CHL (a) and CH (b) configurations.*



(a) (b)

Figure 5. *Comparison of FDS reference measurements to measurements with open disconnectors (shunts included) for CHL (a) and CH (b) configurations.*

In contrary, the results of CH measurements conducted with opened disconnectors, letting the HV cable remain connected to HV bushings, resulted in that the total capacitance (C' shunt, C'' shunt) was in this case much larger than the one obtained in the reference measurement (C', C''), as shown in Figure 5b. This increase in capacitance appeared since the capacitance of the cables (C' cable, C'' cable) added in parallel with that of the transformer insulation and the interpretation of the reference results was practically impossible.

Another factor that can influence dielectric measurement is the appearance of current paths along transformer bushings. The risk of creep from the bushing increases when their surfaces are contaminated, and especially if high humidity or rain appears. The bushing creep has not effect on CHL measurements. Major effects can, on the other hand, be experienced during CH or CL measurements and require application of additional guard electrodes on bushings.

3.2. Calibrations on transformers sent for repair

Generally, possibilities to obtain paper samples from power transformers are very limited. Such studies can thus be performed on defected units, undergoing repair or scraping, where the solid insulation can readily be accessed. A few such units were made available for measurements of dielectric response in parallel to taking oil and paper samples for analyses. One of them was a three-phase transformer, manufactured in 1967 and rated 50 kV/10 kV and 40 MVA, which was open because of a fault of tap-changer. The measurement could be performed at different occasions prior and after the repair. Samples of paper and pressboard for moisture content analyses were collected at different positions, as indicated in Figure 6 together with the respective moisture content values obtained from KFT analyses.

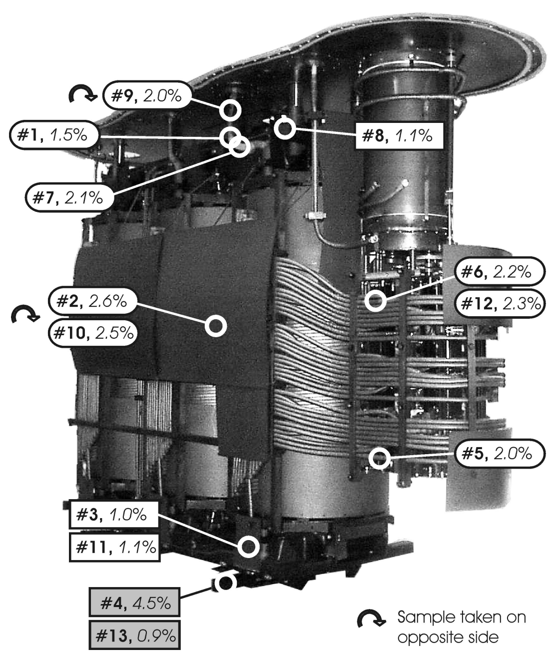


Figure 6. *Moisture levels measured by means of KFT at different locations in power transformer. Rounded white boxes: paper, rectangulat white boxes: pressboard, and rectangular grey boxes: wood.*

The analyses of results from dielectric spectroscopy measurements showed that the estimated moisture contents were in the range of 1.4-2.4%. These estimates were in good agreement with results obtained from the KFT measurements 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 reference. More details on the analeses of this and another study cases can be found in [10, 11].

CONCLUSIONS

The investigations performed allowed for setting a data base of the dielectric response of impregnated pressboard and paper for different moisture contents in frequency range between 10^{-6} Hz – 10^{8} Hz. Moisture and ageing influence mainly the low frequency part of the response. Similar behavior is observed in both impregnated paper and pressboard although there exists small difference, mainly caused by the differences in material density. Computer programs for interpretating the results of dielectric response measurements in terms of moisture content in the solid part of transformer insulation.

Dielectric response measurements, if performed correctly, provide good estimates of moisture content in pressboard and paper. For avoiding the influence of non-linear behavior of oil-paper insulation systems, dielectric response measurements should be performed at as low voltage level as possible. As long as CHL measurements are possible to perform, results of those should be used for interpretation in terms of water content in solid part of transformer insulation system. Guarded CHL measurements minimize the influences from additional loading capacitances to ground as well as from internal and external leakage. Dielectric properties of bushings as well as the properties of all other not disconnected external loading capacitances (e.g. cables and arresters) are always included in the responses of CH or CL measurements. In extreme cases these external influences can dominate over the properties CH and CL of transformer measured making the interpretation difficult.

Moisture estimation based on dielectric response measurements, as well as on KFT analyses of oil samples in combination with the use of the equilibrium curves, yield similar results as the direct KFT analyses of paper samples, if appropriate temperature values were used. The actual insulation temperature should be used for evaluation of the dielectric measurements, while the in-service temperature, corresponding to moisture equilibrium, should be used for evaluations based on analyses of oil samples.

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