Proc. of the 5th WSEAS/IASME Int. Conf. on Electric Power Systems, High Voltages, Electric Machines, Tenerife, Spain, December 16-18, 2005 (pp18-23)

Determination of Water Content in Transformer Solid Insulation by Frequency Domain Spectroscopy

BELÉN GARCÍA, BAUDILIO VALECILLOS, JUAN CARLOS BURGOS
Electrical Engineering Department
University Carlos III, Madrid
C/ Butarque 15, Leganés Madrid
SPAIN
bgarciad@ing.uc3m.es, bvalecill@ing.uc3m.es, jcurgos@ing.uc3m.es
http://electrica.uc3m.es/bgarciad/

Abstract: - Knowing the water content in transformer solid insulation is basic to determine the transformer maximum admissible load. As direct measurement of this variable is not possible, indirect techniques should be used as those based in the measurement of transformer dielectric response in time or frequency domain. By the application of these techniques is possible to get more accurate information that from traditional methods but some problems remain related to the interpretation of measurements. This paper is focused in the application of frequency domain spectroscopy (FDS) to the determination of water content into the different parts of transformer solid insulation. FDS field measurements over real transformer are reported extracting some general conclusions that may be useful to perform this kind of measurements.
Key-Words: - Power transformer, insulation diagnosis, dielectric response, FDS, moisture content, field measurements.

1 Introduction

Water content is a key factor that should be considered to determine the load capability of a power transformer. The presence of water accelerates the ageing processes, being the thermal ageing rate of cellulosic insulation proportional to its water content. Moreover an important water presence significantly decreases the maximum operation temperature as bubbling risk appears for lower temperatures.

As direct measurement of water content in solid insulation is not possible, indirect techniques that provides some information about this aspect must be used. Different techniques are available to assess moisture level in solid insulation by means of the characterization of transformer dielectric response. Some of these techniques, as the Recovery Voltage Measurement (RVM) or the Polarization Depolarization Current Measurement (PDC) are based on the analysis of dielectric response in time domain. The analysis of the dielectric response can also be done in frequency domain as the Frequency Domain Spectroscopy (FDS) technique proposes.

By the application of these techniques is possible to get more accurate information that from traditional methods (tanδ, polarization index etc.), however some problems remain related to the interpretation of measurements. Measurements present a high dependence with the transformer geometry, that is usually unknown, as the manufacturer rarely provides some information about transformer internal dimensions or insulation arrangement. Cigré TF CIGRE TF D1.01.09 [1, 2] was created to analyze the techniques detecting their weak points and proposing solutions the problems detected.

The techniques based in the analysis of dielectric response in frequency domain (FDS), are gaining more and more popularity, as they present less influence from electromagnetic noise that those based in the time domain, being so the obtained results are more reliable.

In this paper a brief description of the three techniques (FDS, RVM, PDC) is presented. A more detailed analysis is made about the application of FDS and the interpretation of the measurements. Finally some FDS field measurements over real transformers are reported.

3 Dielectric response methods

When a dielectric material is submitted to an electric field, its elemental dipoles are oriented in the field direction. Dipole orientation is not instantaneous, but it has certain delay. The dielectric response of a material depends on several aspects, as the material nature or the geometry of the object under study, but it also depends on the water content or the ageing of the material. Dielectric methods are based on the determination of the dielectric response in time or frequency domain.

3.1 PDC

PDC method consists in the measurement of the polarization and depolarization currents that appear during the polarization and depolarization processes in a dielectric material.

Polarization current is measured after the application of a voltage step to the object under study during the so called charging time. This charging time should be long enough to allow the polarization processes in the material to be completed. After this time, the material is short circuited and depolarization current over the object should be registered.

The main disadvantages of this method are its high sensitivity to electromagnetical disturbances and the long time required for its application (this disadvantage is common to all the techniques based in the analysis of the dielectric response) [3].

3.2 RVM

To perform RVM measurements a step voltage is applied to the object under study during certain charging time. The object is then short-circuited during a short period of time (decharging time) and finally it is left in open circuit. In this case a voltage appears between the terminals of the material. This voltage is the so called recovery voltage and is caused by the unfinished depolarization processes in the material.

The measurement of the recovery voltage should be repeated for different charging times, obtaining the so called polarization spectra. To get the polarization spectra the same relation between the charging and decharging time (usually tc=2td) must be kept in all the measurements.

By comparison of polarization spectra with laboratory curves, obtained over controlled moisture samples, an estimation of the moisture content in the object can be extracted.

In the last years RVM method has been quite criticized because the water contents estimated by its application are not coherent with that obtained by direct determination. According to CIGRÉ TF 15.01.09 the problem lays in the simplistic interpretation of the measurements. Alternatives have been proposed to that interpretation [2, 4].

3.3 FDS.

FDS method consists in making discrete measurements of the specimen test impedance in a frequency range between 1000 Hz and 0.001 Hz.

For this propose, a sinusoidal voltage of variable frequency is applied to the object under test and the current flowing across the insulation is registered. Once the object impedance is known, other relevant parameters may be determined as capacitance (C'), dielectric loss (C'') or tangent δ.

The techniques based in the analysis of dielectric response in frequency domain (FDS) present less influence from electromagnetic noise that those based in the time domain, being so the obtained results are more reliable.

4 FDS measurement and interpretation in power transformers

Power transformer insulation is composed by different dielectric materials (oil, paper, pressboard, wood...). Under the effect of an electric field the different materials are polarized. The differences in the response (in time or frequency) of these materials allow separating the effects caused by paper from those caused by oil. Moreover the dielectric response of the different materials is strongly dependent on their water content. The analysis of this dependence is the basis to get information about the water content in the materials by means of dielectric response measurements.

There are several factors that influence the dielectric response of transformer insulation, e.g. the geometry of the duct, the dielectric response of oil (its conductivity and permittivity), the dielectric response of pressboard or paper, and the temperature of the whole insulation system. To obtain the moisture content in solid insulation these variables should be known or estimated as parameters during the modeling. For modeling purposes the transformer main insulation, consisting of cylindrical pressboard barriers in series with oil ducts and spacers (Fig. 1), is represented as shown in Fig. 2, where X and Y are defined as:

$$X = \frac{\textit{radial thickness of total barriers}}{\textit{radial width of the duct}}$$

$$Y = \frac{\textit{total width of the spacers along periphery of the duct}}{\textit{periphery of the duct}}$$

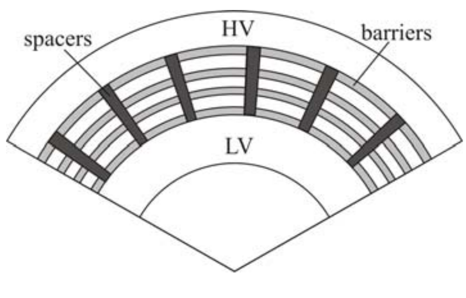

Fig. 1. Section of main insulation in a core type transformer.

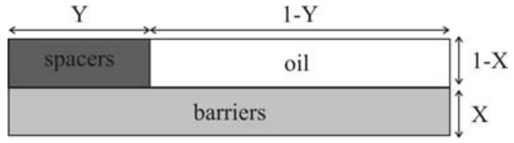

Fig. 2. X-Y representation of transformer main insulation.

The interpretation of the results is based on a best-fit procedure, in which the measured and the modeled responses of oil-pressboard ducts are compared.

Measurements can be performed between high and low voltage windings (so called CHL measurements where indexes H and L indicates 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.

5. Field measurements

The results obtained over three transformers are discussed. From these results, some general recommendations may be extracted that can be useful when measuring FDS.

All the presented measurements were performed using the IDA 200 insulation diagnostic system from Programma, Sweden [5]

5.1 Case 1

FDS measurements were performed over a three-phase unit 30 MV, 132/46 kV YNyn0d11, manufactured in 1997.

Capacitances between every two windings (HV vs. LV, LV vs. tertiary and HV vs. tertiary) and between every winding and ground were measured. In order to interpret the measurements, the software MODS, provided by the IDA 200 instrument manufacturer, were used obtaining the estimations of water content in the different parts of the insulation shown in Table 1.

PART OF THE INSULATION	WC %
Insulation between HV and LV (CHL)	0,3 %
Insulation between HV and ground (CH)	2,2 %
Insulation between LV and ground (CL)	2,1 %
Insulation between LV and tertiary (CLT)	1,4 %
Insulation between tertiary ground (CT)	2,2 %

Table 1: Water estimations in every part of the insulation in transformer case 1.

As can be seen relevant differences appear in the different parts of the insulation estimated water contents. These differences are greater in the case of the interpretation of CH, CL, and CT measurements, whose estimated water contents are quite high in comparison to CHL and CLT. Differences have been also found when interpreting measurements performed over other transformers not reported in this paper.

The XY model, used by MODS, was designed to represent the behaviour of the insulation between HV and LV winding and it is not as reliable to represent the insulation between the windings and ground, that has a completely different geometry (i.e. no spacers are fitted between windings and ground). This defective geometry representation can be the cause of such a great difference.

Problems came up in the measurement of the capacitance between HV and tertiary winding (CHT) because of its low value. The measured capacitance was 66 pF, and according to the specifications of the manufacturer the measuring instrument presents an error margin of 2E-3 in the tangent delta determination when the measured capacitances are below 100 pF. Such a low value for the CHT capacitance is normal if we take into account that between these two windings the LV winding is placed that should be connected to ground during this measurement.

5.1.1 Influence of selected tap

Measurements were repeated selecting three different positions of the on load tap changer in order to test the influence of the tap in FDS measurements. The selected taps were the two extreme positions (taking the maximum number of coils in the two positions of the inverter) and the intermediate position (taking the minimum number of coils).

In Fig. 3 CHL measurements obtained in every position are plotted. All the measurements were performed in the same day, so the same measurement conditions can be assumed.

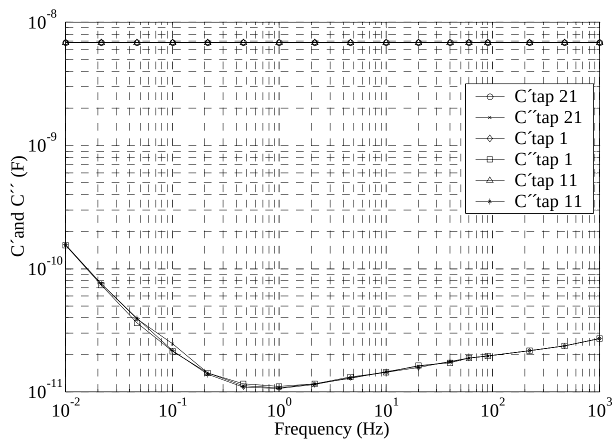

Figure 3: CHL measurement in different taps

As can be seen the registered capacitances in the three cases are almost the same both in real and in imaginary part. Just some non significant discrepancies appears in the range of 0,1 Hz frequency

5.1.2 Influence of weather conditions

Measurements were repeated in a rainy day, to test the influence of the atmospheric conditions in the registered complex capacitance. The presence of water in bushings surface could cause the appearing of creep currents over them.

Fig.2 shows the comparison between measurements taken with and without rain. As can be observed just little differences can be found both in real as in imaginary part. This results logical if we take into account that in CHL measurements ground is guarded, so a contribution of currents along the bushings surface may not appear.

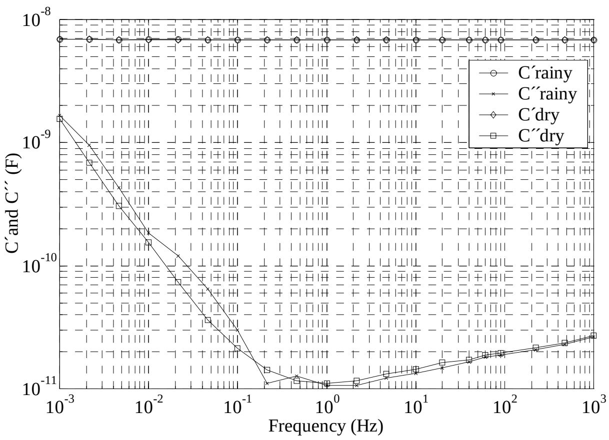

Figure 4: CHL with and without rain

A different behaviour is found when CH measurements are compared in both cases. As can be seen in Fig.5, significant differences appears in the measurement of the capacitance between the HV winding and ground when it was raining and when it was not raining.

In case of CH measurements, if currents along bushings surface appear they will be registered by the FDS device, added to the current flowing between the HV insulation and the tank. The effect of this current adding is not an increase in he capacitance, as current along bushings is resistive, but an increase in the losses.

The same effect appeared in CL measurements.

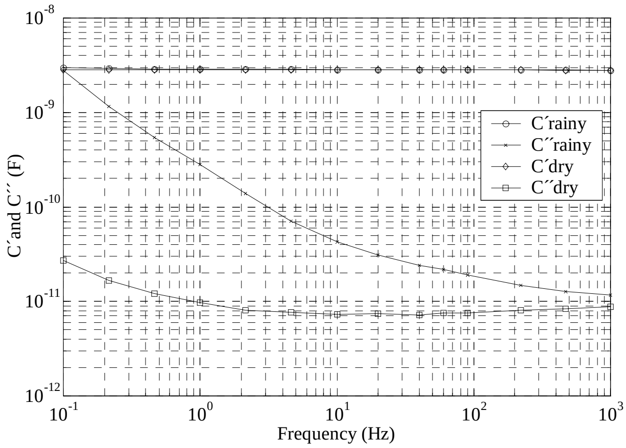

Figure 5: CH measurements with and without rain

5.2 Case 2

The second case analyzed is an autotransformer (144/86 kV, 80 MVA) manufactured in 1967.

In the case of autotransformers, as primary and secondary winding are the same, just capacitance between HV winding and ground (CH), capacitance between tertiary winding and ground (CT) and capacitance between HV and tertiary winding can be determined. .

The interpretation of the measurements determines the moisture contents displayed in table 2.

PART OF THE INSULATION	WC %
Insulation between HV and tertiary (CHT)	2,7 %
Insulation between tertiary and ground (CT)	3,7 %
Insulation between HV and ground (CH)	3,6 %

Table 2: Water estimations in every part of the insulation in transformer case 2.

In Fig. 6 the components of the complex capacitance registered when measuring the insulation between HV winding and tertiary are plotted. These measurements present very important disturbances in the low frequency range.

Very close to the transformer under study crosses a 230 kV line. The distance between the line and the HV bushing of the transformer (showed both in Fig 7) is a little more than two meters. The presence of close lines causes electromagnetical disturbances that can affect the measurements, in special case of measuring low capacitances.

It is important to note that the measuring equipment should register currents in the range of pA, being so the signal to noise ratio is very low in case of measuring capacitances lower than 100 pF.

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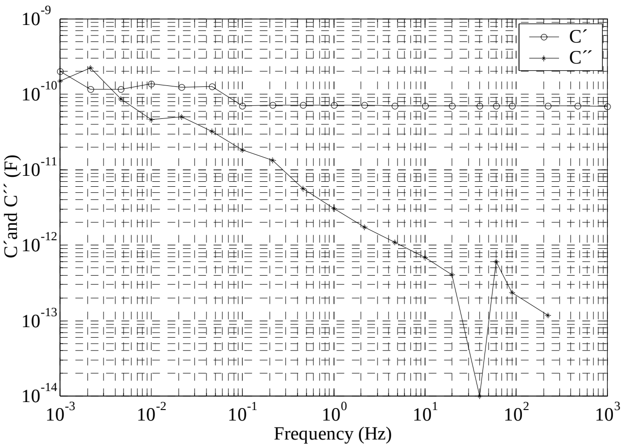

Figure 6: CHT measurement

Figure 7 :230 kV line close to the transformer

CHT capacitance registered over the transformer under study, when measuring at 50 Hz was 70 pF. As aforementioned, the measuring device has an error margin of 2e-3 in tangent delta determination when the capacitance is below 100 pF. In fact, as can be seen in Fig.8 the values of power factor measured for some frequencies were negative, that makes no physical sense.

The low values of the capacitances may be explained by the presence of electrostatic screens connected to ground between HV and tertiary winding that is typical in autotransformers.

As can be seen in Fig. 8 the major disturbances in CHT appear in the low frequency region, that is the part of the curve that provides information about the paper condition. In consequence the estimation of water obtained by MODS for this measurement is not reliable, and the difference between the estimation of water content in that insulation and the estimation in the other parts is explained.

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********************************************************************************
        "Loeches" - "2004-11-18, Loeches" - "3WA-CHT-2.idf"
********************************************************************************
MaxIntegrationtime = 80

Configuration   Hum (50Hz)      Offset          Capacitance (80Hz, 140V (RMS))
UST             87 uA           0,91 nA         71,396 pF
GST-Guard       4,7E2 uA        -               23012 pF
GST-Ground      -               -               23085 pF

#1:Amplitude             = 140 V (RMS)
#1:CHT
#1:Config: UST

#1:Frequency:   Power Factor
==============================
1000            -0,026423
470,59          -0,0091248
222,22          -0,0017981
90,395          0,00012741
60,15           0,0023051
40              0,0031037
20              0,0065493
10              0,0075214
4,6417          0,015431
2,1546          0,026198
1               0,041902
0,46417         0,14602
0,21544         0,41631
```

Fig 8: 50 Hz capacitance and power factor between HV winding and tertiary

Regarding to CH and CT measurements much higher values of capacitance were found (23011pF and 11208 pF respectively) and less problems arose when making the measurements. Fig. 9 shows CT measurements and, as can be seen no disturbances appear in these curves. In this case, as the current magnitude increases significantly, minor effects of elecromagnetic interferences appear.

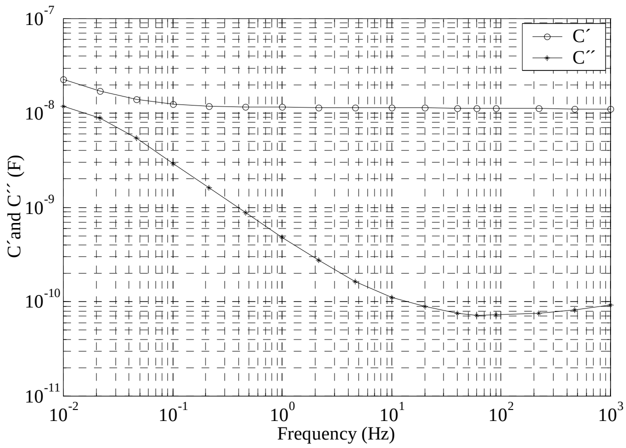

Figure 9: CT measurement

6. Conclusion

In this paper general principles of dielectric response measurements have been described and its application to determine moisture content in transformer insulation has been analyzed.

Time and frequency domain techniques have been briefly described making more emphasis in Frequency Domain Spectroscopy (FDS).

FDS field measurements performed over two power transformers have been reported. The following general conclusions can be extracted from those measurements that can be of general application when measuring transformers in field.

- XY model was conceived to represent the insulation between HV and LV windings. From that, the information about the water content in transformer insulation that may be extracted from CHL measurements is more reliable that those extracted from CH and CL.
- Measurements were compared selecting different positions of the LTC, concluding that FDS measurements are not sensitive to the LTC selected tap.
- Water or dirt on bushings surfaces can give rise to creep current along them. Creep currents, in case of existing, will not affect CHL measurements if guard cable is properly connected to ground. In the case of CH and CL measurements is not possible to eliminate the effect of creep currents and they will be added to those circulating between HV winding (or LV in case of CL measurements) and ground causing an increase in measured losses (C").
- Important problems appear when measuring very low capacitances bellow 100 pF.
- The presence of high voltage lines in service close to the transformer can cause electromagnetic disturbances that affect the measurements. These effects are dramatic in case of measuring very low capacitances.

Acknowledgment:

This work has been carried out at the Electrical Engineering Department of the University Carlos III of Madrid, and has been founded by the Spanish utility Unión Fenosa and by the Spanish Ministry of Science and Technology (MCYT) under the project nº DPI2002-09039-C01-02 of the "Plan Nacional de Investigación Científica, Desarrollo e Innovación Tecnológica". The authors would like to thank to Union Fenosa for their interest and support of the work.

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