Moisture assessment for power transformers using PDC and drying-out processes evaluation

W. Bassi*, H.A.P.Silva*, C.A. Galdeano**, J.H.C. Hossri**

***Resumo*-This paper presents the development and practical results of the polarization and depolarization (PDC) technique for moisture assessment and drying processes performance evaluation for power transformers. The methodology and theoretical basis are presented. Both methods were evaluated: the classical drying method (thermo and vacuum chambers) and also a new approach based on selective filters installed on transformer in regular operation.**

***Index Terms*— transformer – paper insulation – drying-out – PDC – polarization – depolarization - molecular sieve.**

I. INTRODUCTION

MOISTURE on the solid insulation of power transformers represents a critical factor on the insulation characteristic which drastically reduces the reliability of such important electric substation equipment. Several mechanisms lead to the increase of moisture level inside the active part of the transformer during its operation; among these reasons are the accidental ingress of water or wet air, aging of cellulose or oil oxidation.

Usually, the evaluation of moisture present on the solid insulation is obtained by an estimation related to the moisture level in the oil. However, the moisture dynamics within Power Transformers are of extremely complex nature. Up to 99 % of the moisture normally are located in the solid insulation and only 1 % in the oil. So the oil moisture determination in [ppm] has very limited information of the insulations system. Furthermore, there is a rather complex, temperature dependency moisture migration process. Under high temperatures (during full load operation) the moisture moves into the oil - and may even develop free water there.

The evaluation technique is based on the dielectric response analysis of the insulation system, based on the analysis of the polarization (charge) and depolarization (discharge) currents injected in the transformer.

The dielectric response is a function of some parameters such as oil conductivity, geometry and insulation composition and the moisture contents itself.

The moisture assessment consists on the application of a simple but effective model based on the geometrical data from internal insulation for representing the transformer under test combined with the PDC curves evaluation. This ensures specific results as fingerprints.

The new diagnostic tool, the PDC-Analysis, is the center of this paper, where it is presented its very precise capability to quantify moisture content in solid insulation of power transformers. Seen that there is no doubt about the correlation between moisture and reliability, this diagnostic tool turns to be very effective for transformer life management. Additionally two transformers drying methods are evaluated and cross checked with the PDC technique.

II. DIELECTRIC RESPONSE ANALYSIS

The Theory of the Dielectric Response Analysis (DRA) is not new. It was first developed by Jonscher [1] but was never used as a diagnostic tool. Only recently [2-20], that is to say, for the last 10 years, extensive research was centered to this diagnostic technology

There are 3 methods referred to DRA [14]:

1. Recovery Voltage Measurement (RVM)
2. Dielectric Spectroscopy in the time Domain (PDC) Polarisation, Depolarisation Current Measurement
3. Dielectric Frequency Domain Spectroscopy (FDS)

These methods reflect the same fundamental polarization and conduction phenomena. However, the measurements confirm the strong influence of oil gaps, oil condition, especially the oil conductivity. Material properties and geometry must also be taken into account when moisture in the solid insulation is to be derived from any of these three methods.

As for PDC and FDS methods, they are duly considering the oil condition, oil conductivity, insulation geometry and material properties. They derive from the whole response curves by mathematical modeling very good and similar moisture results, which can be verified by alternative methods like Karl Fischer Titration.

The RVM is not considering these parameters and uses so far an old interpretation (derived from homogeneous plate condenser models). Furthermore, RVM only uses the dominant time constant and the maximum of the polarization voltage. Therefore, the moisture content determined by the RVM Technique is considered not to be correct [7, 14].

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A. *The PDC thecnique*

A DC voltage step of some hundred of volts (typically 500V, 1000V) is applied between HV and LV windings during a certain time TP, the so-called polarization duration (Fig. 1a and 1b). Thus, a charging current of the transformer capacitance, i.e. insulation system, the so-called polarization current, flows. It is a pulse-like current during the instant of voltage application, which decreases during the polarization duration to a certain value given by the DC conductivity of the insulation system. After elapsing the polarization duration TP, the switch S goes into the other position and the dielectric is short circuited via the ammeter. Thus, the discharging current jumps to a negative value, which goes gradually towards zero. Both kinds of currents called relaxation currents are stored in the PDC Analyzer Instrument [9].

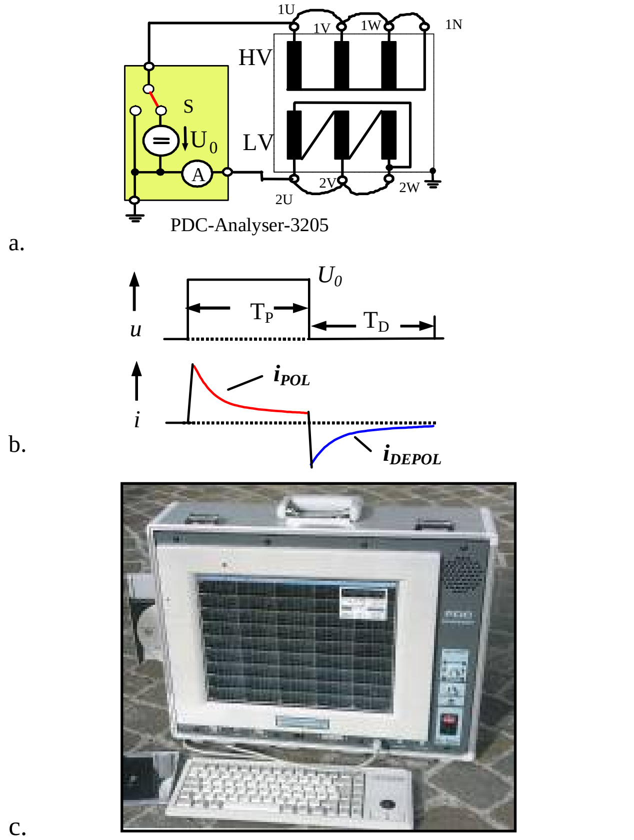


Fig. 1. a) Measurement of the relaxation currents using the PDC-Analyzer measuring system; b) Principle waveform of relaxation currents. c) Portable measuring instrument.

Then, a model for the transformer's main insulation system, which describes its dielectric behavior, is parameterized. All parameters of this model can now be simulated and further determined using already measured characteristics of pressboard material samples with certain water content, oil parameters and the geometry of the main insulation system. The "best fit" between measured and calculated relaxation currents for different moisture contents provides the moisture content in the solid insulation material and the oil conductivity. Together with other diagnostic tools a reliable ageing assessment can thus be realized [3].

Special software [9] was developed for this analysis dealing with the geometrical data, as can be seen in Fig. 2c and 2d. So, a R-C circuit, transparent to the user, is created similar to Fig. 3a and 3b, including the electrical insulating materials and the insulating oil.

According to the linear dielectric theory the lumped model shown in Fig. 2b can be derived to describe a dielectric's behavior by the dielectric response function f(t) in time domain or polarization characteristic $\chi(\omega)$ and conductivity σ in the frequency domain [5, 10]. Fig. 2c shows the principal arrangement of barriers, spacers and oil ducts in the main insulation system of power transformers. For modeling, this arrangement can be simplified (Fig. 3d). Using the R-C-model of an arbitrary dielectric as shown in Fig. 2b, the model for the dielectric behavior of a complete transformer can be derived (Fig. 3). It consists of a first R-C-circuit modeling the oil (indices "O") in parallel to a second circuit modeling the spacers (indices "S"), and a third circuit in series to the above mentioned parts one and two which simulates the barriers (indices "B"). The dispersion of oil for measuring times above 1 s can be neglected so that oil can be well simulated using only its conductivity and relative permittivity ($\varepsilon_{r,oil} = 2.2$). Therefore, the model for the oil contains only the capacitance C_O of the oil ducts and the resistance R_O.

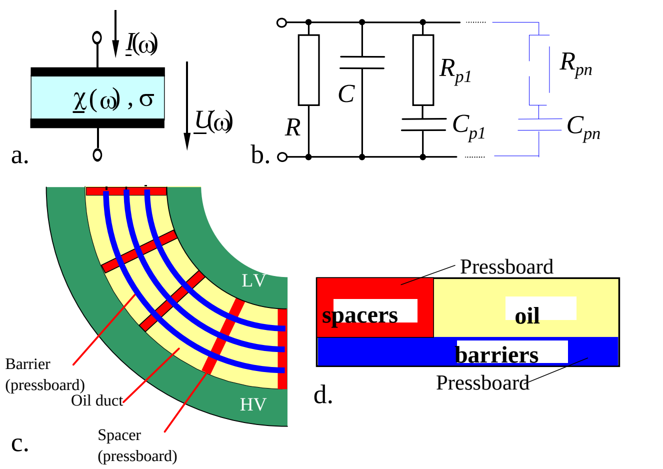


Fig. 2. a) Plate capacitor as a model for dielectric arrangements; b) Model for the behavior of a dielectric with arbitrary polarization characteristic and conductivity; c) Part of the cross-section of a power transformer main insulation system between HV and LV windings; d) Simplified geometry model for the main components oil, barriers and spacers.

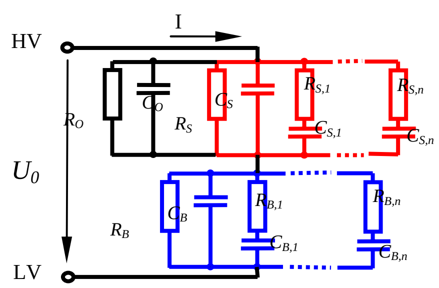


Fig. 3. Dielectric model for the insulation system of power transformers. Indices "O" are for oil, "S" for spacers, and "B" for barriers.

Fig. 4 shows the effects of oil conductivity (at left) and moisture content in the solid insulation material (at right) on the polarization current. For typical measuring conditions the conductivity of the oil affects the polarization current mainly in a time range $t < 100$ s.

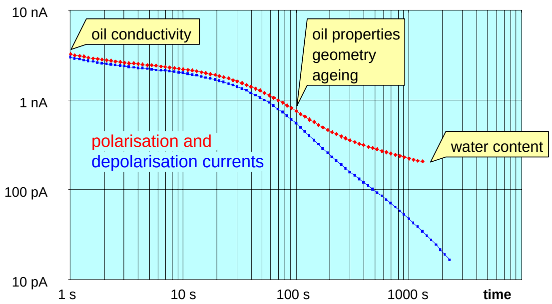


Fig. 4. Oil conductivity, oil properties, geometry, ageing and water content influence on the PDC-Curves.

B. Comparison of PDC analysis with other methods

It had been shown by Kachler [4] comparisons between PDC analysis and results from Karl-Fischer-Titration and dew-point measurement have been carried out on numerous transformers with different ratings and designs. The PDC results show a good match between the results of Karl-Fischer and dew-point measurement (Fig. 5). This proves the applicability and reliability of the PDC method for determining moisture in the solid insulation material of power transformers.

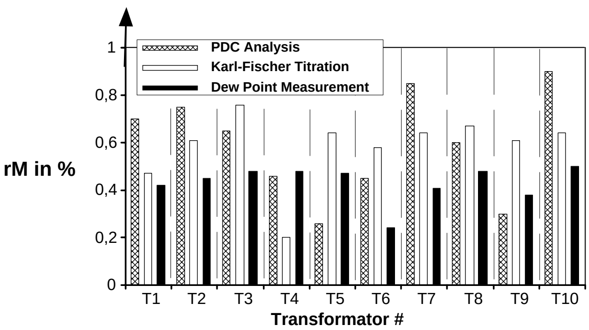


Fig. 5. Comparison of the PDC analysis with other methods for moisture content determination in the solid insulation material of new power transformers.

III. DEVELOPMENT

The study was developed with partnership with a electrical utility in Brazil. The company has facilities to repair their own transformers including thermo and vacuum chambers.

The analyzed transformers are in the range of nominal power from 7 MVA to 15 MVA.

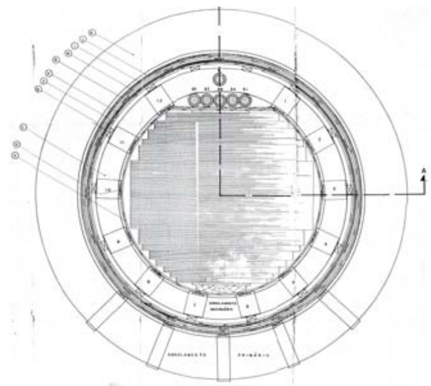
Additionally to the classical drying-out process of the active power, a new technique was carried out and evalutaded. This process is based on molecular sieve filters installed on normal operating transformers.

A. Thermo-vaccum drying-out process

On a recent Research and Development project with a power utility in São Paulo-Brazil (AES-Eletropaulo) it was possible to check step by step all the capabilities of the PDC method. Eg. in one of the several transformers tested the one shown in Fig. 6 was performed a sequence of drying-out steps. This transformer was selected by the high level of moisture on its active part, estimated to be over 5% in weight.

Fig. 6. Transformer used for PDC measurements and traditional drying-out.

Internal insulation was analyzed using the dimensional drawings as shown in Fig. 7. These insulation system dimensions were used to calculate the lumped parameters inserted on the PDC-Analysis software for performing the moisture content evaluation.



MEDIDAS RADIAIS							
ITEM	DESCRIÇÃO	QUANT. P/FASE	COMP.	LARG.	ESPES.	DIÂMETROS INT.	DIÂMETROS EXT.
A	TUBO PAPELÃO (3 x 1mm)	1	950	—	3	428	434
B	TALA PAPELÃO	12	920	21	4	434	446
	GUIA P/FIXAÇÃO RABO ANDORINHA	12	920	26	2		
C	ENROLAMENTO SECUNDÁRIO	1	775	—	±48	446	542
D	TALA PAPELÃO	14	902	20	9	542	560
E	TUBO PAPELÃO (4 x 1mm)	1	940	—	4	560	568
F	CHAPÉU ISOLANTE	2	—	—	5	568	578
G	TALA PAPELÃO	16	820	20	4	578	586
H	TUBO PAPELÃO (4 x 1mm)	1	820	—	4	586	594
I	CHAPÉU ISOLANTE	2	—	—	4,5	594	603
J	TALA PAPELÃO	16	800	10	6	603	615
K	ENROLAMENTO PRIMÁRIO	1	751	—	92	615	799

Fig. 7. Transformer insulation drawing showing the geometry and associated dimensions.

The traditional process for drying-out the active part as used in the power utility consists of 3 days in thermal chamber (Fig. 8) followed by 2 days on vacuum chamber (Fig. 9). This procedure was applied to the transformer in the fist stage of the experiment.

Fig. 8. Thermo chamber for drying-out processes.

Fig. 9. Vacuum chamber for drying-out processes.

After this initial drying-out process the PDC-Analysis showed a persistent high level of moisture, estimated as 4%, as show in Fig. 10.

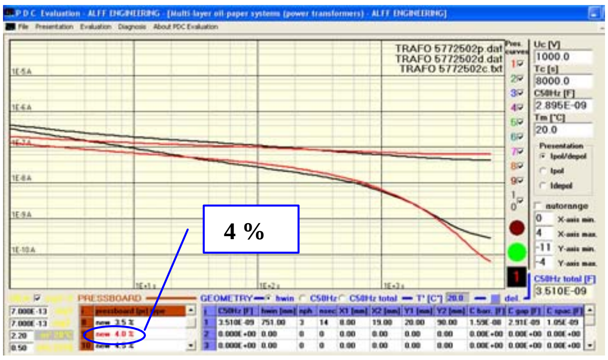


Fig. 10. Evaluation of moisture contents after first drying-out (4%.)

In order to enhance the process, the usual procedure was extended to 5 days in the thermal chamber followed by 3 days in the vacuum chamber. Another moisture evaluation detected an additional decreased in the range of 2.5% as show in Fig.11.

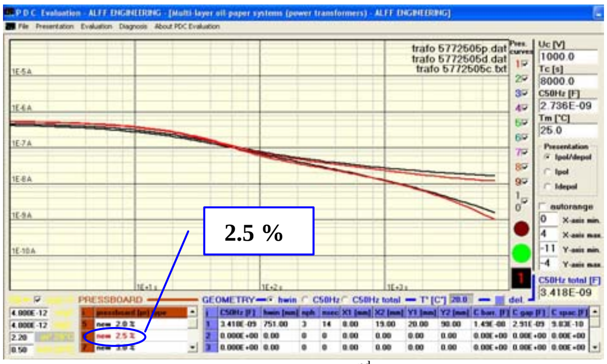


Fig. 11. Moisture evaluation contents after 2nd round of drying-out (2.5%).

One can observe that even the long period on the chambers (total of 8 days in the thermo chamber and 5 days in the vacuum chamber) was not enough to dry-out the active part to a reasonable value of 1% for instance.

The exposition of the insulating systems for several days (or hours) to elevated temperatures may lead to, among others, the paper degradation. The mechanical characteristic may be significantly changed, reflecting in some parameters such as the polymerization degree of the paper.

On other hand, one can observe the limited efficiency of this process. The heating flux affects only the external superficial parts. The moisture present on internal parts is barely removed.

B. Recyclable Molecular Sieve Drying-out System

This promising technique for drying the transformer on site without disconnecting it from the grid was then applied on site. A 12 MVA transformer as show in Fig.12 was used for this purpose together with the PDC evaluation.

Fig. 12. Drying-out system installed on an in-service power transformer (12MVA).

The removal of moisture from insulating oil by using molecular sieve adsorbents is a very effective process. However, the adsorbent materials available in the Brazilian market are not recyclable. The molecular sieve used are from adsorbents produced from carbon and ceramic raw materials based on the literature [31]. Also a totally automated and unattended oil drying-out system was designed using such adsorbents. The drying-out system (Fig. 12) is connected to the transformer outlet valve at the bottom of the main tank, the oil is pumped through the system filters, and then back to the transformer into the outlet valve at the bottom of the oil expansion tank. The system valves are automatically controlled in order to avoid any oil leaks. Both inlet and outlet oil parameters such as temperature (ºC), water content (ppm) and relative saturation (%) are monitored by the system. Finally the data collected are remotely sent to the utility operations center. Such data can also be accessed remotely by a cell phone (Fig. 13).

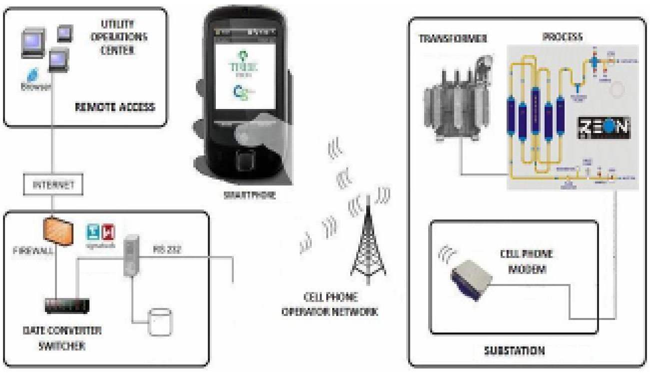


Fig. 13. Schematic diagram of the drying-out system data processing.

Due to the process concept, a relatively long period is need for a very effective moisture removal. The final result is very dependent of some factors such as the moisture level itself, temperature operation, size of the transformer etc. Typically several weeks of continuous working of the system are required (20 weeks or more). Nevertheless, the transformer still in normal operation, been "cleaned" as time goes on.

The initial values for moisture contents in the power transformer measured with the PDC was around 4% as shown in Fig. 14.

After 5 weeks, running with the drying-out system the PDC-Analysis revealed a reduction to the moisture content registering 3.5% as shown in Fig.15.

The longer the time the more expressive reduction results are to be expected, without any physical, mechanical or chemical attack to the transformer active parts.

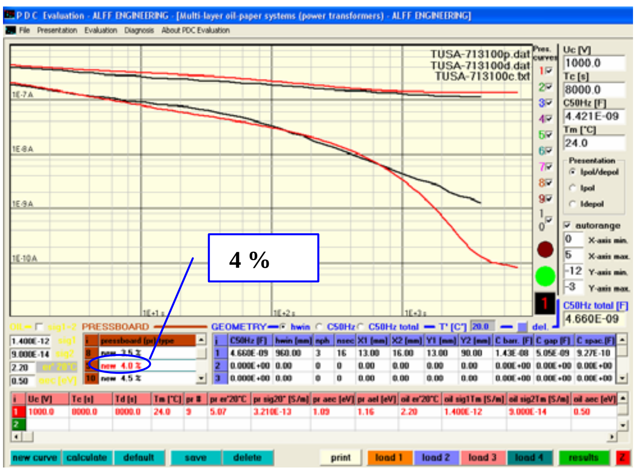


Fig. 14. Initial moisture evaluation using the PDC. Value 4,0 %

Fig.15. Moisture contents evaluation using PDC after 5 weeks running the molecular sieve drying-out system. Value 3.5 %.

IV. CONCLUSIONS

The most important aspects, results and applicability in relation to the study for implementing the moisture evaluation in power transformer using PDC (polarization and depolarization currents) methodology were presented in this paper. Moisture contents represents an important information concerning reliability when planning the operation and for transformer life management.

Several real measurements and interaction with the utility facilities (such as chamber and transformers repair equipment) have leaded to consolidate the PDC technique as an effective test for moisture evaluation on power transformers. The PDC method has been definitely included on the routine procedure for each transformer being repaired and also for transformers in regular operation. The instrument is portable and fully controlled by an internal computer.

Besides, a new technique based on sieve adsorbents has been experienced and evaluated with the PDC technique. This new system presented many advantages: is not invasive, not aggressive (thermal or chemical attack) and may be carried out with the transformer in service at normal operation.

New studies are currently being carried out with promising results as alternative applications for the PDC in this field of power equipment insulation system diagnosis: The LCM (Liquid Conductivity Measurement), an accessory of PDC instrument, gives the possibility of field measurements of oil parameters, such as conductivity, tangent dealt and permittivity of the insulating oil at ambient temperature and it correlation with several quality indexes such as acidity, dielectric strength, moisture on oil etc. Another very powerful tool, as a product of PDC Analysis is the possibility to derivate the Power Factor and Capacitance in a large range of frequencies [3, 5, 6, 9]. The evaluation of these parameters in other frequencies may reveal changes in the insulation characteristics more pronounced than the measurements performed only at 50 Hz/60 Hz.

Several other equipment such as bushings [28], high voltage cables [29] e metal oxide surge arresters [30], had shown to fit perfectly with the PDC insulation diagnosis evaluation.

Currently, another research has being started for applying the PDC technique in order to assess insulation degradation caused by the phenomenon associated with the corrosive sulphur present in the insulating oil.

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VI. BIOGRAPHIES

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