Stage 4: Demonstration of functionality and utility of insulation investigation technology model based on dielectric spectroscopy

Introduction

Dielectric spectroscopy is based on the interaction between the electric field E, polarisation P and properties of studied dielectric properties characterised by susceptibility χ:

$$\underline{P} = \chi \varepsilon_0 \underline{E} \tag{1}$$

Electric susceptibility of material χ is a dimensionless quantity that gathers all types of polarisation processes from dielectric.

In case of an isotropic dielectric material electrical D is described by equation (1):

$$\underline{D}(t) = \varepsilon_0 \underline{E}(t) + \underline{P}(t) = \varepsilon_0 (1 + \chi) \underline{E}(t) \tag{2}$$

The polarisation processes have different delays related to electric field occurrence moment.

Fig. 1 presents time domain polarisation process that, according to eq. (1) can be described by relation:

$$\frac{\underline{P}(t)}{E_0} = \varepsilon_0 \chi(t) 1(t) \tag{3}$$

Where $\chi(t)$ and P(t) represent the response functions to a step excitation.

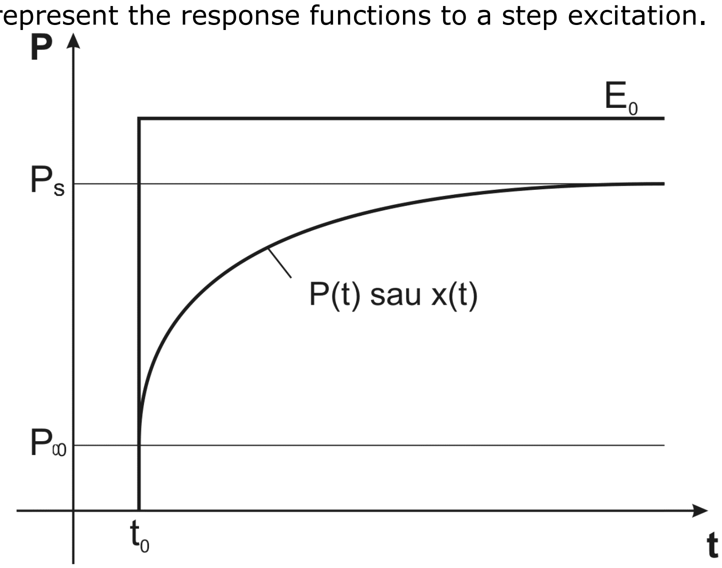


Fig.1. Dielectric polarisation under the action of an electric step field

Where: P_∞ is instantaneous polarisation that includes not only electronic polarisation but also some very fast polarisation processes.

After a certain time all polarisation processes are stabilised to a magnitude that becomes "static" polarisation after P_s.

According to Fig. 1 the polarisation phenomenon may be described by relation:

$$\underline{P}(t) = P_\infty + (P_s - P_\infty) g(t - t_0) \quad (4)$$

Where g(t) is a monotonous increasing function.

Relation (3) may be then written as follows:

$$\underline{P}(t) = \varepsilon_0 \left[\chi_\infty + (\chi_s - \chi_\infty) g(t - t_0)\right] E_0 \quad (5)$$

If relative permittivity $\varepsilon = 1 + \chi$ is introduced we get:

$$\underline{P}(t) = \varepsilon_0 \left[(\varepsilon_\infty - 1) + (\varepsilon_s - \varepsilon_\infty) g(t - t_0)\right] E_0 \quad (6)$$

In order to obtain a relation which to describe the time variation of polarisation vector versus time variation of electric field vector, irrespective of this variation type, Duhamel integral will be used:

$$\underline{P}(t) = \varepsilon_0 \chi_\infty \underline{E}(t) + \varepsilon_0 \int_{-\infty}^{t} f(t - \tau) \underline{E}(\tau) d\tau \quad (7)$$

Where f(t) is the response function of the dielectric

$$f(t) = (\chi_s - \chi_\infty) \frac{\partial g(t)}{\partial t} = (\varepsilon_s - \varepsilon_\infty) \frac{\partial g(t)}{\partial t} \quad (8)$$

From relation (8) it is noticed that f(t) is a monotonous decreasing function with dimension 1/s and its amplitude is connected to C_0, the geometric capacity of the dielectric made sandwich.

For frequency domain analysis, C_0 is the "high frequency" capacity of the dielectric measured at moment t_0 when current measurement begun.

According to Maxwell law the current density is given by relation:

$$\underline{j}(t) = \sigma_0 \underline{E}(t) + \frac{\partial \underline{D}(t)}{\partial t} = \sigma_0 \underline{E}(t) + \varepsilon_0 \frac{\partial \underline{E}(t)}{\partial t} + \frac{\partial \underline{P}(t)}{\partial t} \quad (9)$$

Translation from time domain to frequency domain may be made by rewriting equations (7) and (9) using Laplace or Fourier transform:

$$j(p) = \sigma_0 E(p) + \varepsilon_0 p E(p) + \varepsilon_0 p F(p) E(p) \quad (10)$$

for $p = i\omega$ it follows:

$$\underline{j}(\omega) = \underline{E}(\omega)\left[\sigma_0 + i\omega\varepsilon_0 (1 + \underline{F}(\omega)\right] \quad (11)$$

Where $\underline{F}(\omega)$ represents the Fourier transform of dielectric response function f(t)or complex susceptibility.

$$\underline{\chi}(\omega) = F(\omega) = \chi^{'}(\omega) - i\chi^{''}(\omega) \quad (12)$$

Current density expression in frequency domain results from (11):

$$\underline{j}(\omega) = \{\sigma_0 + \varepsilon_0 \omega \chi^{''}(\omega) + i\omega\varepsilon_0 [1 + \chi^{'}(\omega)]\}\underline{E}(\omega) \qquad (13)$$

To be noticed that the instruments used for frequency response analysis cannot make discrimination between DC conductivity current contribution σ_0 and the one brought by dielectric losses $\chi''(\omega)$.

This means that the measured relative dielectric permittivity $\underline{\varepsilon}_{rm}$ is different from relative permittivity given by expression:

$$\underline{\varepsilon}(\omega) = \varepsilon^{'}(\omega) - i\varepsilon^{''}(\omega) = [1 + \chi^{'}(\omega)] - i\chi^{''}(\omega) \qquad (14)$$

Measured relative permittivity $\underline{\varepsilon}_{rm}$ has the expression:

$$\underline{\varepsilon}_{rm}(\omega) = \varepsilon^{'}_{rm}(\omega) - i\varepsilon^{''}_{rm}(\omega) = \varepsilon^{'}_{rm}(\omega) - i\left[\varepsilon^{''}(\omega) + \frac{\sigma_0}{\varepsilon_0 \omega}\right] \qquad (15)$$

The real part of equation (15) represents the capacitance of the tested object while the imaginary part represents the dielectric losses, so:

$$\tan\delta(\omega) = \frac{\varepsilon^{''}_{rm}(\omega)}{\varepsilon^{'}_{rm}(\omega)} = \frac{\varepsilon^{''}_{rm}(\omega) + \frac{\sigma_0}{\varepsilon_0 \omega}}{\varepsilon^{'}_{rm}(\omega)} \qquad (16)$$

From (16) it follows that both terms defining tanδ by their ratio depend on frequency meaning that dielectric insulation condition assessment for HV equipment using only tanδ power frequency measurement result does not provide enough information on the thermal and electrical ageing or on insulation water content.

Measurement and Result processing technique applying dielectric spectroscopy in frequency domain

The measurement technique is a generalisation of capacitance and loss factor (tanδ) measurement at power frequency (50/ 60 Hz). The difference is that several measurements are performed at different frequencies instead of a single measurement at a fixed frequency.

The principle of the method can be described so: a special digital signal processing unit generates a sine voltage with a given frequency. This signal is amplified by an internal amplifier and then is applied to the investigated object. The applied voltage, current through object and phase shift between the two quantities are measured with high accuracy.

The electric diagram of the measuring circuit is presented in Fig. 2 where G is a 100 V voltage generator with a frequency discretely varying in the range 0,1 mHz – 1 kHz.

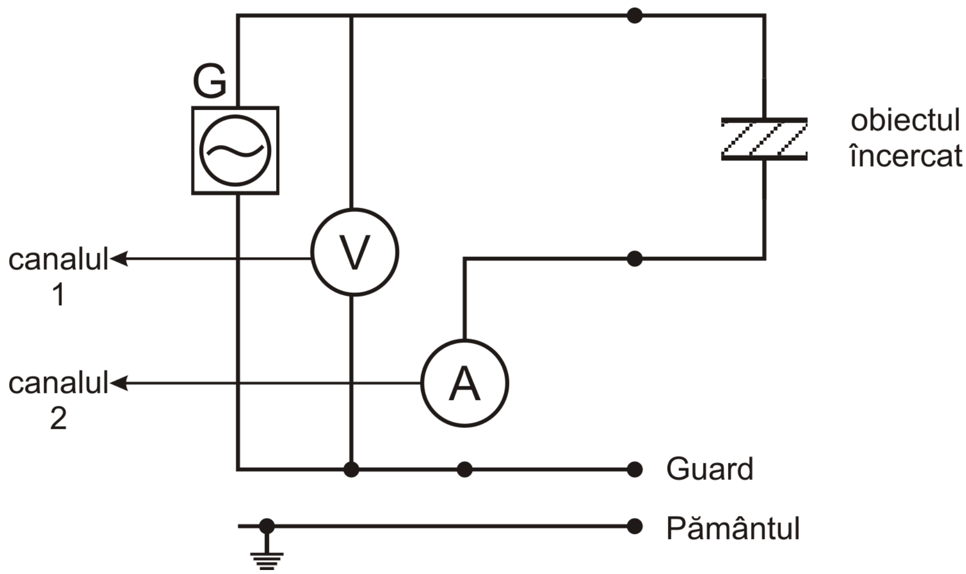
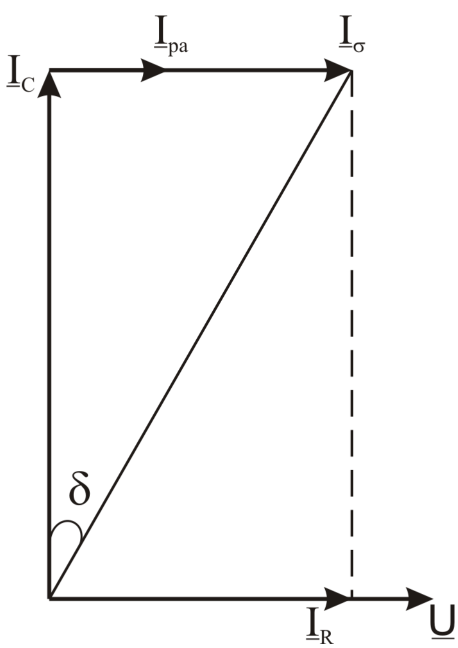


Fig.2. Block diagram of the equipment used for frequency domain spectroscopy

The phase shift between voltage and current is determined from the time record of the two quantities (Fig. 3).



$\underline{U}$ - voltage applied to dielectric;

$\underline{I}_R$ - active component of current through dielectric;

$\underline{I}_{pa}$ - active polarisation current;

$\underline{I}_\sigma$ - leakage current by conductivity;

$\underline{I}_C$ - capacitive current component through dielectric;

δ - dielectric loss angle

Fig.3. Vector diagram of currents in a dielectric subjected to AC voltage

In the previous stage, a database containing tanδ(f) standard curves for paper-oil insulation in the following conditions was achieved:

- Now insulation with different moisture contents (0,5; 1; 2; 3 and 4% of initial weight in dry state). The measurements were performed for each moisture content at temperatures of: 50, 80, 90 and 120°C;
- Thermally aged insulation at temperatures of 80, 90, 110, 135°C and moisture contents of 0,5; 1; 2; 3 and 4%. The measurements were performed at temperatures of 50, 80, 90 and 120°C.

These investigations were performed within the frame of Electric Materials Laboratory from ICMET Craiova.

In order to make easier and more accurate the comparison between tanδ variation curves versus frequency and dielectric response measurement curves in frequency domain at power and instrument transformers, intermediary standard curves were created. The specific technical literature uses for approximation Havriliak – Negami expression for $\varepsilon_{rm}^{'}$:

$$\varepsilon_{rm}^{'} = A\omega^{-n} + \varepsilon_{\infty} + R_e((\varepsilon_s - \varepsilon_{\infty})(1 + i\omega\tau)^{1-\alpha})^{-\beta} \qquad (17)$$

And Kramers – Kronig transform of Havriliak – Negami expression for $\varepsilon_{rm}^{''}$:

$$\varepsilon_{rm}^{''} = A\omega^{-n}\cot((1-n)\frac{\pi}{2}) + I_m((\varepsilon_s - \varepsilon_{\infty})(1 + i\omega\tau)^{1-\alpha})^{-\beta} + \frac{\sigma_{DC}}{\varepsilon_0\omega} \qquad (18)$$

Parameters A, n, α, β, τ and ε_s are determined using the least square method to approximate the virtual curve with the measured permittivites, adjacent to the one to the one obtained by calculation.

ε_{∞} was evaluated as permittivity value at the highest measured frequency.

The virtual curves tanδ(f) for different moisture contents and at different temperatures, that were not determined by direct measurements, were calculated according to the procedure described in Annex 1.

Moisture content determination in simple geometry equipment insulation.

The insulation systems used at high voltage electrical equipment are different due to the ways of arranging the different dielectric materials and to their dimensions. The instrument transformers as well as medium and high voltage transformers were considered to belong to simple geometry equipment category because electric field distribution is achieved in a homogenous insulation system with non-zero conductivity, but linear, isotropic and with no permanent electric polarisation.

The standard curves for the paper-oil insulation system own to the instrument transformers were determined using the materials currently used by Divizia Aparataj a S.C. Electroputere Craiova.

The standard curves for the insulation system of XLPE material of the medium voltage cables were determined using paper samples placed at disposal by IPROEB Bistriţa and Holding Kablovi , Serbia.

The frequency domain investigation may be easily understood if the relation between the measured sine current $\underline{I}(\omega)$ and measured sine voltage $\underline{U}(\omega)$is established:

$$\underline{I}(\omega) = i\omega\underline{C}(\omega)\underline{U}(\omega) \qquad (19)$$

Where $\underline{C}(\omega)$ is the complex capacity:

$$\underline{C}(\omega) = C^{'}(\omega) - iC^{''}(\omega) \qquad (20)$$

According to fig. 3 it follows:

$$\underline{I}_c = \omega\varepsilon_{rm}^{'}(\omega)C_0\underline{U} \text{ where } C^{'}(\omega) = \varepsilon_{rm}^{'}(\omega)C_0 \qquad (21)$$

and

$$\underline{I}_R = \omega(\varepsilon_{rm}^{''}(\omega) + \frac{\tau_0}{\varepsilon_0 \omega})C_0 \underline{U} \text{ where } C^{''}(\omega) = (\varepsilon_{rm}^{''}(\omega) + \frac{\tau_0}{\varepsilon_0 \omega})C_0 \qquad (22)$$

In relations (21) and (22) C_0 represents the void geometric capacitance of the tested object and τ_0 represents the conductivity of the tested object.

A new expression for the dielectric loss factor tan$\delta(\omega)$ results:

$$\tan\delta(\omega) = \frac{I_R}{I_C} = \frac{\omega C^{''}(\omega)U}{\omega C^{'}(\omega)U} = \frac{C^{''}(\omega)}{C^{'}(\omega)} \qquad (23)$$

The initial moment of the measurement is considered the one when a high frequency (1kHz) sine voltage is applied. At that time there is no polarisation and the measured current I is given by:

$$I = \omega C_0 U \text{ from which } C_0 = \frac{I}{\omega U} \qquad (24)$$

Where U = 100 V and $\omega = 2\cdot\pi\cdot 1000$ [rad/ s]

For any frequency $f_i = \frac{\omega_i}{2\pi}$ for which U_i, I_i and δ_i are measured, it follows:

$$I_{c_i} = I_i \cos\delta_i = \varepsilon_{rm}^{'}(\omega_i)C_0 U \qquad (25)$$

$$\varepsilon_{rm_i}^{'} = \frac{I_i \cos\delta_i}{C_0 U} \qquad (26)$$

$$I_{R_i} = I_i \sin\delta_i = (\varepsilon_{rm}^{''}(\omega_i) + \frac{\sigma_0}{\varepsilon_0 \omega_i})C_0 U \qquad (27)$$

$$\varepsilon_{rm_i}^{''} = \frac{I_i \sin\delta_i}{C_0 U} - \frac{\sigma_0}{\varepsilon_0 \omega_i} \qquad (28)$$

After the measurements on the entire frequency range are finished, in order to compare the similar standard curves of $\varepsilon_{rm_i}^{'}(\omega)$ and $\varepsilon_{rm_i}^{''}(\omega)$ their correction with the factor $k = \frac{C_0}{C_{etalon}}$, is necessary, C_0 is the void capacitance of the tested object and $C_{standard}$ is the void capacitance of of the measuring cell, tanδ versus frequency curve is plotted: $\tan\delta_i = \frac{\varepsilon_{rm_i}^{''}}{\varepsilon_{rm_i}^{'}}$.

After measuring the insulation system temperature to which the measurements have been performed the standard curve approximating the best the measured curve is searched in stated temperature data base. The standard curve shows the moisture content of the investigated insulation system.

Moisture content determination in power transformer insulation

Power transformers have a complex insulation system consisting of: barriers, spacers, wire paper insulation and oil (see Fig. 4).

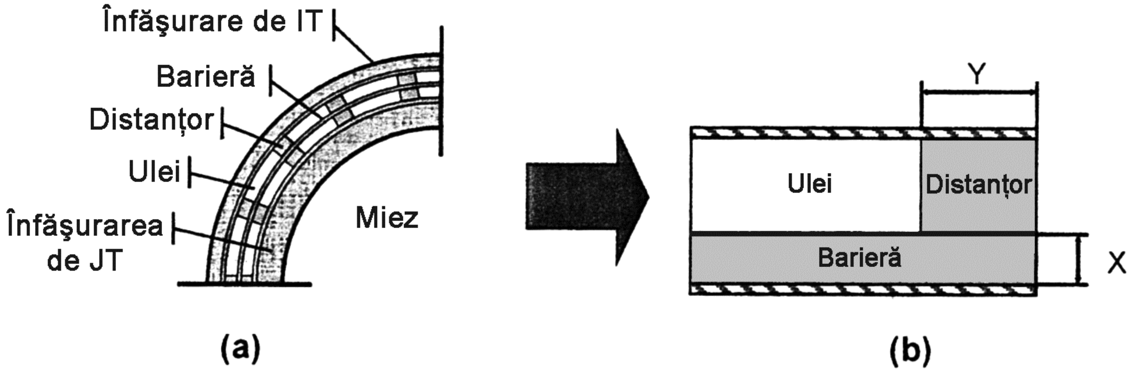


Fig.4. Basic structure of transformer insulation system
a) cross section ; b) X-Y plot

Evaluation of moisture content located in transformer solid insulation may be performed using the so-called X-Y model that represents the volume of parts the insulation system consists of.

Transformer insulation consists of oil impregnated pressboard concentric clinders and axial spacers.

In order to simplify the complex geometry of transformer insulation it is reduced to two measurable parameters namely:

$$X = \frac{\text{total barrier thickness}}{\text{cooling channel width}} \qquad Y = \frac{\text{total spacer width}}{\text{cooling channel length}}$$

X and Y have values within the range 0,2 – 0,5 respectively 0,15 – 0,25.

In paper „A Fast and Reliable Dielectric Diagnostic Method to Determine Moisture in Power Transformers. Intern.Conf. on Condition Monitoring and Diagnostics, CMD 2008, Beijing, April 21+24, 2008, paper no. 143" it is described the so-called "Pancake Model" implemented in the software of three traded equipments for moisture content measurement in transformer solid insulation where X and Y values are given for different transformer geometries.

Within the project frame, the designs of seven power transformers achieved by Electroputere and Retrasib were analysed. The projects were selected for the transformers that are to be implemented in the National Power Grid.

In order to achieve X – Y model, the following ratios were selected as parameters:

$$X = \frac{\text{massive insulation weight}}{\text{oil weight}} \qquad Y = \frac{\text{spacers weight}}{\text{oil weight}}$$

In order to achieve X – Y model, the moisture migration inertia from and to the oil depending on temperature was taken into account. In the previous stages experiments were performed resulting that moisture in solid insulation (wire paper insulation, pressboard cylinders, spacers, coil pressing pieces) is given by the massive insulation pieces of transformer because they have an increased inertia in moisture absorption when the temperature decreases as well as in releasing it to the oil when the temperature increases.

In the table below X and Y values for different transformer types are given

Transformer type	X	Y
40 MVA,110/ 20 kV	0,0972	0,0158
200/ 200/ 60 MVA, 231/ 121/ 10.5 kV	0,1028	0,0158
339 MVA, 400/ 17 kV	0,1144	0,0153

Introducing X and Y parameters referring to transformer geometry, insulation system permittivity $\underline{\varepsilon}_{tot}$ has the expression:

$$\underline{\varepsilon}_{tot} = \frac{1-Y}{\dfrac{1-X}{\underline{\varepsilon}_{ulei}} + \dfrac{X}{\underline{\varepsilon}_{rm}}} + Y\underline{\varepsilon}_{rm} \quad (29)$$

where:

$$\underline{\varepsilon}_{ulei} = 2{,}2 - i\frac{\sigma_{ulei}}{\varepsilon_0 \omega} \quad (30)$$

The moisture content determination technique is the same as for the simple insulation.

ε'_{rm} and ε''_{rm} are determined for each frequency and finally ε'_{total} is determined as real part of $\underline{\varepsilon}_{total}$ and ε''_{total} as imaginary part.

tanδ depending on frequency is determined by relating ε''_{total} to ε'_{total} for each frequency. The curve obtained by measurement is compared to the standard curves from the data base taking as identification parameter the insulation system temperature to which the measurement was performed. The standard curve resembling the best the measurement resulted curve will give the moisture content from the solid insulation.

Considerations on moisture content evaluation using dielectric frequency response analysis

The classical periodic measurements performed so far in the evaluation process of power and instrument transformer as well as of electric cables operational condition do not allow the owners to turn to another maintenance type namely the reliability based one. Due to economic and organisational reasons it is aimed to replace the periodic type maintenance with another one which to enable equipment operation evaluation activities to be focused only on the equipments where deficiencies were identified. Up to the present, routine tests are performed to test insulation strength, oil dielectric strength, polarisation factor and dielectric loss factor at power frequency.

Measuring technique development enabled the following tests to be integrated in the evaluation program:

a) Oil Dissolved Gas Analysis (DGA) allowing the identification of insulation system failure ;
b) Frequency Response Analysis (FRA) allowing the failures related to coil geometry and connections inside the transformer to be identified ;
c) Partial discharge measurement allowing lower or higher energy electric discharges from insulation, screens, core to be identified.

In order to perform a correct diagnosis of the failure, a measurement means for the moisture from the solid insulation is necessary because a high moisture content drastically decreases transformer or cable lifetime.

Unfortunately, there is no direct measurement means and that is why indirect measurement means as dielectric frequency response analysis were developed.

The project was proposed to improve the existing measuring technique with a view to understanding the commercial softwares from the market and to achieving a personalized software for the equipments manufactured by the Romanian enterprises: Electroputere Craiova, Retrasib Sibiu and IPROEB Bistriţa.

To this end laboratory measurements were performed on samples of insulation currently used by the said enterprises. The obtained standard curves have certain particularities in comparison with the ones presented in the papers „Frequency Response of Oil Impregnated Pressboard and Paper Samples for Estimating Moisture in Transformer Insulation, IEEE Transactions on Power Delivery, vol. 21, No. 3, July 2006, pp. 1309-1317” şi „Insulation diagnosis by polarization and depolarization current measurements. 13th Int.Symp. on High Voltage Engineering, ISH 03, Deft, 2003". At the same time, in comparison with the existing softwares where X and Y are selected without a real basis practically, in the achieved calculation model they are selected based on the projects of the inspected transformers.

The approximations introduced in moisture content evaluation lead to the conclusion that the result has an error margin of ±5% that was communicated to the specialists from Transelectrica, Electrica, Cernavodă Nuclear Power Plant, etc. not to make decisions based only on this measurement and to correlate it with partial discharge measurement results, which due to their value and location to the high voltage, point out whether the insulation is wet or not.

This measurement result evaluation should be performed by a specialist so that to identify if:

a) Solid insulation is wet;
b) Solid insulation is thermally aged;
c) Oil is aged;
d) Oil has particles.

This is necessary because a perfect comparison between the measured curves and the ones existing in the data base cannot be performed by software. This comparison shall be monitored by a specialist. This is one more reason to implement this evaluation method.

Unfortunately for the specialists involved in the diagnosis process and fortunately for the ones commercialising such equipments the method results cannot be controlled by an objective process.

Within the project frame solid insulation (pressboard) was implementing in a 200 MVA autotransformer knowing that it should be inspected after a 3 years period. The autotransformer worked in the electric station of Thermal Power Plant from Işalniţa. The said pressboard samples were placed in the laboratory in a sealed vessel with oil having a moisture of 0,3%. The pressboard moisture was determined by Karl – Fisher coulometric method and the result was 2,5%. The measurements performed prior to opening autotransformer window to take the pressboard samples indicated a moisture of 0,7% in autotransformer solid insulation. It is possible that the sample to have been infected with moisture during the time from taking from transformer to placing in Este Karl – Fisher instrument for titration.

Performance of spectroscopic measurements on transformers

Within the project frame a lot of tests were performed in the High Voltage Laboratory of ICMET ″finish″ the program for moisture assessment in the solid insulation of power transformers. Taking into account that there is no reference objective method which to validate the results of moisture assessment program, in the first stage comparisons were made between tanδ value obtained using the method described in the previous chapters for a 50 Hz frequency and the one obtained by measuring it with a classical Schering bridge using equipment made by Megger and Siemens. The calculated standard curves were adjusted until a measurement identity up to the 4-th significant digit for tanδ at 50 Hz was got.

In the following stage, measurements on new transformers manufactured by Electroputere and Retrasib (v. Fig. 5, 6, 7 and 8) were performed. The said measurements were performed at the headquarters of the above companies after the technological process of insulation forming was finalised but before beginning the type tests. Analysing the results referring to the moisture from the solid insulation an advantage for Retrasib transformers was noticed due to the fact that a new drying equipment with kerosene vapours was used. The similar equipment used by Electroputere has been in operation for more than 30 years and does not have modern drying process monitoring and automatic control systems.

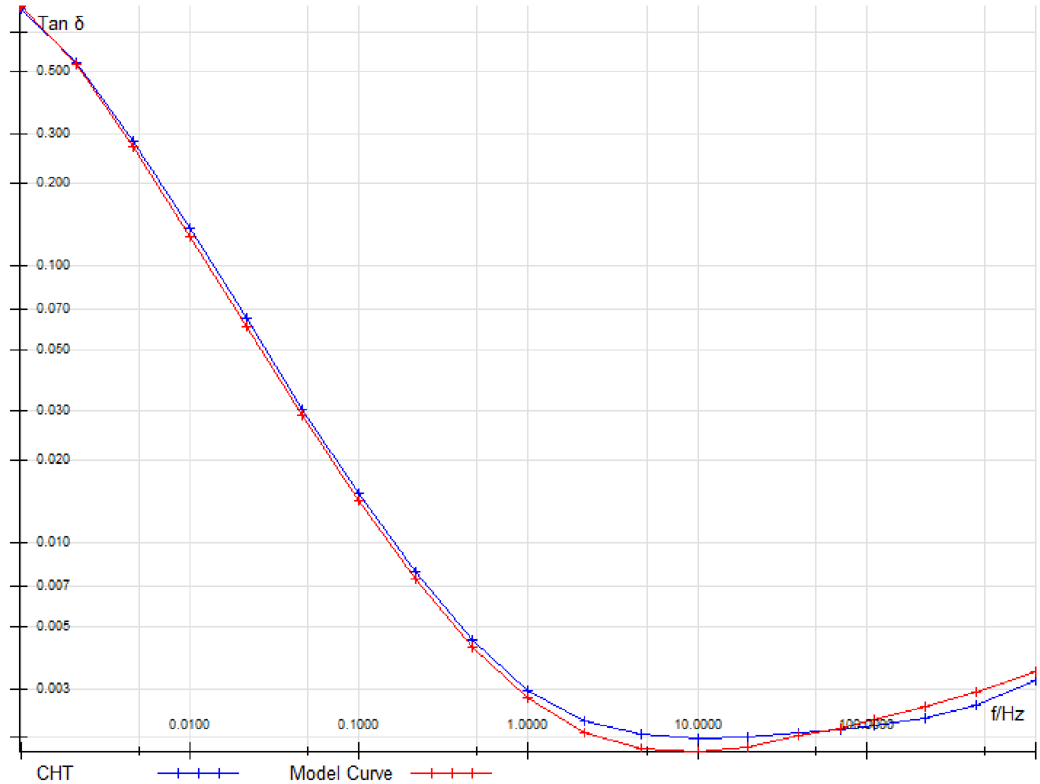


Fig. 5. Moisture measurement at 200 MVA transformer of RETRASIB Sibiu
Moisture =0.3% between HV-LV windings

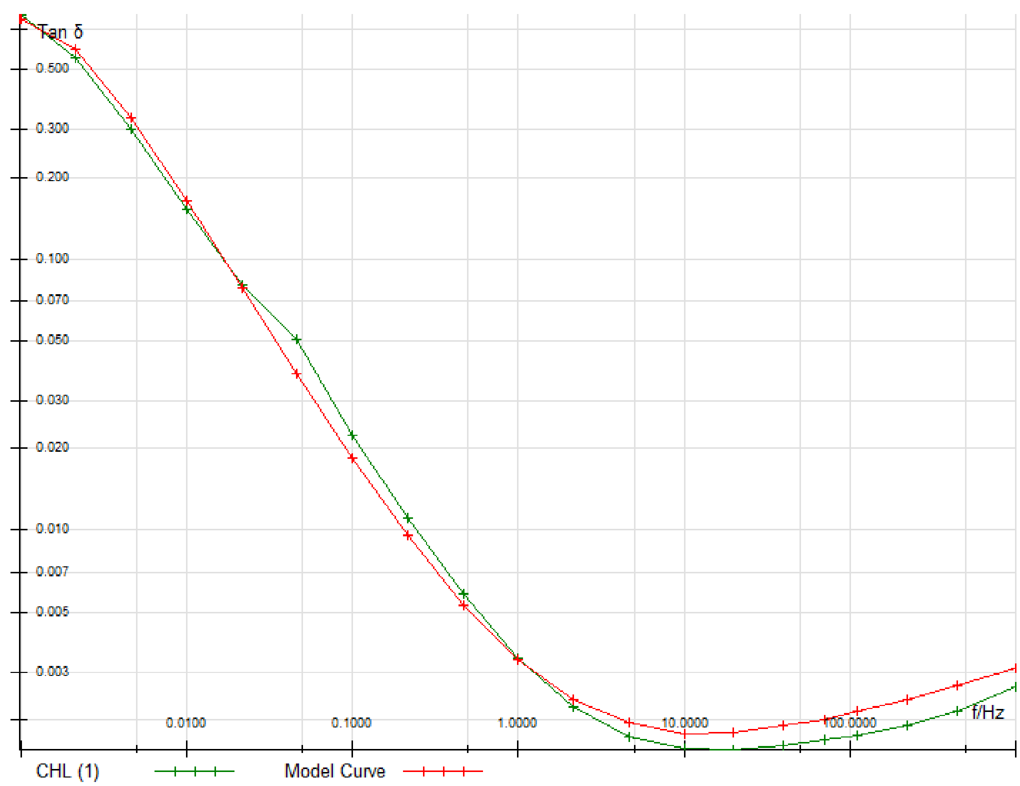


Fig. 6. Moisture measurement at 400 MVA transformer of RETRASIB Sibiu
Moisture =0.3% between HV-LV windings

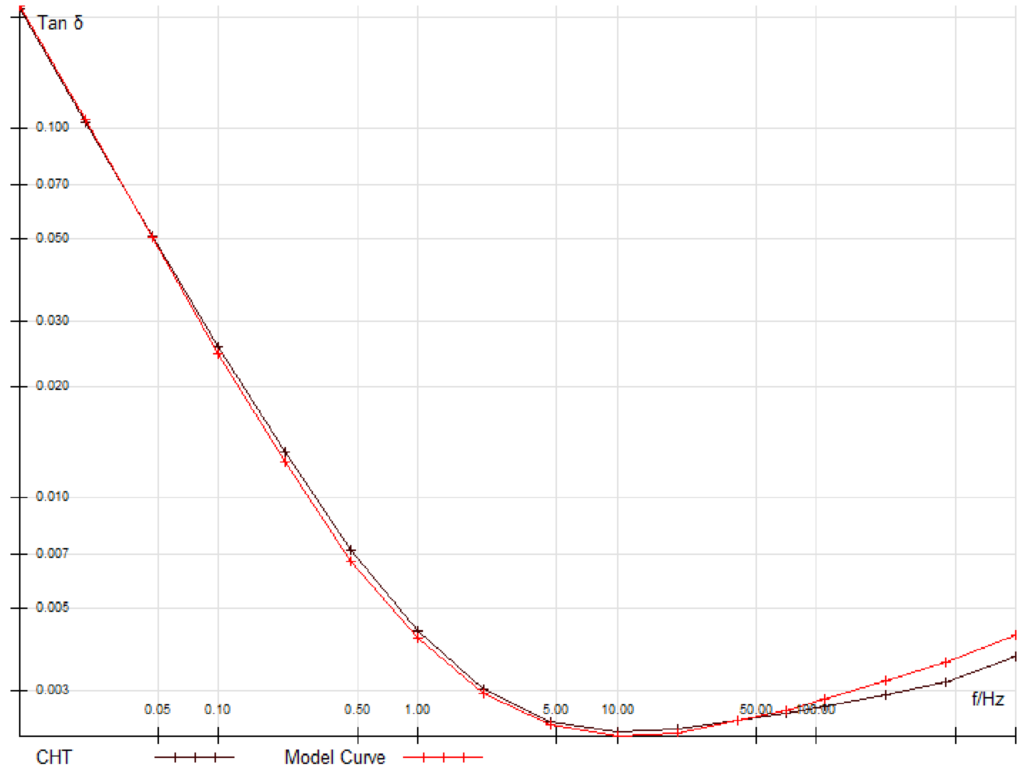


Fig. 7. Moisture measurement at 200 MVA transformer of ELECTROPUTERE Craiova Moisture=0.5% between HV-LV windings

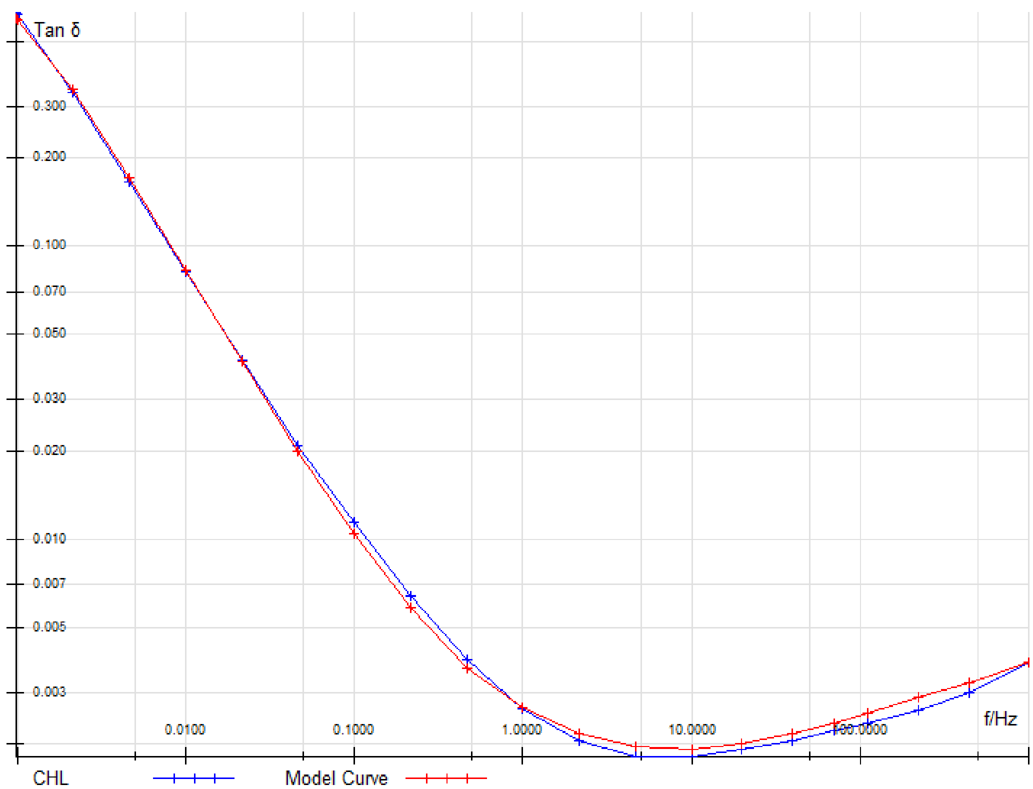


Fig. 8. Moisture measurement at 400 MVA transformer of ELECTROPUTERE Craiova Moisture =0.8% between HV-LV windings

The measuring circuits are presented in Figs. 9, 10 and 11.

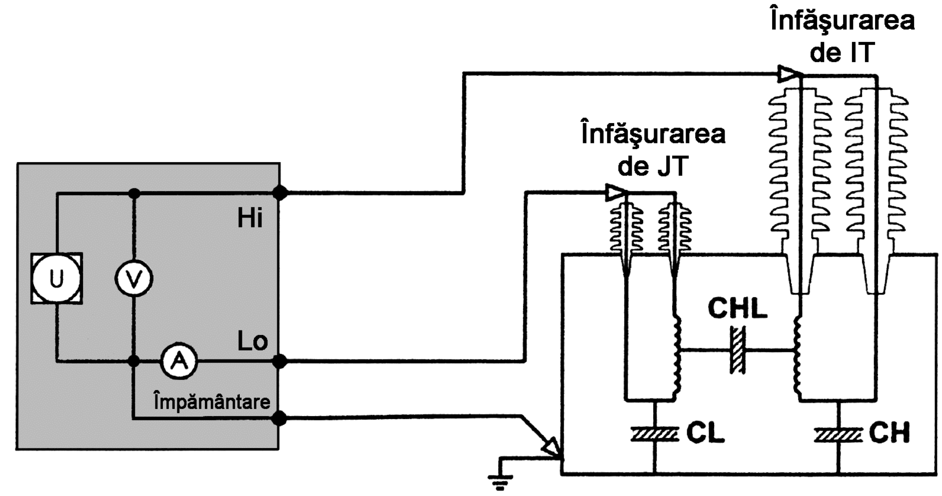


Fig. 9. Measurement between two transformer terminals not directly connected to ground

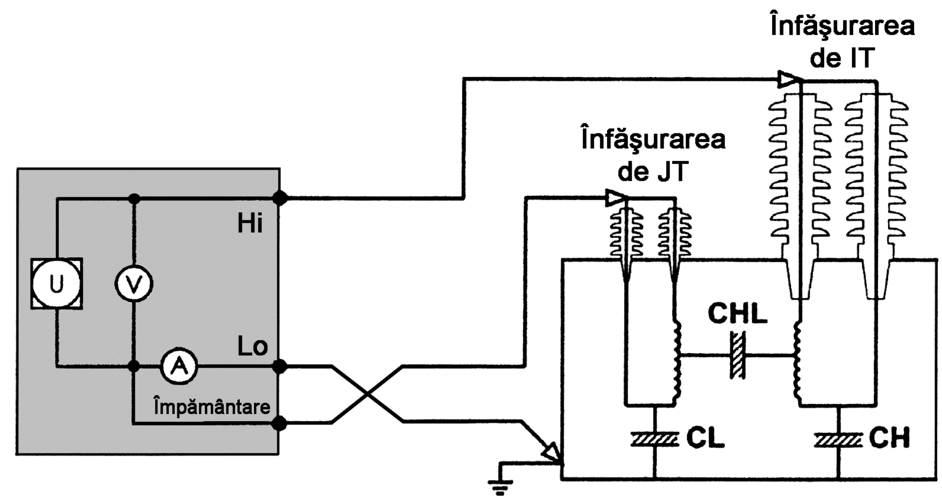


Fig. 10. Measurement between two transformer terminals one of which is connected to ground

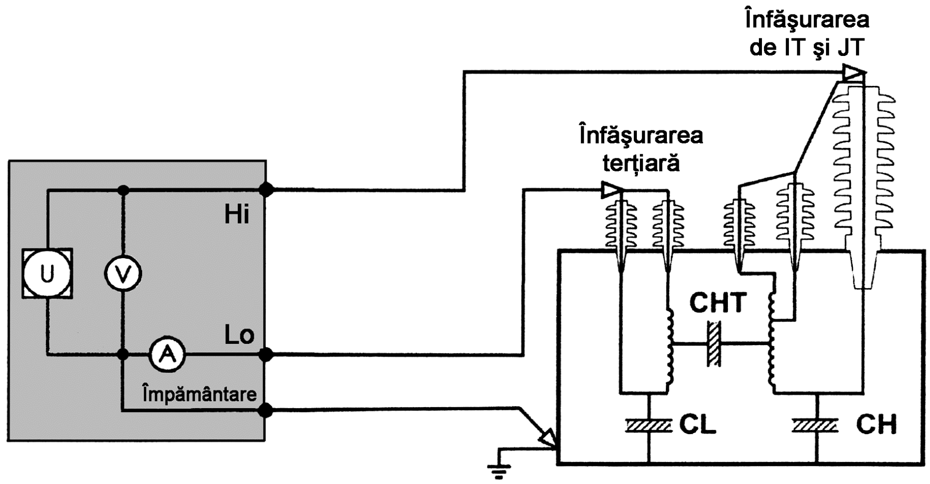


Fig. 11. Measurement between two autotransformer terminals not directly connected to ground

Fig. 12 presents moisture content evolution in a current instrument transformer during the drying process achieved by thermal flux radiation in a sealed oven. The present drying process alternates the periods of heating at 110°C in air (to improve thermal radiation process efficiency) with the ones of voiding intended to absorb moisture from solid insulation. The equipment for dielectric loss factor measurement depending on frequency was connected to the instrument transformer during the whole measurement process (v. Fig. 13).

This measurement was the basis for a patent proposal aiming at optimising the duration of the insulation thermal treatment process and not only.

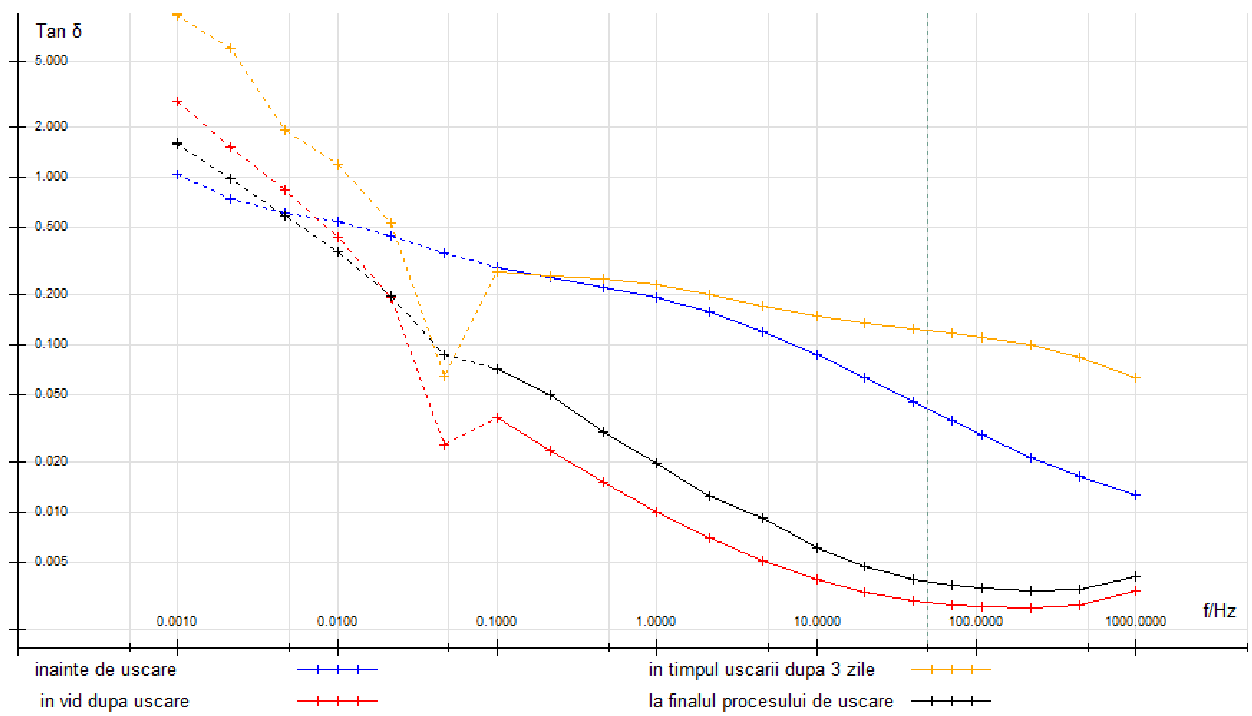


Fig. 12. Moisture content evolution in 123 kV current transformer insulation

Where :

1) Blue - 4.2% moisture
2) Yellow - 1.2% moisture
3) Red - 1% moisture
4) Black - 0.8% moisture

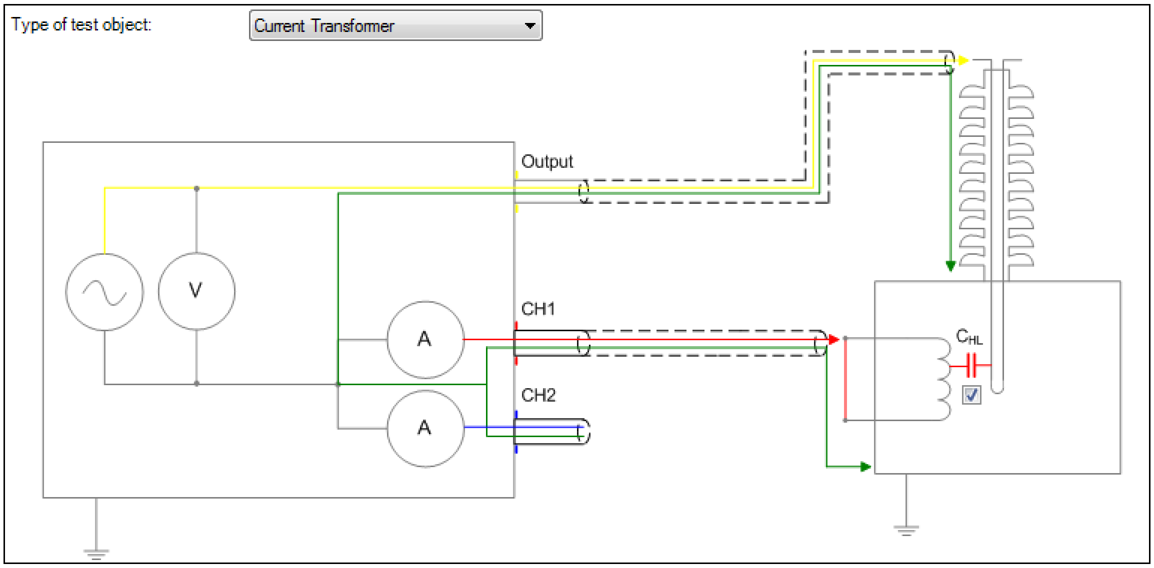


Fig. 13. Dielectric loss factor measurement

Once put on a solid basis the working procedure applied to assess the operational condition of the insulation at the following transformers in service:

– 200 MVA electric station Bacău (v. Fig. 14);
– 200 MVA electric station Roman (v. Fig. 15);
– 200 MVA electric station Işalniţa;
– 250 MVA electric station Suceava;
– 200 MVA electric station Sărdăneşti.

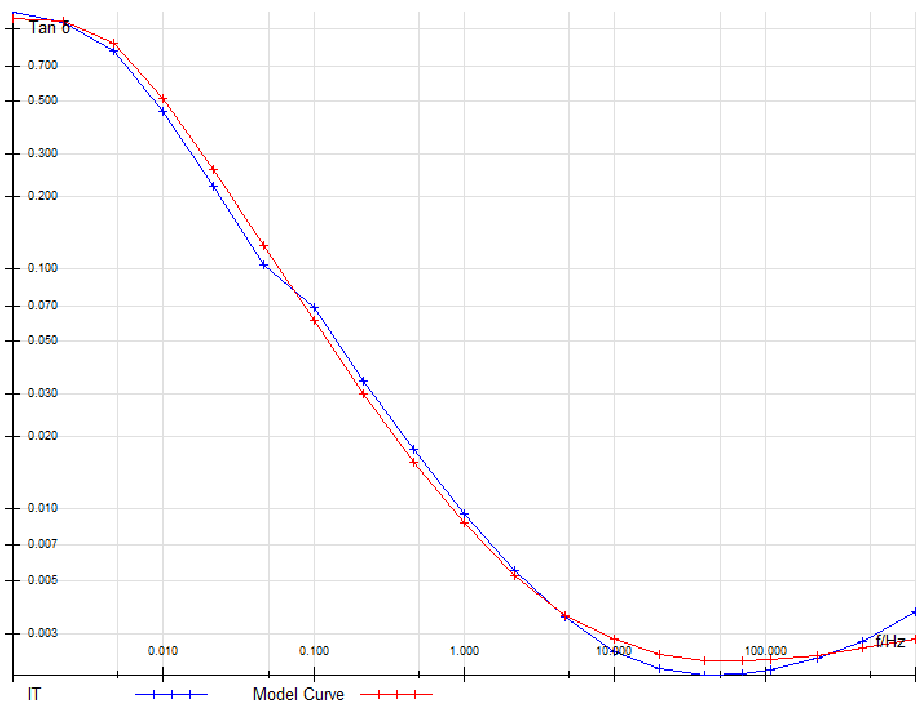


Fig. 14. Moisture measurement at 250 MVA transformer of ELECTROPUTERE Craiova in electric station Bacău, Moisture=2.2% between the HV- LV windings

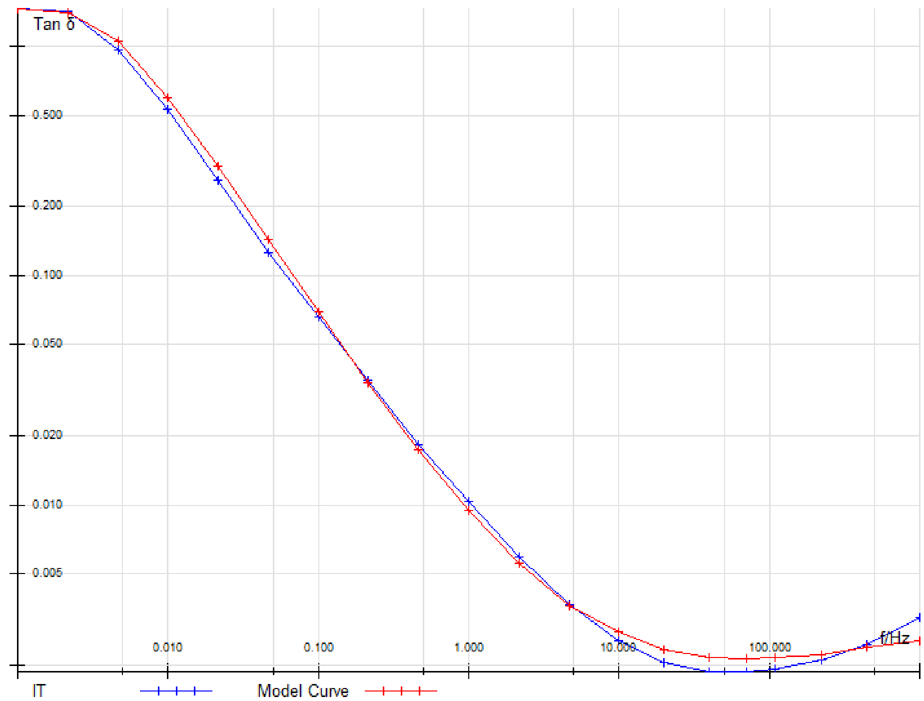


Fig. 15. Moisture measurement at 250 MVA transformer of ELECTROPUTERE Craiova in electric station Roman, Moisture =2.3% between the HV- LV windings

Performance of spectroscopic measurements on medium voltage cables

Standard IEC 60502-2/ 2005 referring to medium voltage cables specifies the tests that shall be performed on a new cable and the assessment criteria if it passes or not the test.

We were curious to compare dielectric response of Al-XLPE/ Al foil/ PE wp 1x150/ 25 mm^2, 12/ 20 kV type cable before and after the tests described in TEST REPORT No. 43031

From Fig. 16 it follows that the mechanical, thermal and electrical tests influenced the structure and dielectric properties of XLPE type insulation and yet the cable is declared as compliant according to the acceptance criteria of the in force IEC standard.

It is interesting to notice that tanδ value measured at 50Hz is almost the same in the three cases namely:

0,030% according to Test Report No. 43031 ;

0,029% according to "new - nou" cable curve of Fig.16;

0,034% according to "old - vechi" cable curve of Fig.16.

And yet tanδ characteristics depending on frequency are obviously different before and after the type tests.

The investigations will continue so that to have a data base necessary to present this phenomenon in the next meeting of the International Electrotechnical Committee that is to be held next year in Paris.

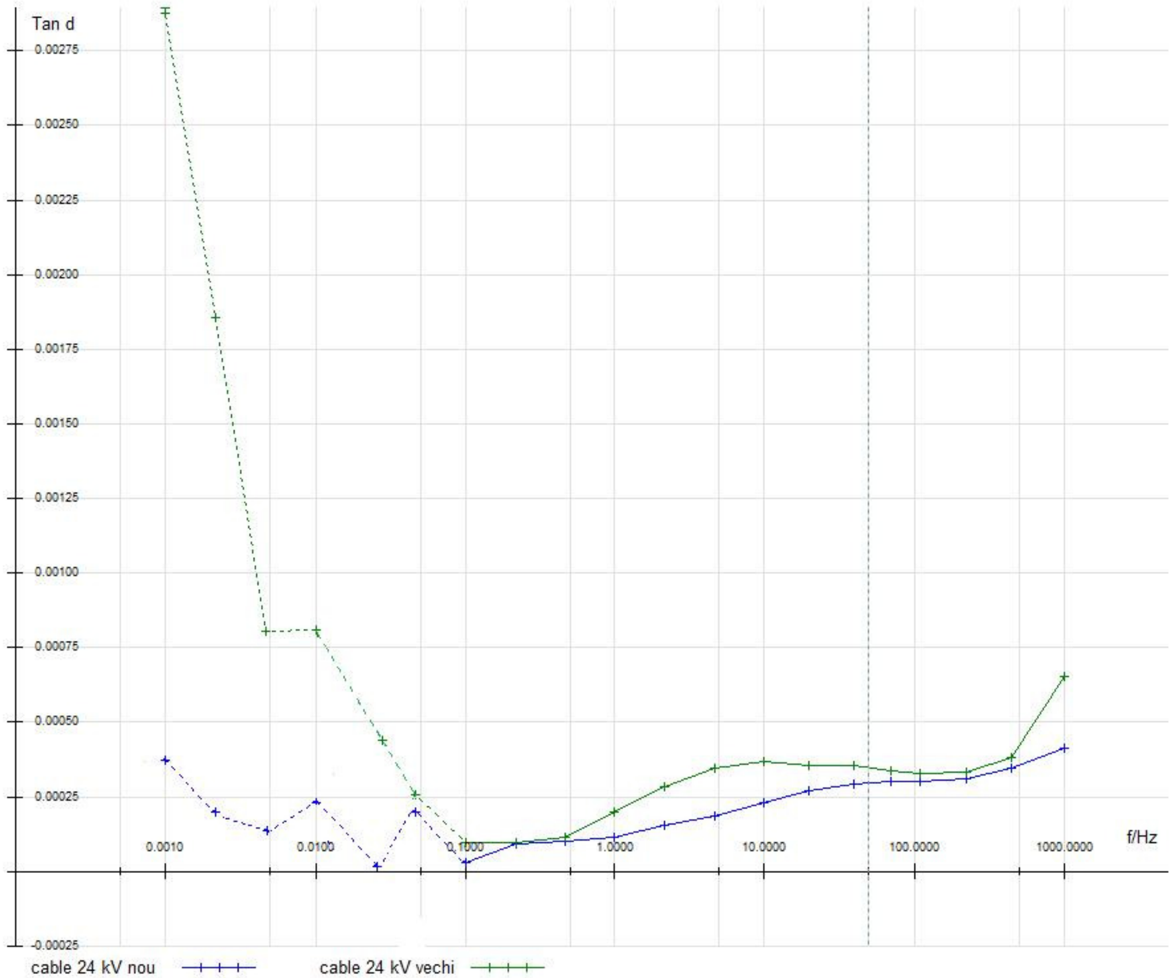


Fig. 16. Dielectric responses of a medium voltage cable before (new - nou cable)and after (old- vechi cable) the type tests

Project result dissemination

Following the project finalization diagnosis services were performed at five transformers in service.

The diagnosis process assumed on-site and laboratory measurement to be performed as well as their result correlation and interpretation.

There were performed:

- Oil dissolved gas analysis;
- Oil moisture degree determination;
- Solid insulation moisture degree determination;
- Partial discharge measurement.

To perform such a service was a good opportunity to disseminate the dielectric spectroscopy method to electric power operators from Moldova, Gorj and Dolj.

Project topic enabled the university partners to involve students in the research activity. The following projects for students were proposed:

- Dielectric properties of synthetic insulation of electric cables (Master degree dissertation at University of Craiova)
- Electromagnetic field modelling in low voltage equipment (Master degree dissertation at University of Piteşti)

It was proposed a patent with the title: ″Method and system for the automatic control of dimensional stabilisation process at power transformer windings ″, authors: Popa Dorin and Vintilă Adrian de la ICMET Craiova, registered at OSIM no. A/ 00917/ 19.09.2011 .

The technical issue of the patent was inspired by an older requirement of Electroputere referring to the decrease of thermal and electric energy consumption own to the technological drying process of transformer windings. The achieved equipment was successful both in decreasing the thermal and electric energy consumption and moisture removing period and in obtaining the designed dimensions of transformer windings.

Conclusions

- The project was finalised by achieving an indirect method for moisture measurement in cable and instrument and power transformer insulation ;
- The measurement method was adapted to the materials used Electroputere Craiova, Retrasib Sibiu and IPROEB Bistriţa to improve the measurement accuracy in comparison with the softwares commercialised on the world market. ;
- The list of modern measurements used in high voltage power equipment was completed with dielectric spectroscopy technique;
- Accurate diagnosis enables the passing from periodical maintenance of electric power equipment to predictive maintenance providing reduced expenses with personnel and operational condition assessment ;
- This measurement method may be applied in the technological process for power and instrument transformer manufacturing in order to monitor their insulation condition after each stage of their manufacturing;
- The patent application handed in at OSIM Bucureşti is based on an operational model that gave good results with respect to optimising the costs and duration of treatment and thermal stabilisation processes at power transformer windings;
- Result dissemination was made mainly by applying the method in the diagnosis process of transformers in service and in the assessment of insulation capability to pass successfully the tests provided for new transformer certification. ;
- Practice validation of the performed diagnosis was the best advertisement.

Anexa 1

Determinarea unei expresii analitice pentru curbele etalon

1.Introducere

Raspunsul izolatiei cu cu diferite continuturi de umiditate (1%, 2%, 3%, 4%) a fost studiat in domeniul de frecventa 10^{-4} - 10^{3} Hz.
Se doreste determinarea unei relatii analitice pentru partea reala si imaginara a permititivitatii complexe $\varepsilon = \varepsilon^{'} - j\varepsilon^{''}$ in functie de frecventa pentru diferite valori ale umiditatii la 50°C.
Raspunsul in frecventa al izolatiei pentru diferite umiditati este prezentat in Fig.1.

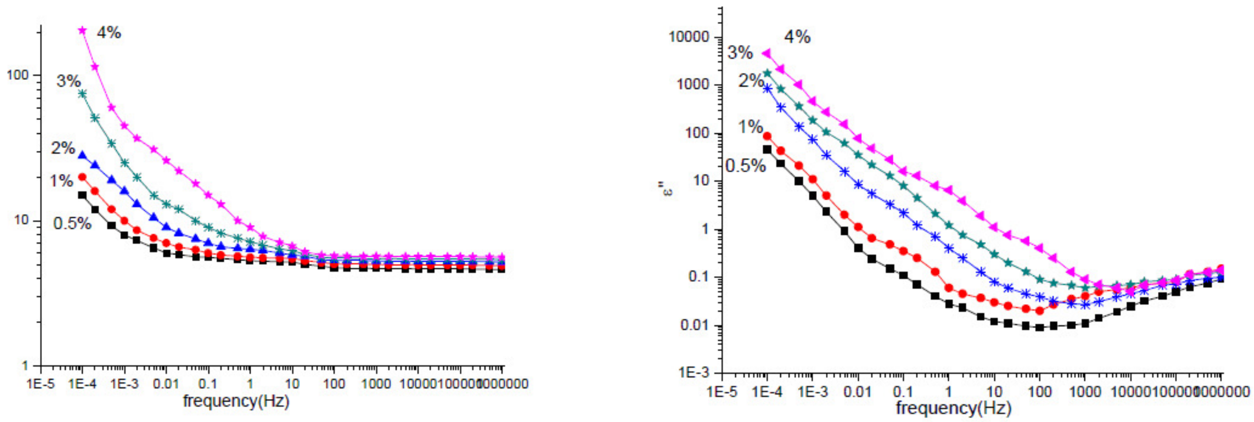


Fig.1

Se observa ca atit partea reala cit si cea imaginara a permitivitatii cresc odata cu scaderea frecventei la umiditate constanta.De asemenea ele cresc odata cu umiditatea la frecventa constanta,pregnant la frecvente mici.

2Modulul Curve fitting (Aproximarea curbelor)

Acest modul este o colectie de interfete grafice (GUIs) si de fisiere functie de tip m avind ca suport mediul de calcul Matlab.Principalele caracteristici ale modulului sunt:

- procesarea datelor
- aproximarea parametrica si neparametrica a datelor Se pot efectua aproximari parametrice ale datelor folosind o biblioteca de ecuatii sau o ecuatie utilizator.
- aproximare liniara cu cele mai mici patrate, aproximare neliniara cu cele mai mici patrate.
- analiza statistica pentru evaluarea calitatii aproximarii

2.1Evaluarea calitatii aproximarii

Dupa aproximarea datelor cu un anumit model trebuie sa evaluam calitatae aproximarii.
Un prim pas ar fi o examinare vizuala a curbei aproximate reprezentata in modulul curve fitting.
In afara de aceasta metoda modulul ofera tehnicile urmatoare atit pentru aproximarile parametrice liniare cit si neliniare :
- calculul si repezentarea reziduurilor

- calitatea statisticii aproximarii
- increderea si limitele de predictie

Aceste tehnici pot fi grupate in doua categorii : grafice si numerice.

Reziduurile si limitele de predictie sunt grafice in timp ce calitatea statisticii aproximarii si limitele de predictie sunt tehnici numerice.Tehnicile grafice sunt benefice deoarece permit vizualizarea intregului set de date si afisarea unui numar mare de relatii intre model si date.

Metodele numerice sunt focalizate pe un aspect particular al datelor si deseori concentreaza informatia intr-un singur numar.

2.2Calculul si repezentarea reziduurilor

Reziduurile unui model aproximat se definesc ca diferenta intre valorile raspuns y date si cele estimate y_{aprox}, pentru fiecare valoare a datelor de intrare.

$$r = y_i - y_{i\,aprox} \tag{1}$$

Presupunind ca modelul care aproximeaza datele este corect reziduurile aproximeaza erorile aleatoare.

2.3Calitatea statisticii aproximarii

Dupa utilizarea metodelor grafice de evaluare a calitatii aproximarii trebuie examinata calitatea statisticii aproximarii.Modulul Curve fitting permite aceasta pentru modelele parametrice prin urmatoarele marimi :

1.suma patratelor datorate erorilor (sum of squares due to error) SSE.Se mai numeste si suma patratelor reziduurilor.Expresia SSE este:

$$SSE = \sum_{i=1}^{n} \omega_i (y - y_{aprox})^2 = \sum_{i=1}^{n} r_i^2 \tag{2}$$

Daca valoarea lui SSE este apropiata de zero atunci se poate considera ca modelul de aproximare este bun.

2.R-square : Acest parametru indica eficienta aproximarii prin explicarea variatiei datelor.Altfel spus acest parametru reprezinta patratul corelatiei dintre valorile raspunsurilor si ale celor aproximate.El se determina ca suma patratelor regresiei (SSR) si suma totala a patratelor(SST).

SSR se defineste ca :

$$SSE = \sum_{i=1}^{n} \omega_i (y - \overline{y})^2 \tag{3}$$

SST se defineste ca:

$$SST = \sum_{i=1}^{n} \omega_i (y_i - \overline{y})^2 \tag{4}$$

unde $\overline{y}$ este valoarea medie.

Relatia dintre cei 3 parametri este : SST= SSR + SSE.

Pe baza acestor definitii R-square se exprima astfel :

R-square = SSR/ SST = 1- SSE/SST.

R-square poate lua valori intre 0 si 1.O valoare apropiata de 1 indica o aproximare buna.

3. Aproximarea raspunsului in frecventa la umiditate constanta

Aproximarea se va face cu ajutorul metodei neliniare a celor mai mici patrate implementate in modulul curve fitting tool din Matlab.

Consideram curbele $\varepsilon^{'}(f)$ pentru u = 3 % si u = 4 %, date tabelar in Tabelul 1si 2.

u = 3 %

$\varepsilon^{'}$	70	44	16	8.8	7	6.9	6.81	6.7
f[Hz]	0.0001	0.001	0.01	0.1	1	10	100	1000

Tabel 1

u = 4 %,

$\varepsilon^{'}$	280	70	42	15	9	7	6.92	6.87
f[Hz]	0.0001	0.001	0.01	0.1	1	10	100	1000

Tabel 2

Cele doua cazuri sunt reprezentate in Fig.2.

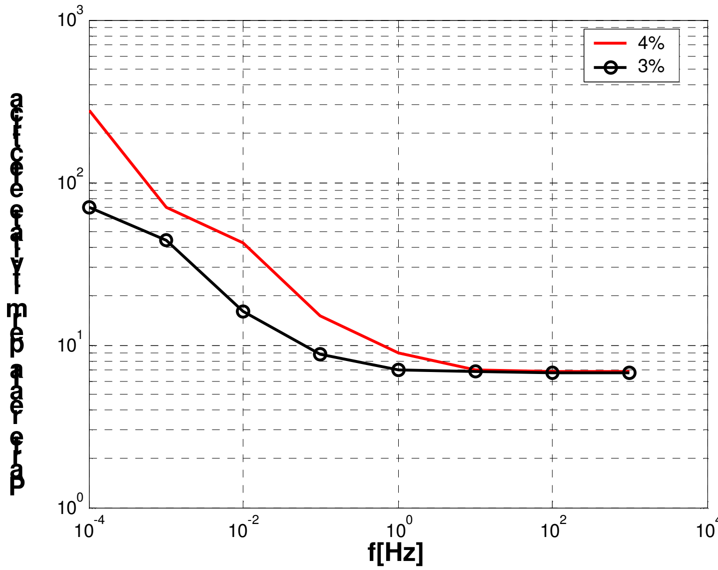


Fig.2

Pentru generarea curbelor intermediare, corepunzatoare altor valori ale umiditatii,s-au folosit expresii analitice de tip putere de forma:

$$\varepsilon^{'} = a \cdot f^{b} + c \qquad (5)$$

Expresia analitica pentru curba intermediara corepunzatoare umiditatii u = 3.5% s-a obtinut prin mediarea valorilor din Tabelele 1 si 2 si aplicarea algoritmului neliniar al celor mai mici patrate, obtinindu-se expresia :

$$\varepsilon^{'} = 1.665 \cdot f^{-0.5} + 6.86 \qquad (6)$$

Valorile obtinute pentru coeficienti corespund unor limite de incredere de 95.5 %.
Se observa o valoare maxima foarte scazuta a reziduurilor : $|r| = 2*10^{-14}$ ceea ce indica o buna aproximare.De asemenea $SSE = 6.967 \cdot 10^{-27}$ si R-square =1.
Reprezentarea celor 3 curbe , corepunzatoare umiditatilor 3%, 3.5% si 4% este prezentata in Fig.3.

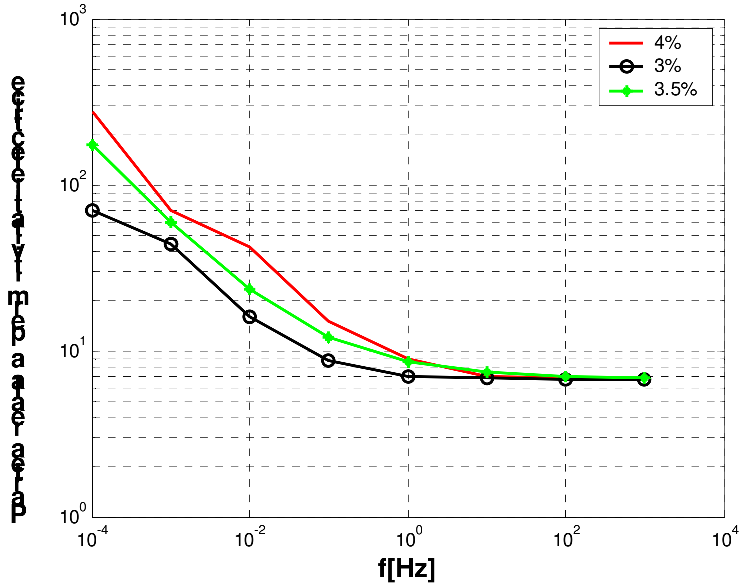


Fig.3

Aplicind acelasi algoritm s-a aproximat curba pentru umiditate 3.75%, aceasta fiind reprezentata in Fig.4.

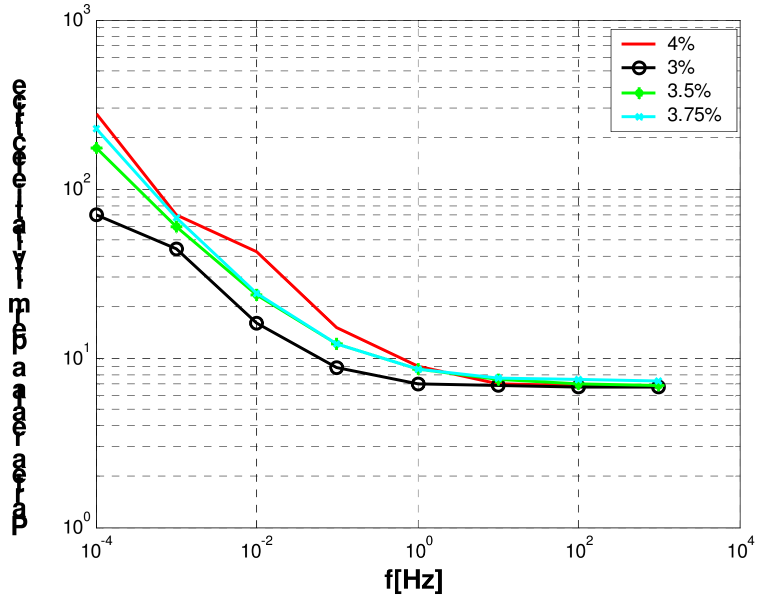


Fig.4

Acelasi algoritm s-a aplicat si pentru partea imaginara a permitivitatii electrice ε''.

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