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APPLICATION OF MODERN TECHNIQUES FOR THE CONDITION ASSESSMENT OF POWER TRANSFORMERS

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1. Summary

The outstanding technical and economical importance of power transformers in the electrical transmission and distribution networks does not need to be discussed. The continuous awareness of the evolution of the conditions of the insulation system and of the internal mechanical sturdiness is of great value for the system operator as it allows to optimise the lifecycle management of the machine as well as the scheduling of the maintenance operations. Power transformers are designed to withstand dielectric stresses linked with the operating voltage and overvoltages as calculated in the insulation coordination process, thermal stresses linked with their loading guide and electrodynamical stresses linked with external short-circuits. Internal displacements or damages may be generated during the transportation of the machines if the internal mechanical structure of the windings and core are not correctly tight together. When a transformer has undergone abnormal stresses, it is necessary to check its response to the stresses and consequently its conditions, to be aware of its residual ability to withstand further abnormal forces. The Sweep Frequency Response Analysis method (SFRA) has been found to be adequate for the evaluation of possible displacements and deformation of the windings as well as for the pointing out of short circuits among coils. Furthermore, the level of humidity in the paper-oil insulation system may cause a premature ageing and, in presence of abrupt variation of the temperature, formation of bubbles leading to potential internal discharges in the machine. The Polarization and Depolarization Current (PDC) method has been deeply investigated and analyzed on machines in service and in the workshop and has appeared to be effective in pointing out defects in this respect. The paper reports and discusses the results of part of the activity in the frame of an extensive research program carried out in the laboratory, in the field and in the manufacturers workshop; the acquisition and elaboration techniques are dealt with and some hints for the correct interpretation of test results, based on the experience, are given.

2. Introduction

The activity discussed in the present paper has been carried out in the frame of the research projects foreseen in the Decree of the Italian Ministry for Industry and Trade dated 26 January 2000

Monitoring and diagnostics of electrical components, and in particular of power transformers which constitute the heart of the electricity generation, transmission and distribution networks are, since long, object of great interest. The dramatic changes in the stresses undergone by the machines linked with the modification in the operating conditions of plants in a deregulated environment, the increased market competition, the important reduction of investment possibilities for old transformers replacement and the necessary reduction of the operating costs, call for new knowledge in the specification, design and in follow-

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up of machines not to allow failure rates and time of unavailability to increase. Maintenance policies of major components are being drastically changed, shifting from a time based maintenance towards a predictive approach, in which any corrective operation is carried out as a function of the present conditions of the components and of their strategic importance to the achievements of the objectives of the portion of electrical system to which they belong. In order to apply the predictive maintenance policy it is of vital importance to set up monitoring and diagnostic techniques capable of assessing the conditions of machines and to help in the evaluation of their potential residual life. The enhanced consciousness about the risks for the environment and the safety of personnel in the event of a failure causing a fire or an explosion is again motivating the development of such diagnostic techniques.
Among the different diagnostic options, some methods allow an on-line check: i.e. the possibility of acquiring information about some aspects of the conditions of the machine without removing it from service; other methods, more finalized to checking specific aspects, require the machine to be taken out of service and possibly be disconnected from the network. The level of invasiveness of off-line methods, however, can vary greatly, as some of them require the machine to be disconnected only for very short time.

3. Sweep Frequency Response Analysis (SFRA) for the condition assessment of power transformers

The SFRA method is used to check the eventual change in the internal geometry of the active part of the transformer: displacements or deformations. The main causes of such defects may be linked with the transportation or with the working conditions of the machine, such as the presence of external short-circuits with the consequent development of important mechanical stresses linked with electrodynamic forces (radial or axial depending on the constructive technology of the machine), affecting the tightness of the relative connections in the core and/or in the windings. Once the transformer has been damaged, even if not extensively, its capability to withstand further stresses may be heavily jeopardized. Defects of this nature evolve generally towards the complete destruction of the machine in a dielectric breakdown as a consequence of a mechanical collapse during electrodynamic stresses or in a progressive deterioration of the insulation leading to a dielectric breakdown of internal solid insulation (partial discharges). In such a context it is important to check that the windings are not affected by incipient mechanical deformations.
The classical method adopted for checking the presence of such internal defects is the measurement of the leakage inductance; however, practical experience has shown that only radial deformations can be seen using this method, while axial deformations linked with localised mechanical stresses on the winding extremities may not be detected. The SFRA method was developed to cope with this lack of sensitivity [1], [2]. It is based on the assumption that any mechanical deformation may be associated with a change in the capacitive-inductive equivalent circuit and therefore detectable through a transfer function. In essence, the method consists in applying on one end of machine winding a low voltage sinusoidal signal made of a sweep of frequencies covering a range between 10Hz and 2MHz and measuring on the other end of the winding the corresponding response in terms of amplitude ratio with respect to the input signal. The applied sweep maintains the same level of energy for each frequency analysed in such a way as to obtain accurate and reproducible results. Little influence from the test set-up is evidenced: the same testing accuracy can therefore be obtained in the laboratory and in the field. This method being essentially based on a comparison approach it is useful to have reference data: in particular it would be advisable to have reference tests on the machine when new, so to compare data in different stages of the machine life. The test is carried out typically considering two configurations for the winding opposite to the tested one: i.e. winding open and floating and winding short-circuited. These testing conditions allow the selective evaluation of the presence of defects: in fact, in the conditions in which the winding opposite to the tested one is open and floating, the effect of the mutual coupling between the HV and LV windings can be seen in addition to the to the effect of the magnetic circuit; in the other testing configurations (short-circuited winding) the effects of the mutual coupling and of the magnetic circuit are masked and the effect of the single winding is to be seen.
The experience has shown that in the evaluation of the test results, the behaviour in three different ranges of frequencies must be considered:

- Frequency < 10 kHz: in this range phenomena linked with the transformer core and magnetic circuits are evidenced: the analysis in this range must take into consideration the residual magnetisation which can slightly modify the obtained response from one test to the other. In this range coil faults, winding interruptions, magnetic circuits problems are brought to light;
- Frequency in the range 5 kHz to 500 kHz: in this range phenomena linked with radial relative geometrical movements between windings are evidenced;

- Frequency > 200 kHz: in this range axial deformations of each single winding are evidenced.

4. SFRA results Case 1: three-phase step-up transformer in service, 130 MVA 15/400 kV

The power transformer subjected to the test had tripped on differential protection without any Buchholtz tripping. An additional check on the on-line DGA system showed an important increase in the hydrogen equivalent total gases and the machine was removed from service and planned for an off-line thorough check. As no reference data existed for that specific machine, the SFRA test, carried out after disconnection of the transformer was elaborated through comparison among different circuit configurations.

Measurements carried out on the high voltage windings (400kV) star connection

The result of the measurements carried out on the high voltage windings are reported in Figure 1 and Figure 2 for the configurations with the low voltage windings open and floating and with the low voltage windings short-circuited respectively.

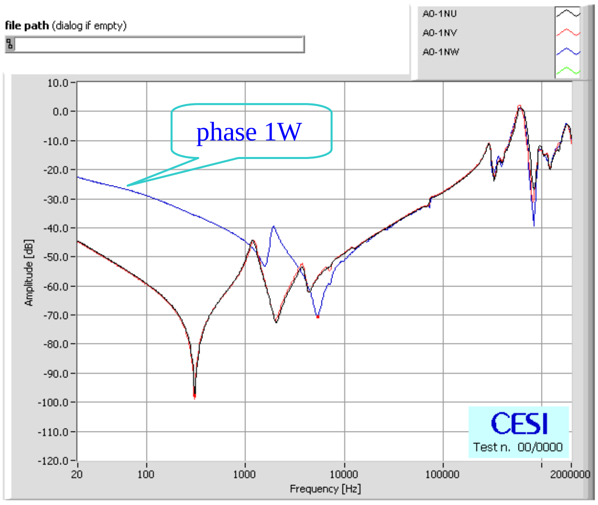


Figure 1: Measurements carried out on the HV windings with the LV winding open and floating

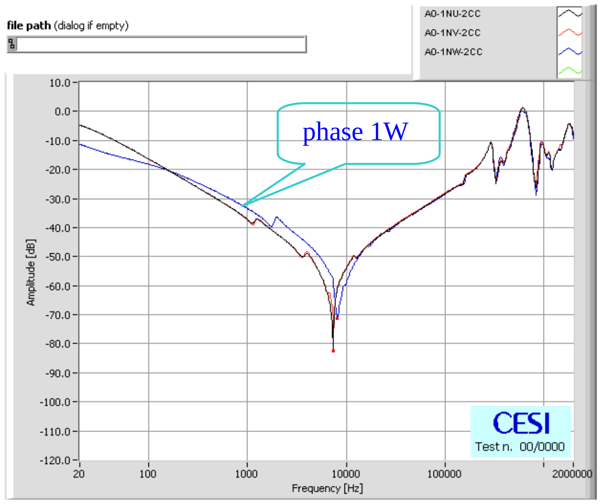


Figure 2: Measurements carried out on the HV windings with the LV winding short-circuited

It can be seen in Figure 1 that the shape of the frequency response corresponding to phase W deviates substantially from that of the other two phases of the machine, especially in the open-circuit configuration and for a frequency range under 20 kHz. The response to higher frequencies is not substantially affected, thus excluding the possibility of geometrical deformations of the faulted winding. Such huge deviations in the low frequency range, as shown in Figure 1 can only be linked with a variation of the turns ratio of one phase (possibly due to an internal partial short circuit of one winding and/or to the opening and separation of part of the winding, affecting the magnetic coupling). This electrical change is also visible in the low frequency range in Figure 2: however, the deviation appears much lower: in fact, when the winding opposite to the tested one is short circuited, inductive coupling is very much affected and the sensitivity at low frequencies becomes much less; moreover, being the short-circuit reactance much smaller than the no-load reactance, the signal attenuation in the low voltage range is much smaller;

Measurements carried out on the low voltage windings (15 kV) delta connection

The SFRA measurements were repeated on the low voltage windings opening the delta connection and keeping the high voltage windings open and floating or short-circuited. The respective diagrams obtained are shown in the Figure 3 and Figure 4. Waveshapes confirmed that the fault was confined on phase W. The check carried out with the opposite winding short-circuited, showing a perfect superposition of all tracks, confirmed the idea of a problem on the HV winding.

No further elaboration of the SFRA data was deemed necessary (e.g. numerical evaluation of the shape differences of the damaged phase with respect to the sound phases, etc.) because a major fault was detected and it was unavoidable to open the machine and carry out the necessary repair operations. A series of traditional checks were carried out after the SFRA, such as the turns ratio, the winding resistance and the leakage inductance: all the checks confirmed the hypothesis.

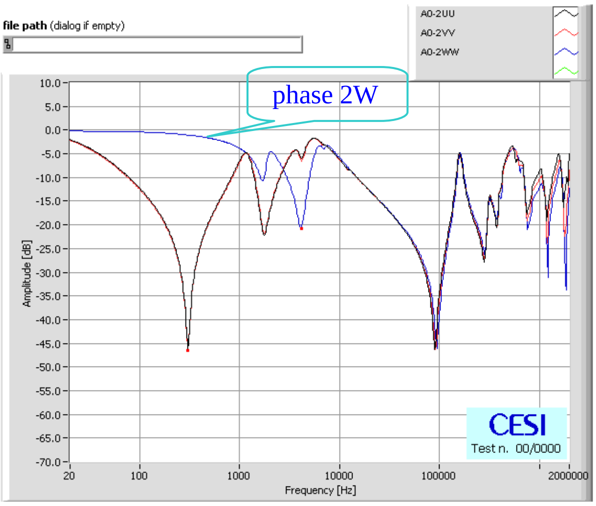


Figure 3: Measurements carried out on the LV windings with the HV winding open and floating

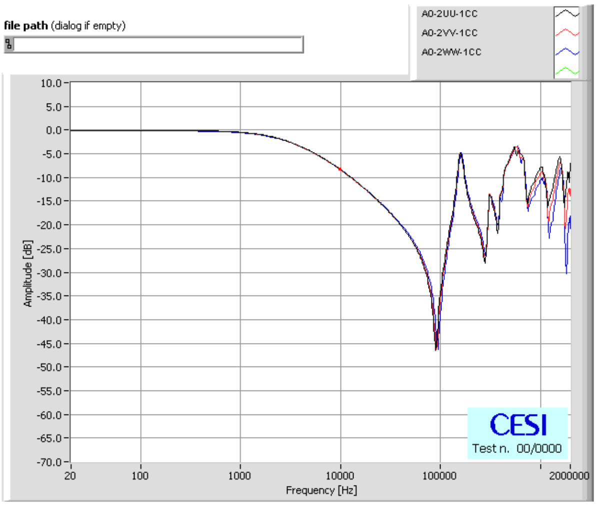


Figure 4: Measurements carried out on the LV windings with the HV winding short-circuited

The opening of the machine, with the visual inspection of the windings has confirmed the hypothesis, as shown in Figure 5: a short-circuit between two coils of the HV winding of the phase W was noticed, with the interruption of part of the HV winding. No mechanical deformation was seen on the windings. The transformer was repaired on site through the replacement of the HV winding of phase W.

Figure 5: Damage to the HV winding of phase W as seen after opening of the machine

5. SFRA results Case 2: single-phase transformer during a short circuit withstand test, 60/30-30 MVA 400/27.5-27.5 kV

A single phase transformer with two secondary windings (LV1 and LV2) positioned on separate columns was subjected to short circuit withstand test and the SFRA method was used, in addition to the leakage inductance measurement to check the effects of the power test. On the low voltage winding LV2, after the last current application, an anomalous behaviour was noticed, confirmed by a variation of 6% in the leakage inductance measurements.

In particular, the following SFRA traces were found testing the low voltage windings LV1 and LV2, shown in Figure 6 and Figure 7 respectively:

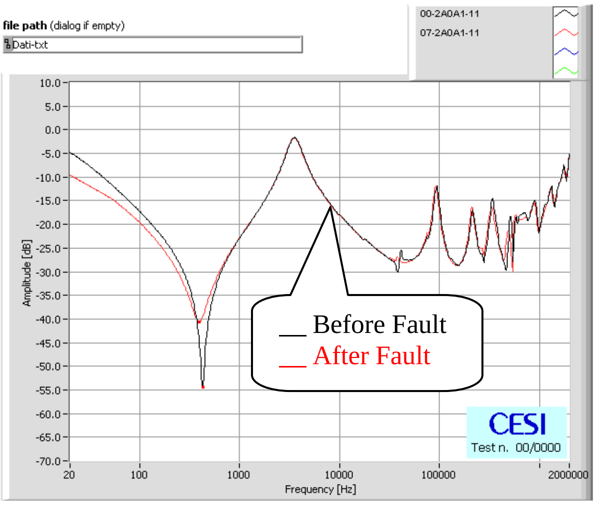


Figure 6: Measurements carried out on the LV winding LV1 with the HV windings open

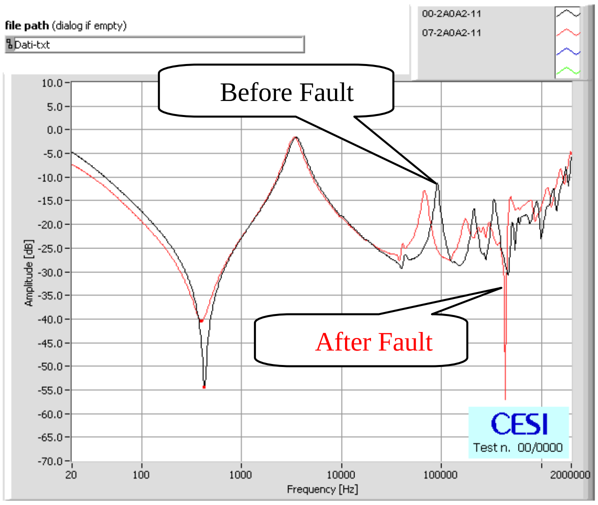


Figure 7: Measurements carried out on the LV winding LV2 with the HV windings open

In particular the figures report the comparison between the initial and the final SFRA measurements on the concerned low voltage windings. The traces of the Figure 7 are shown Figure 8, together with a curve representing the difference calculated of the two responses. Very important variations between the SFRA waveshapes can be seen. The values of the difference, expressed in dB is small (within 5 dB) for frequencies lower that 50 kHz (if we exclude the shifting of the low frequency peak linked with the residual magnetisation). Higher values of difference are noted for frequencies higher that 50 kHz.

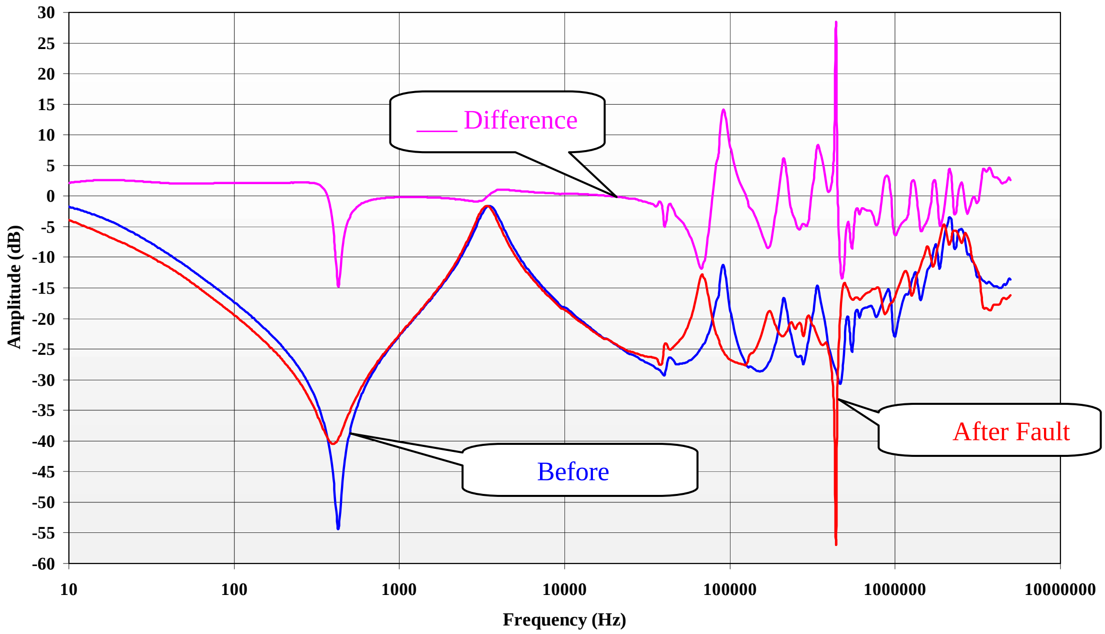


Figure 8: Measurements carried out on the LV winding LV2 with the HV windings open; trace of difference is shown

The indication, given by the difference in the waveshapes shown in Figure 8, is linked with the effects of the electrodynamic stresses of the short circuit current that have generated geometrical variations in the internal structure of the machine which have caused a variation in the capacitive coupling both longitudinal and transversal.

The machine was successively opened for internal inspection and the findings confirmed the hypothesis put forward in the instrumental analysis: a localised deformation was seen on the low voltage winding LV2, linked with a missing axial support on the top end of the coil, causing a longitudinal deformation of the winding LV2, as can be seen in Figure 9. The picture shows the important axial deformation of the low voltage winding LV2, which has generated longitudinal capacitance variations on the entire length of the winding and transversal capacitance variations on the top part of the winding.

Figure 9: Damage to the low voltage winding LV2 as seen after opening of the machine

The experience gained through the extended application of SFRA both in the field and in the laboratory with different types of defects allowed the validation of some of the most important general rules for the interpretation of the SFRA waveshapes and the two cases reported in this paper confirm these rules. The information gained with SFRA are very effective; however, the confirmation of the results must always be looked for with other traditional methods for a sounder condition assessment. The sensitivity of SFRA has been confirmed as very high and the repeatability of the results is such as to allow to visualize also minor defects. The SFRA method is based on a comparison analysis: the availability of a reference path for a given type of construction could also allow to point out construction differences over production lots of machines of the same design. In order to minimize the necessity of an expert interpretation, it is important to set up threshold values to evaluate quantitatively the criticity of deviations in the SFRA waveshapes. At present, on the base of the experience gained, we have observed that variations higher that 5 dB in specific ranges of frequency, could indicate the presence of critical defects in the machine. In such occurrence, further checks, using other more conventional dedicated methods, should be used to confirm the diagnosis and point out the location and the importance of the defect before proceeding to the eventual untanking of the machine.

6. Condition assessment of paper-oil insulation

Diagnostic methods and tools have been set-up to assess the condition of the paper-oil insulation, where the characteristics of the single components are interlinked. The most common methods refer to physical, chemical and chromatographic analysis of oil samples taken from transformers. On the other hand are the so-called "component" test methods, applied on the terminals of the off-line power transformers, which allow to assess the whole oil-paper insulation system and to measure some specific quantities related to its dielectric properties: i.e the capacitance and the loss factor at power frequency or the insulation resistance and the polarisation index in time domain. The measurement of polarisation and depolarisation currents (PDC) is a new, unconventional, simple and direct method, based on linear polarisation phenomena, that allows the "dielectric response function" of the composite oil-paper insulation to be quantified in a wide time domain and all significant parameters of the different parts of the insulation to be evaluated by adequate post processing [3]. The working principle of the PDC method is based on the following effect: when a step-like DC charging voltage U_c is suddenly switched to the sample, previously uncharged, there is a motion of charges, due to the interaction of the electrical field with the free and the different kinds of bound charge within the dielectric. This so-called polarisation current $i_{pol}(t)$ is a pulse-like current at time=0, then decreases during the polarisation time T_c down to a certain value related to the insulation intrinsic conductivity. The polarisation current can be stopped when it becomes stable or very low. If the sample is then suddenly short-circuited, a discharging current $i_{depol}(t)$ (depolarisation current) jumps to a negative value that gradually decreases down to zero. If T_c is large $i_{depol}(t)$ becomes directly proportional to the dielectric response function. The method investigated [4] used a so-called "two active electrodes" technique to measure the polarisation and depolarisation currents. The insulation to be tested must be located between two electrically accessible electrodes forming a capacitor with the insulation as dielectric. One of the electrodes is arbitrarily chosen as "excitation plate" and a test voltage is applied to it, referenced to ground; the second electrode called "sensing plate" is shorted to ground via a micro-ammeter. In this arrangement stray capacitances and insulation properties between the electrodes and ground as well as cable capacitances and cable insulating properties do not interfere with the measurement (see Figure 10).

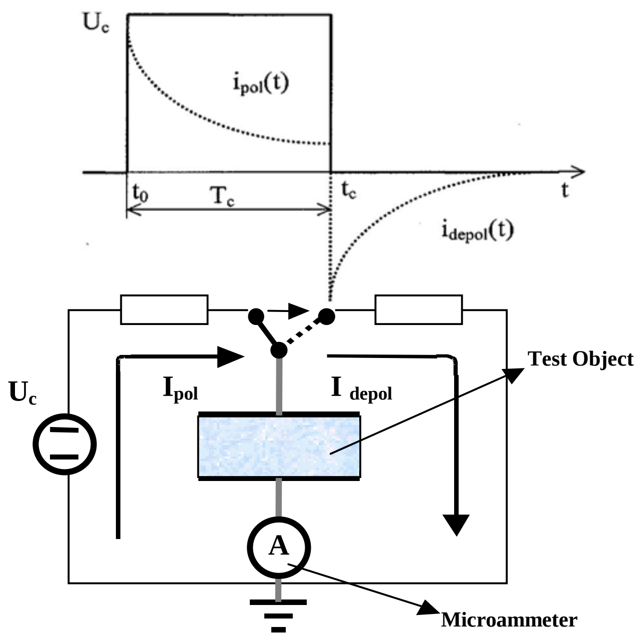


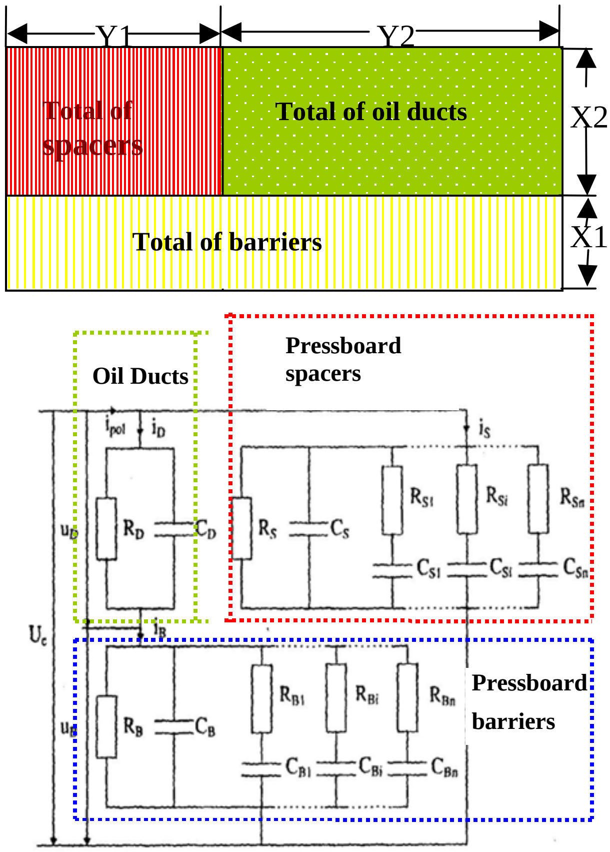
Figure 10: The working principle and test circuit for the measurement of currents $i_{pol}(t)$ e $i_{depol}(t)$

The connection configuration for a power transformer foresees that all the HV bushings and the neutral terminal be connected together: in this configuration, the HV windings behave as the first electrode of the capacitor. All the LV short-circuited bushings constitute the second electrode. The currents are measured between the LV windings and ground and during the measurement the transformer tank must be grounded. This connection allows a selective measurement of the main insulation between LV and HV windings. The influence of the insulation between the windings and the yokes can usually be neglected owing to the fact that the winding axial dimensions are larger than the radial distance between windings. The system can be represented with an equivalent circuit [5] divided into three components, lumping all oil ducts, all barriers and all spacers together, to form one oil duct in series with a single barrier and, in parallel to this, a single spacer. Using the R-C model of a linear dielectric with alternating layers of oil and paper, an extended equivalent circuit for transformer main insulation can be derived, such as that shown in Figure 11. In this circuit, the oil ducts are well simulated by using only their resistance R_D and their capacitance C_D because the oil dielectric dispersion is neglegible at low frequency (≤ 50 Hz). The conductivity and the relative permettivity of the oil and the duct geometric capacitance allow R_D and C_D to be calculated.
The pressboard barrier and the spacer are modelled by:

- their DC resistance R_B and R_S, and their 50 Hz capacitance C_B and C_S trough the conductivity and the relative permettivity of the pressboard and the geometrical capacitances of barriers and spacers;
- a number of *n* parallel arrangements of R-C elements, that represent the polarisation processes and can be calculated from the polarisation and depolarisation currents previously measured on pressboard samples with well set moisture content.

This extended equivalent circuit for transformer and on a lot of laboratory measurements made on pressboard and oil samples [5], allow to distinguish the main influences on PDC currents in transformers oil-barrier systems (see Figure 13):

- oil conductivity, mainly due to the movement of ionic impurities, affects the initial amplitude and exponential shape of the relaxation currents: a higher conductivity leads to a higher current;
- geometry and oil properties affects the transient current variation where the barrier capacitances are charged via oil gap resistances(interfacial polarisation);
- after saturation of the interfacial polarisation the influence of the barriers and spacers becomes visible and affects mainly the shape of the relaxation currents at long times.



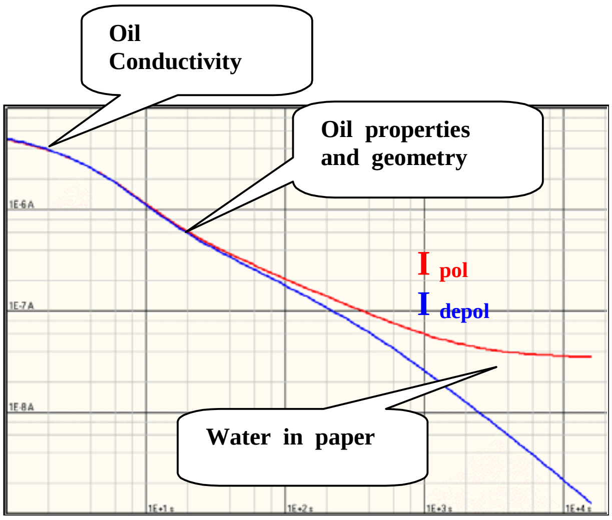


Figure 11: Lumped insulation system and equivalent circuit of the main insulation of a power transformer

Figure 12: Main influences on PDC curves in transformer oil-paper systems

The method used, implemented with an advanced diagnosis software taking into account the circuit of Figure 11 and the experimental results, permitted the PDC analysis and offered a quantitative determination of the moisture content in pressboard and the evaluation of the oil conductivity for power transformer insulation systems, helping to evaluate their ageing conditions. The determination of these quantities is based on a best fit of the measured relaxation currents (see Figure 13), taking into account the geometrical dimensions and composition of the samples considered and with the following steps:

- a research of an oil conductivity value to obtain a good best fit at short time about <100 s
- a research of a moisture content value in pressboard giving a good best fit of measured i_{pol} e i_{depol} curves at long time >1000 s.

With this method it was also possible to calculate the value of the 50 Hz relative permittivity and the DC conductivity of oil and pressboard at 20°C so that a comparison among tests, made at different temperatures on the same transformer, can be made. Moreover the method adopted permitted the calculation of other derived dielectric quantities sush as the polarisation index PI, important for generator and motor insulation diagnosis, the polarisation spectrum PS, the complex capacitance and the dissipation/loss factor.

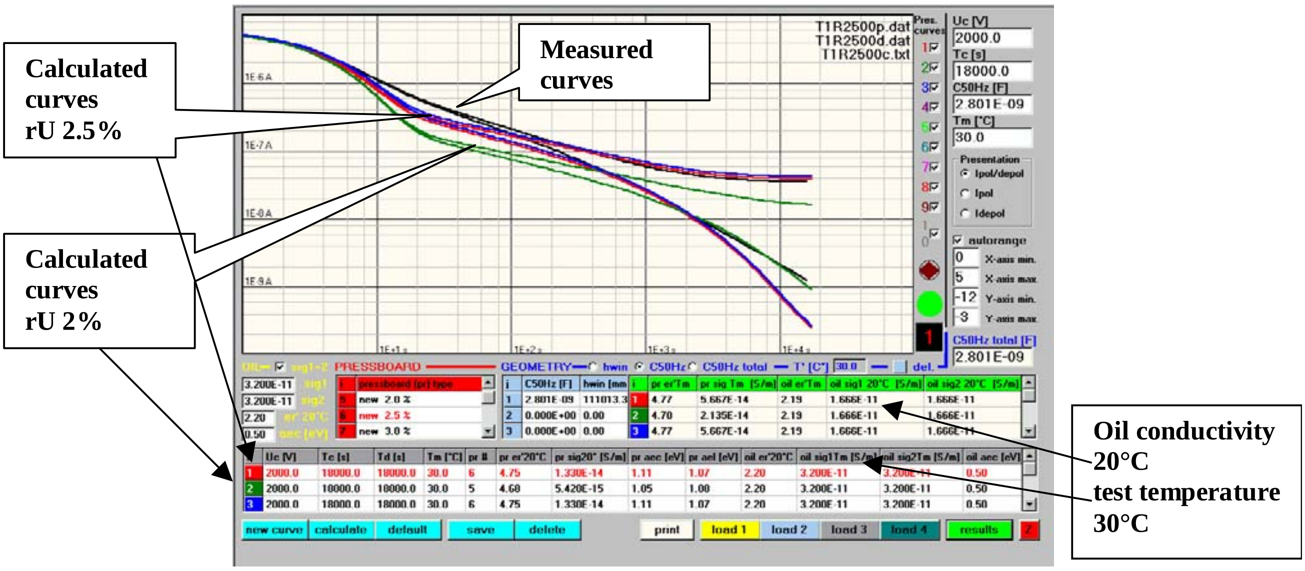


Figure 13: Comparison between measured and calculated relaxation currents as a function of geometrical parameters and moisture content in the pressboard

7. PDC results Case 1: new step-up power transformer 70 MVA, 15/220 kV

A new three phases 70 MVA power transformer, was measured in the factory before its delivery to the customer. The oil temperature was 20°C, the adopted DC charging voltage was 1000V and the polarisation and depolarisation duration was 6000s. The 50 Hz capacitance C_{50Hz} measured during the test was 6440pF. For this transformer the manufacturer supplied all geometrical parameters and the arrangement of the main insulation between HV and LV windings. Figure 14 shows the measured polarisation and depolarisation currents (black curves) in comparison to the calculated currents for moisture contents in pressboard of 1% (green curves), 0.5% (red curves) and 1.5% (blue curves) for the transformer. The measured i_{pol} in the time range >1000s laying between the red and the green calculated curves it can be concluded that the moisture content in the solid insulation of the transformer is in the range 0.5% ÷ 1%. The best fit between measured and calculated currents was obtained with oil conductivity values about 3pS/m. The initial difference between the measured i_{pol} and i_{depol} curves and their shape for t < 2s can be linked with a non complete interfacial polarisation and with non-linear effects caused by the too high excitation voltage level for such a new transformer. The tgδ value is ~0.0001 at 50 Hz and ~0.05 at 0.1Hz and the polarisation index, calculated between 15s and 60s of the polarisation step, is 1.45. The spectrum shows one maximum of ~250V at ~150s, i.e the τ_{pi} value. These results show an insulation in very good conditions such as the insulation of a new transformer.

Figure 14: Comparison between measured and calculated relaxation currents as a function of moisture content in pressboard.

8. PDC results Case 2: n. 2 step-up power transformers 20 MVA, 8.4/130 kV manufactured in 1958

Two three phases 20 MVA step-up transformers (called TR1 and TR2), manufactured in 1958 by the same manufacturer and with the same arrangement, operating in a small hydroelectric power station were tested. These samples were of interest because of their very long service life. The DC charging voltage was 1000V and the polarisation and depolarisation duration was 5000s, the oil temperature was 31°C for TR1 and 5°C for TR2. The 50 Hz capacitance C_{50Hz} measured during the test was 5129pF for TR1 and 4994pF for TR2.

Figure 15 shows the measured polarisation and depolarisation currents (black curves) in comparison to the calculated currents for different moisture contents in pressboard: the red curves and parameters are the best possible calculated curves and values for the best fit. In this case the best fit was made not only on oil conductivity and pressboard moisture content, but also on geometrical arrangement because these data were not available. In these tests the correct excitation voltage was used, but the polarisation and depolarisation duration was not long enough to complete the interfacial polarisation process: this explains the different initial values of the relaxation currents. The analysis gives a pressboard moisture content and an oil conductivity of 3.5% and 12pS/m for TR1 and 4.9% and 16pS/m for TR2. The best comparison between the two transformers can however be made using the values calculated at 20°C. At 20°C TR1 oil conductivity is ~ 6pS/m and TR2 oil conductivity is ~ 47pS/m, pressboard permittivity is 4.96 for TR1 and 5.25 for TR2; TR2 pressboard conductivity is 9 times that of TR1. As any temperature increase shifts the tgδ curve along the x-axis towards higher frequencies with the same shape, the tgδ curves of TR1 and TR2 could be compared at 31°C. Figure 16 shows a decade displacement of TR2 relative maximum: this means a much faster interfacial polarisation due to higher values of oil conductivity and pressboard moisture content in TR2 insulation. The comparison shows a remarkable degradation of both transformer insulation, much higher in TR2. Water content in oil was measured according to CEI 10-13 standard and for both transformers the results was 41 ppm. Taking into account the temperature of the oil drawing (at 25°C and 15°C for TR1 and TR2 respectively), TR2 oil is more degraded than TR1 oil. HPLC analysis of oils gave a 2FAL value of 1.169mg/kg for TR1 and 2.956mg/kg for TR2, so confirming the PDC diagnosis and the presence of cellulose de-polymerisation.

The two examples show that reliable information about the condition of transformer insulation can be obtained from PDC method after an analysis of the measured polarisation and depolarisation currents. Analysis of oil samples gives information about the oil alone. But solid insulation components are very hygroscopic so they can be humid even if the oil is dry or its water content is acceptable. Therefore solid insulation could only be supervised unequivocally by opening the transformer and taking pressboard samples. In most cases this is obviously not possible. Now the non-destructive PDC method [3], [5], [6] can provide the moisture content in solid insulation material and the conductivity of the oil giving a complete diagnosis of paper-oil condition in a power transformer.

Figure 15: Comparison between measured and calculated relaxation currents for TR1 and TR2 transformers

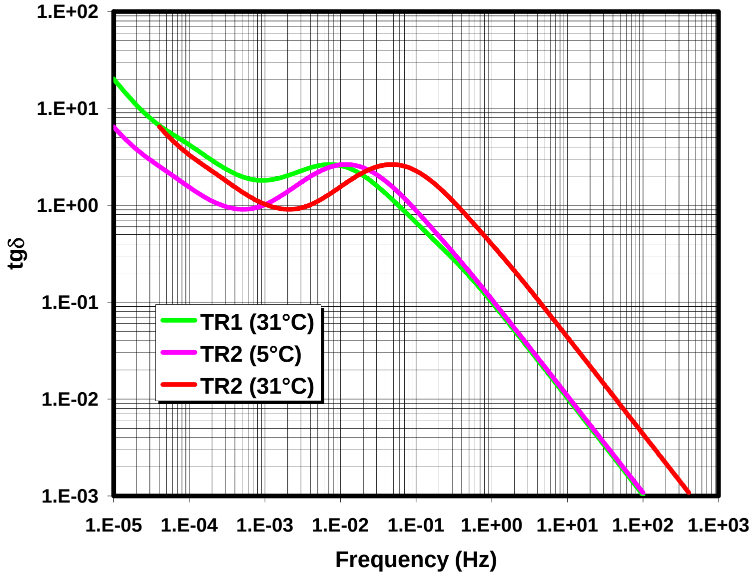


Figure 16: Comparison between tgδ curves for TR1 and TR2 transformers

9. Conclusions

A very intensive activity is being carried out for the validation of innovative diagnostic indicators and condition assessment techniques for power transformers using the modern acquisition and elaboration techniques available. Among the most interesting methods, we have illustrated the use of the SFRA technique to assess the mechanical integrity of power transformers and the PDC method to evaluate the conditions of the paper-oil insulation. Both methods have been validated at the light of numerous cases, among which two are described and discussed for each system in the present paper. The main conclusions which can be drawn from the work carried out are the following:

- Condition assessment techniques are rapidly evolving and new more precise tools are available for the user and the manufacturer; these tools complement effectively the traditional methods and allow an always more precise diagnosis; in any case, being the diagnostics of power transformers a very complex matter, a human expert advise together with the knowledge of the design is fundamental for the interpretation of most critical cases;
- The SFRA method has been validated and the basic rules of interpretation of the waveshapes and of their variation have been confirmed. This type of condition assessment check has been proven to be sensitive, efficient and very reproducible. These features could motivate the use of the method in the thorough verification of a wide transformer population and also to check the uniformity of transformers production lots. The main interpretation rule being by comparison of the waveshapes in different moments of the machine life or on machines having the same design, it is useful to define threshold values for the assessment of the existence of criticities: on the base of the experience gained, we have observed that variations in the SFRA waveshapes higher that 5 dB in specific ranges of frequency, could indicate the presence of critical defects in the machine.
- The PDC method, based on the elaboration of the polarisation response of the paper-oil insulation is an interesting complement to the classical chemical, physical and instrumental checks on power transformers: its capability of evaluating the level of humidity in the paper and pressboards is an outstanding advantage with respect to the mere oil analysis, which shows the eventuality of false-positive results (i.e. situations in which the quantity of water in the oil seem acceptable, while the real moisture in the insulation is excessive for a reliable operation of the machine). Its extensive application to a wide variety of cases would allow to increase the knowledge on which all the interpretation are based.

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