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Insulation Diagnostics on Power Transformers using the Polarisation and Depolarisation Current (PDC) Analysis

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Abstract: **A lot of power transformers currently in operation have been installed in the 60's and 70's. Now, they might have reached a critical age with an operating time of 30 years and more. Utilities have to make a decision either continuing to use these transformers or replacing them. As a basis for this decision information about the condition of the currently operating power transformers is required. Ageing processes are caused by dielectric, chemical, thermal and electrodynamic stresses. They are of very complex nature. As an example Water in the solid insulation material acts as a catalyst and enforces the ageing processes. Due to variable load there is a complex temperature dependent moisture dynamic behaviour of the oil paper insulation system.**

Well-known methods like Karl-Fischer-Titration and dew point measurement cannot be applied on transformers in operation since it is risky and difficult to open the transformer for getting a material sample. Recently, new methods of dielectric spectroscopy have been developed to overcome this implication. The PDC-Analysis (*P*olarisation and *D*epolarisation *C*urrent Analysis) is a non-destructive method for determining the moisture content in the solid insulation material of a power transformer. On the basis of this reliable analysis one can decide about further actions like an on-site drying of the active part.

This paper presents the PDC technique and results of measurements on new and aged transformers.

1. INTRODUCTION

The globalisation of the energy market results in an increasing cost consciousness of utilities and other electrical power equipment operators. Power transformers are among the most expensive parts of a power network. Therefore, utilities try to postpone replacement investments for those equipment and even try to cutback maintenance costs. On the other hand, numerous transformers have reached a considerable age well beyond 30 years. Further operation means an increasing risk of an outage. A damage of a transformers means not only costs for replacement but also considerable extra costs for lost sales of energy and environmental damages.

Ageing of the oil paper insulation system of power transformers is determined by various mechanisms. Moisture stored in the solid insulation material acts as a catalyst for the ageing process and encourages cracking of the cellulose molecules of which pressboard exists. This process is called depolymerization and can be expressed by the so-called depolymerization degree (DP). Depolymerization results in a reduced mechanical strength of the insulation system and the transformer becomes more vulnerable to mechanical stresses, as e. g. caused by a short circuit in the power network nearby the transformer. Beside this, the break down voltage of the insulating oil is reduced with increasing moisture content in the oil. Thus, knowledge about the water content in the solid insulation material is an important basis for the decision about any further action like e. g. on-site drying of the active part.

Until now, the PDC-Analysis and FDS (**F**requency **D**omain **S**pectroscopy) are the only reliable non-destructive methods for determining the moisture content on the solid insulation material like paper and pressboard [1]. For PDC-Analysis a DC voltage step (amplitude U_0) of some 100 V is applied between HV and LV windings during a certain time T_P, the so-called polarisation duration. Thus, a charging current of the transformer capacitance, i.e. insulation system, the so-called polarisation current, flows. It is a pulse-like current during the instant of voltage application which decreases during the polarisation duration to a certain value given by the conductivity of the insulation system. After elapsing the polarisation duration T_P, the switch S goes into the other position and the dielectric is short circuited via the ammeter. Thus, a discharging current jumps to a negative value, which goes gradually towards zero. Both kinds of currents ("relaxation currents") are stored in the PDC Analyser.

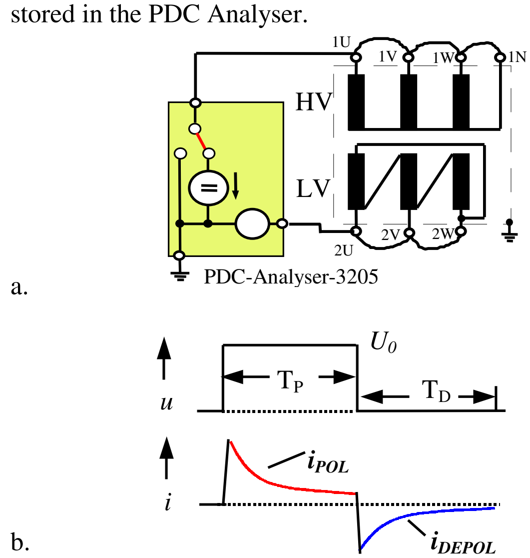

Fig. 1 a. Measurement of the relaxation currents using the Siemens measuring system *PDC-Analyser-3205 [4]*
b. Principle waveform of relaxation currents

Then, a model for the transformer's main insulation system which describes its dielectric behaviour is parameterised. All parameters of this model can now be simulated and further determined using already measured characteristics of pressboard material samples with a 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 oil conductivity. Together with other diagnostic tools a reliable ageing assessment can thus be realised [2].

2. BASICS OF PDC ANALYSIS

According to the linear dielectric theory the model shown in **Fig. 2a/b** can be derived for describing a dielectric's behaviour by an arbitrary dielectric response function $f(t)$ in time domain or polarisation characteristic $\chi(\omega)$ and conductivity σ in frequency domain [1].

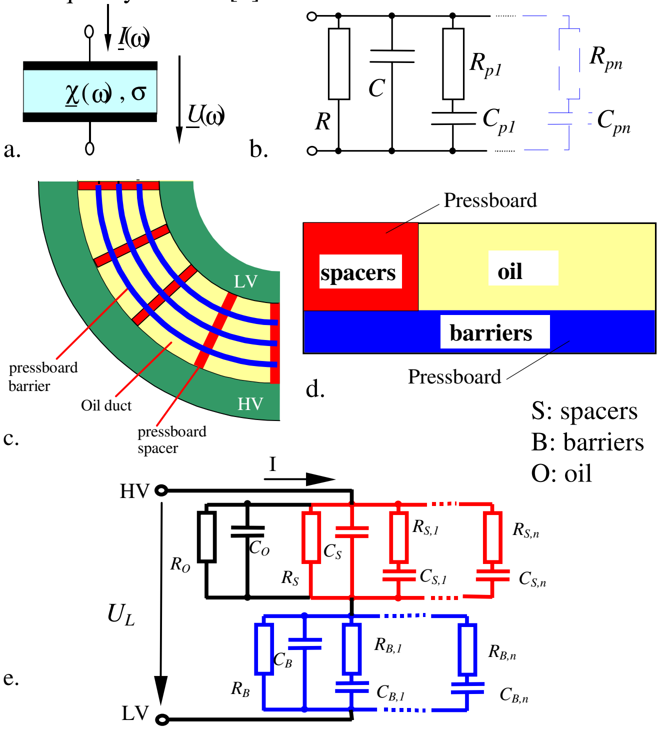

Fig. 2 a. Plate condenser as a model for dielectric arrangements
b. Model for the behaviour of a dielectric with arbitrary polarisation characteristic and conductivity
c. Part of the cross-section of a power transformer main insulation system between HV and LV windings
d. Simplified geometry model for the main components oil, barriers and spacers
e. Dielectric model for the insulation system of power transformers

Fig. 2c shows the principal arrangement of barriers, spacers and oil ducts in the main insulation system of power transformers. For modelling, this arrangement can be simplified (**Fig. 2d**). Using the R-C-model of an arbitrary dielectric as shown in **Fig. 2b**, the model for the dielectric behaviour of a complete transformer can be derived (**Fig. 2e**). It consists of a first R-C-circuit modelling the oil (indices "O") in parallel to a second circuit modelling the spacers (indices "S"), and a third circuit modelling the barriers (indices "B") in series to the above mentioned parts one and two. The dispersion of oil for meauring times above 1 s can be neglected. Thus, oil can be well simulated by 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 which results from the oil conductivity σ_{Oil}. The values of the elements describing barriers (C_B, R_B, C_{Bi}, R_{Bi}) and spacers (C_S, R_S, C_{Si}, R_{Si}) in **Fig. 2e** can be calculated from relaxation current measurements on pressboard samples with well set moisture content by taking into account the geometrical capacitance of barriers and spacers. The measuring apparatus PDC-Analyser-3205 [4] includes an evaluation software permitting precisely this parameterisation of the values of the model **Fig. 2e** by making use of laboratory sample information coming with the software.

3. INTERPRETATION OF PDC MEASUREMENTS

Fig. 3 shows the effects of oil conductivity and moisture content in the solid insulation material on the polarisation current. For typical measuring conditions the conductivity of the oil affects the polarisation current mainly in a time range t < 100 s. A higher oil conductivity leads to a higher current. Water in the solid insulation affects its polarisation characteristic mainly in the time range t > 1000 s as it is clearly visible by an increasing difference of the relaxation currents in this time range. This characteristic of oil-paper insulation systems allows to separate the effects of oil quality and moisture content in the solid insulation on the relaxation currents from each other. **Fig. 3b** shows the measured polarisation current in comparison to the calculated currents for moisture contents of 0.5 % and 1.0 % for a newly manufactured 392 MVA power transformer. The measured polarisation current in the time range t > 1000 s is in between the calculated currents for moisture contents of 0.5 % and 1.0 %. Thus, it can be concluded that the moisture content in the solid insulation material of this transformer is well below 1.0 %. The oil conductivity giving the best fit between measured and simulated current is $0.3 \cdot 10^{-12}$ 1/Ωm. The moisture content of newly manufactured transformers is determined in the Nuremberg power transformer factory as a routine quality check directly after the dry-and-treatment process by the Karl-Fischer-Titration. For the 392 MVA transformer, the result was 0.61 %. Also as a routine procedure the moisture content of the insulation system is determined by the dew point temperature of the nitrogen filling directly after making the transformer ready for shipment. The value for the 392 MVA transformer was 0.45 %. Obviously, there is a good match between PDC analysis and other moisture determination methods.

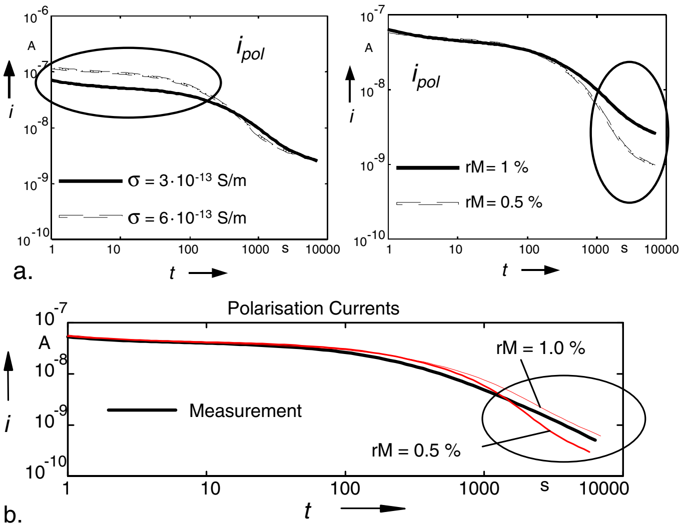

Fig. 3 a. Effect of oil conductivity and moisture content in the solid insulation material on the polarisation current (i_{pol})
b. PDC analysis of a 392 MVA transformer

4. COMPARISON OF PDC WITH OTHER METHODS

In our factory comparisons between the PDC results and results from Karl-Fischer-Titration and dew-point measurement have been carried out on numerous transformers. PDC measurements on transformers with different ratings and designs show a good match between the results of Karl-Fischer and dew-point measurement (**Fig. 4**). This proves the applicability and reliability of the PDC method for "determining" moisture in the solid insulation material of power transformers.

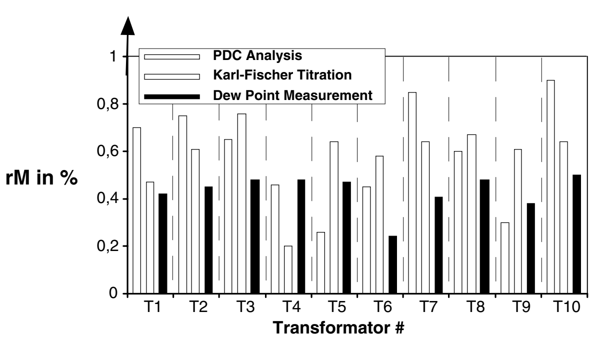

Fig. 4 Comparison of the PDC analysis with other methods for moisture content determination in the solid insulation material of new power transformers

5. ON-SITE PDC MEASUREMENTS

In this chapter the results of PDC measurements on a 40 MVA, 110 kV transformer manufactured in 1961 and on a 350 MVA, 400 kV transformer built in 1976 will be discussed. **Fig. 5a** shows the measured and calculated polarisation currents for the 40 MVA transformer. The "best fit" in a time range t > 1000s of measured and calculated currents provides a moisture content of rM = 2.5 % as the result of the PDC analysis. In the case of the 350 MVA interconnecting transformer the insulation system between HV and MV as well as that between MV and LV can be analysed (**Fig. 5b and 5c**). The PDC analysis shows results with rM = 2 % for HV-MV and rM = 2,5 % for MV-LV very close to each other. The difference of about 0.5 % might be occurred due to temperature and moisture gradients inside the transformer during the measuring period. In conclusion, the moisture content of both transformers is around 2.5 %. According to values published from authors all over the world these values are normal for transformers with an age of about 30 years and do not indicate excessive ageing processes of these transformers.

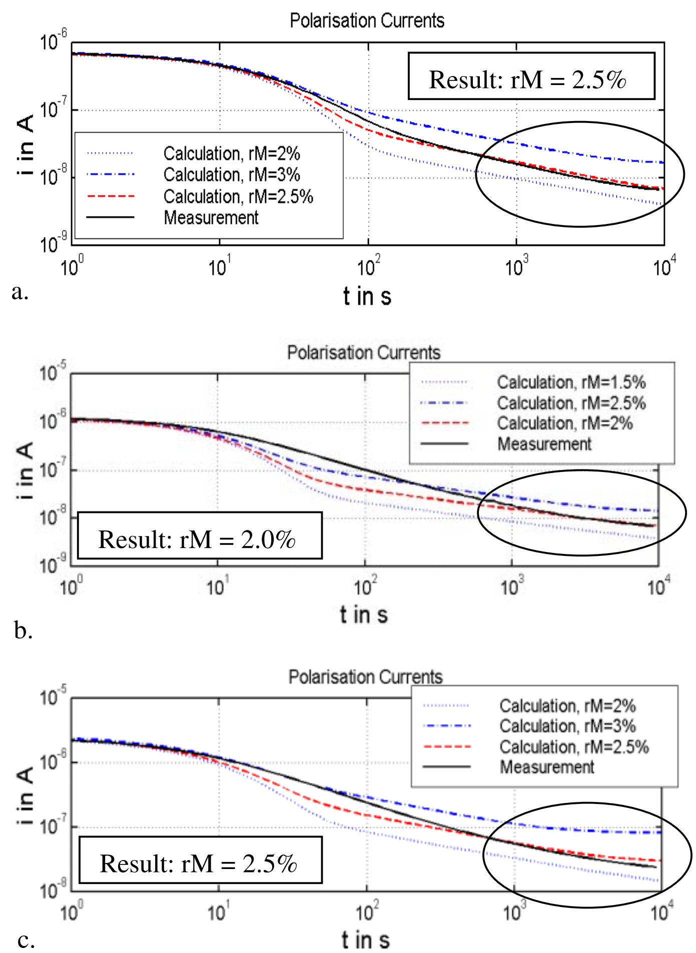

Fig. 5 PDC evaluation of a
a. 40 MVA transformer, manufactured in 1961, HV-LV, rM = 2.5 %
and a 350 MVA transformer, manufactured in 1976
b. HV-MV, rM = 2 %
c. MV-LV, rM = 2.5%

Although the PDC analysis needs basically no support from other transformer diagnostics methods it is reasonable to evaluate the gas-in-oil analysis (DGA) and compare it with PDC results. Some DGA results are given in **Table 1**. The oil conductivity of the 350 MVA transformer is with about $9 \cdot 10^{-12}$ 1/Ωm higher than that of the 40 MVA transformer ($6 \cdot 10^{-12}$ 1/Ωm). This indicates a slightly higher degradation of the oil inside the 350 MVA transformer.

In the literature equilibrium curves showing the relationship between moisture in oil and moisture in the solid insulation material can be found [3] as sketched in **Fig. 6**. However, these curves are only valid if the moisture distribution inside the transformer is in a complete equilibrium condition which is strongly dependent on temperature. Since the time constant of moisture migration from oil to solid insulation and vice versa is known to be also dependent on temperature and in the range of several days or even weeks, a transformer in operation is almost never in such an equilibrium condition. Thus, in practice the application of the equilibrium curves leads with high probability to inaccurate results for the moisture content in the solid insulation material.

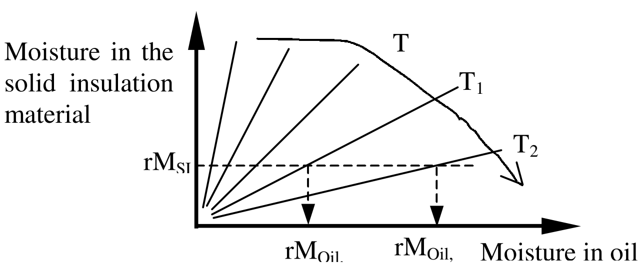

Fig. 6 Equilibrium curves between moisture in oil and moisture in the solid insulation material with the oil temperature T as a parameter

However, the equilibrium curves can be used for qualitative considerations. According to **Fig. 6** a certain moisture content in the solid insulation material of rM_{SI} results in an moisture-in-oil content of $rM_{Oil,\,1}$ at an oil temperature of T_1 and in an moisture-in-oil content of $rM_{Oil,\,2}$ at an oil temperature of T_2, with $rM_{Oil,\,2} > rM_{Oil,\,1}$ and $T_2 > T_1$.

Transformer	40 MVA	350 MVA	
Quantity	HV – LV	HV – MV	MV - LV
Relative Moisture rM in % (PDC)	≈ 2.5	≈ 2.0	≈ 2.5
Oil conductivity σ_{Oil} in 1/Ωm (PDC)	$6.0 \cdot 10^{-12}$	$9.0 \cdot 10^{-12}$	$9.8 \cdot 10^{-12}$
mg H_20 per kg oil in ppm	6 at T_O=36°C	11 at T_O=48°C	

Table 1: Results of PDC and oil sample analysis of the 40 MVA and the 350 MVA transformer (T_o = operating temperature)

The moisture content in the solid insulation material of both transformers is almost the same (about 2.5 %). For the 350 MVA transformer a moisture in oil content of 11 ppm at 48 °C has been obtained (**Table 1**). This corresponds according to **Fig. 6** to a moisture in oil content less than 11 ppm below an oil temperature of 48 °C. In fact, the measured moisture in oil content of the 40 MVA transformer is 6 ppm at 36 °C. This supports the PDC result of a roughly identical moisture content in the solid insulation of the two transformers.

6. CONCLUSIONS

The PDC analysis is a non-destructive method which provides reliable information about the range of moisture content in the solid insulation material of power transformers. Apart of this, the PDC analysis can be applied for investigating the quality of other HV apparatus like capacitors, cables and machine winings.

Investigating numerous transformers of different designs, voltage levels and ratings in the Nuremberg transformer factory it could be shown that there is a good correlation between the PDC results and the results of Karl-Fischer titration and dew point measurement.

Furthermore, a good correlation between oil sample analysis and PDC results has been obtained analysing transformers being in service for about 30 years.

7. References

[1] Alff, J.-J.; Der Houhanessian, V.; Zaengl, W. S. and Kachler, A. J.: "A Novel, Compact Instrument for the Measurement and Evaluation of Relaxation Currents Conceived for On-Site Diagnosis of Electric Power Apparatus". 2000 IEEE International Symposium on Electrical Insulation, Anaheim, USA, April 2-5, 2000, pp. 161-167.

[2] A. J. Kachler, "One-Site Diagnosis of Power and Special Transformers", Conference Record of the 2000 IEEE International Symposium on Electrical Insulation, IEEE Publication 00CH37075, pp.362-367.

[3] Du, Y.; Zahn, M.; Lesieutre, B.C.; Mamishev, A.V.; Lindgren, S.R.: Moisture equilibrium in tranformer oil paper systems, IEE Electrical Insulation, Vol. 15, No.1, January/Febuary 1999.

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