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Ageing and Moisture Analysis of Power Transformer Insulation Systems

by

T. Leibfried and A. J. Kachler*
Siemens AG
Nürnberg, Germany

W. S. Zaengl
Prof. em., ETH Zurich
Zurich, Switzerland

V. Der Houhanessian
ALFF Engineering
Hausen am Albis, Switzerland

A. Küchler
FH Würzburg-Schweinfurt
Schweinfurt, Germany

B. Breitenbauch
E.ON AG
Bamberg, Germany

(Germany)

ABSTRACT

Deregulation and strong international competition are forcing utilities throughout the world to cut back drastically the electric energy generation and transmission costs. Well established time-based maintenance by experienced maintenance staff as well as conservative replacement planning are being sacrificed now. Condition based maintenance by hired staff and online monitoring as an early warning system are gaining importance in insulation ageing assessment of power transformers in service. Insulation ageing is a four dimensional problem due to dielectric, chemical, thermal and electromechanic stresses, which are highly depending on operational conditions. All these ageing processes lead to the formation of water molecules. Therefore, water plays a key role for the ageing of oil paper insulation systems since water acts as a catalyst for the ageing process.

Due to the complex nature of moisture migration a multitude of different analytical diagnostic procedures is required [1]. To date ageing and moisture can only be reliably detected by paper sample shaving at critical locations (leads, outer winding) and analysing these samples in the laboratory by Karl-Fischer titration and determination of degree of polymerisation. This paper presents the **P**olarisation and **D**epolarisation **C**urrent analysis (PDC analysis) as an excellent and non-destructive method for determination of the moisture content in the solid insulation material of power transformers. On the basis of this reliable information one can decide about further actions like on-site drying of the active part of a power transformer.

KEYWORDS

Power Transformer, **P**olarisation and **D**epolarisation **C**urrent (PDC) Analysis, Moisture in solid insulation material

1. INTRODUCTION

Numerous transformers which are currently in service have been installed 30 or even more years ago. They might be close to their end of life. Today, utilities and other electrical power equipment operators are under pressure to reduce costs for maintenance and replacement. On the other hand there are industries which require a high level of energy supply quality and availability. In addition environmental aspects such as consequential damages, fire, pollution are of high risk. These are the main reasons why insulation diagnostics on power transformers is an important part of a modern power equipment maintenance strategy.

Ageing of the oil paper insulation system of power transformers is determined by various stresses, namely dielectric, thermal and electromechanical and chemical stresses. Dielectric and thermal stresses lead to degradation processes of oil and cellulose. Cellulose consists of molecule chains which are characterized by their degree of Depolymerisation (DP). For new cellulose the DP value is about 1100. The molecule length of degraded cellulose is reduced to a DP value of about 200. In this condition cellulose is brittle and the durability against mechanical stresses is strongly reduced.

This cracking process of cellulose molecule chains produces water in the solid insualtion which acts as a catalyst. Further, the breakdown voltage of the insulating oil is reduced with increasing moisture content in the oil. Thus, knowledge about the water content both in the oil and 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.

The PDC-Analysis is a non-destructive method for determining the moisture content in the solid insulation material like paper and pressboard [2, 4]. A DC voltage

* Siemens AG, Transformatorenwerk Nürnberg, Katzwanger Strasse 150, 90461 Nürnberg, Germany

step of some 100 V is applied between HV and LV windings during a certain time T_P, the so-called polarisation duration (**Fig. 1**). 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 DC 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, 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 Analyser-3205 [2, 3].

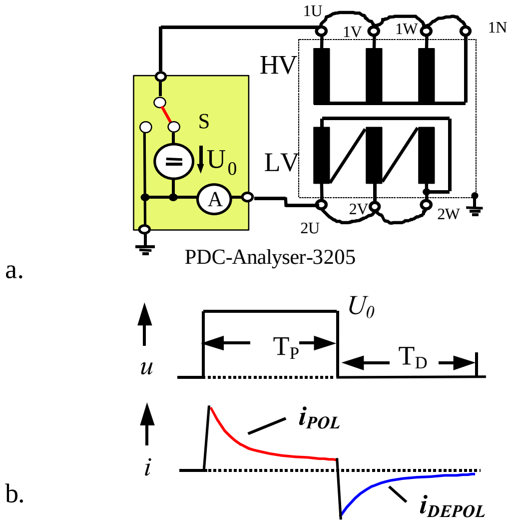

Fig. 1 a. Measurement of the relaxation currents using the Siemens measuring system PDC-Analyser-3205 [3]
b. Principle waveform of relaxation currents

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 the oil conductivity. Together with other diagnostic tools a reliable ageing assessment can thus be realised [1].

2. BASICS OF PDC ANALYSIS

According to the linear dielectric theory the lumped model shown in **Fig. 2b** can be derived to describe a dielectric's behaviour by the dielectric response function $f(t)$ in time domain or polarisation characteristic $\chi(\omega)$ and conductivity σ in the frequency domain [4, 6]. **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 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.

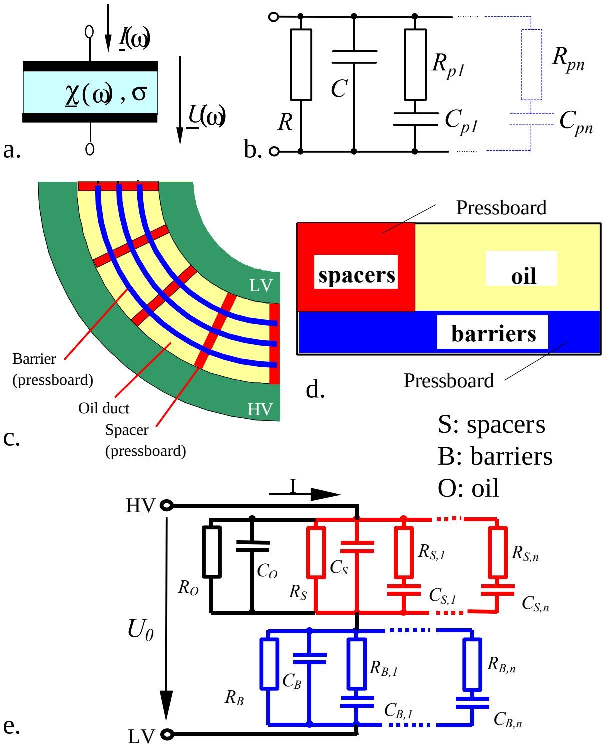

Fig. 2 a. Plate capacitor as a model for dielectric arrangements
b. Model for the behaviour of a dielectric with arbitrary polarisation characteristic and conductivity
c. Part of the cross-section of a power transformer main insulation system between HV and LV windings
d. Simplified geometry model for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

The values of the elements describing the 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 [2, 3] 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. 3a shows the effects of oil conductivity (at left) and moisture content in the solid insulation material (at right) 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.

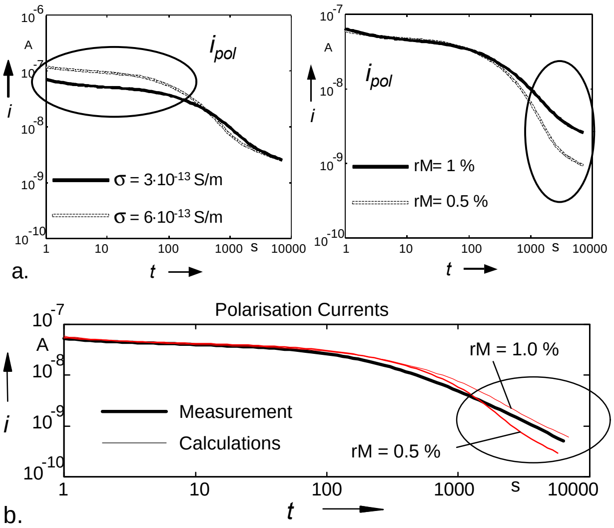

Fig. 3 a. Effect of oil conductivity and moisture content in the solid insulation material on the polarisation current (i_{pol})
b. PDC analysis of a 392 MVA transformer

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. In the time range t > 1000 s the measured polarisation current 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 measurement 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.

4. COMPARISON OF PDC ANALYSIS WITH OTHER METHODS

In Siemens transformer factory in Nuremberg 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. 4**). This proves the applicability and reliability of the PDC method for determining moisture in the solid insulation material of power transformers.

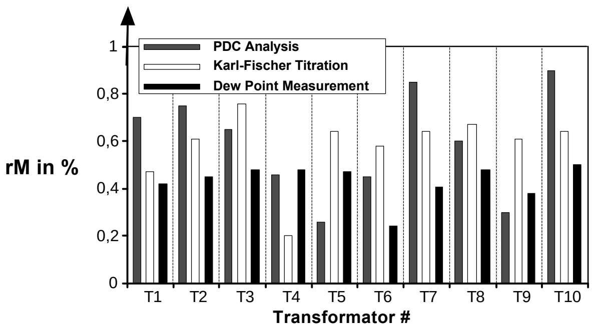

Fig. 4 Comparison of the PDC analysis with other methods for moisture content determination in the solid insulation material of new power transformers

5. PDC MEASUREMENTS ON POWER TRANSFORMERS IN SERVICE

5.1 Measurements on a 40 MVA and a 350 MVA power transformer

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 which are very close to each other: rM = 2 % for HV-MV and rM ≤ 2.5 % for MV-LV. The difference of about 0.5 % might result from temperature and moisture gradients inside the transformer during the measuring period. In conclusion, the moisture content of both transformers is round about 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.

The PDC analysis provides also the conductivity of the oil (**Table 1**). The higher oil conductivity of about $9{\cdot}10^{-12}$ 1/Ωm for the 350 MVA transformer than that of the 40 MVA transformer ($6{\cdot}10^{-12}$ 1/Ωm) indicates a slightly higher degradation of the oil inside the 350 MVA transformer.

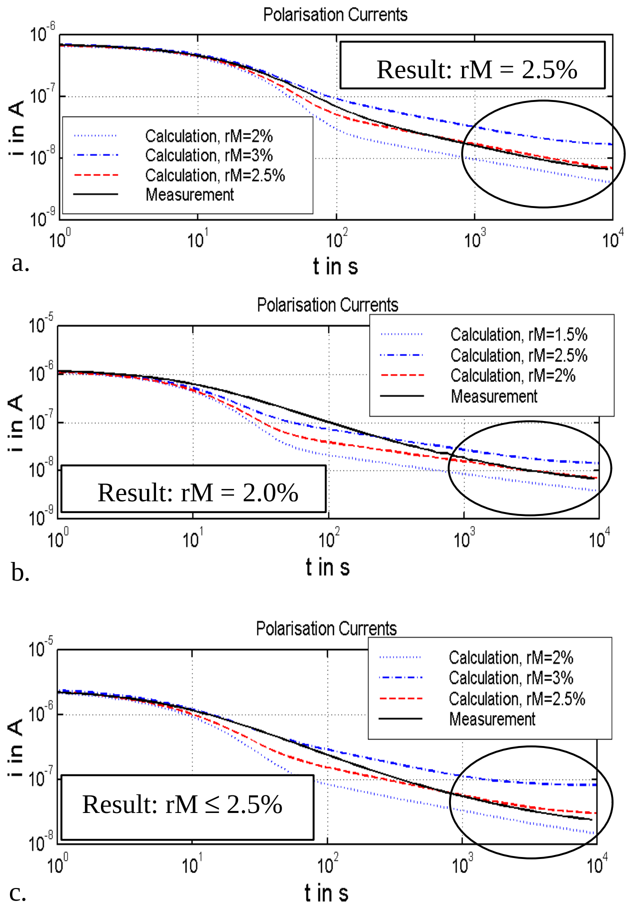

Fig. 5 PDC evaluation of a

a. 40 MVA transformer, manufactured in 1961, HV-LV, rM = 2.5 %

and a

b. 350 MVA transformer, manufactured in 1976, HV-MV, rM = 2 %

c. the same 350 MVA transformer, MV-LV, rM ≤ 2.5%

In the literature equilibrium curves showing the relationship between moisture in oil and moisture in the solid insulation material can be found [5] 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. As 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.

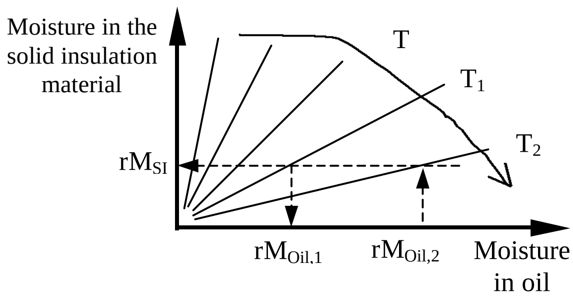

Fig. 6 Principal Equilibrium curves between moisture in oil and moisture in the solid insulation material with the oil temperature T as a parameter

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 a moisture in oil content of $rM_{Oil,1}$ at an oil temperature of T_1 and in a 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 / Quantity	40 MVA HV – LV	350 MVA HV – MV	350 MVA 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 = oil 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 ($rM_{Oil,2}$) at an oil temperature of 48 °C (T_2) 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.

5.2 Measurements on 300 MVA power transformer

The oil of a 300 MVA transformer manufactured in 1978 was found sludged after 23 years of uninterrupted operation. Therefore, the utility decided to exchange the oil. Prior and after the oil change diagnostic measurements namely PDC, RVM as well as tan δ at 0.1 Hz with a transportable on-site measuring system, have been carried out. **Table 2** gives a summary of the results. Furthermore, a paper sample was shaved at a lead of a tap winding. The degree of depolymerisation is DP = 352, which indicates a normal thermal ageing of the paper.

Measurements	Prior to oil change	After oil change
tan δ at 0.1 Hz, directly measured	0.894	0.1867
tan δ at 0.1 Hz, from PDC analysis	0.901	0.191
conductivity σ_{oil} of the oil, from PDC analysis in 1/Ωm	$\approx 4.5 \cdot 10^{-11}$	$\approx 3.5 \cdot 10^{-12}$
Moisture in the solid insulation material, from PDC analysis	3 %	2.7 %
Moisture in the solid insulation material, from RVM measurements	3.45 %	2.48 %
Polarisation index, R_{60}/R_{15}	3.16	2.11
Depolymerization degree	352	

Table 2 Results of diagnostic measurements of the 300 MVA transformer carried out prior and after the oil exchange

The PDC analysis provides some information in form of so-called “fingerprints” or „initial state characteristics“. These “fingerprints” are tan δ in a frequency range from about 10 Hz down to 10^{-5} Hz, the oil conductivity σ_{oil}, the polarisation spectrum and polarisation indexes, e. g. R_{60}/R_{15}. **Fig. 7a/b** shows a comparison of the polarisation currents measured prior and after the oil change as well as the tan δ calculated from these currents. The currents show differences in the whole time range. However, the differences are more significant for short measurement times. This indicates a much lower conductivity of the new oil, in fact the conductivity σ_{oil} is reduced by about one decade as shown in **Table 2**. Furthermore, the tan δ value is drastically reduced after the oil change. The comparison of the tan δ values obtained by the transportable measuring system and the results from the PDC analysis shows almost the same values. However, the determination of tan δ using the PDC method is much easier and has the advantage to get tan δ over a wide frequency range.

Fig. 7c/d shows the PDC analysis of measurements taken prior and after the oil exchange. The results are with rM = 3 % before the oil change and rM = 2.7 % after the oil change very close to each other. Due to the low moisture absorption capability of oil, it is not possible to decrease significantly the moisture in the solid insulation by exchanging the oil of a transformer. Assuming a weight of the solid insulation of 10000 kg and a moisture content of 3 %, we have a total water content of 300 kg. Assuming further an oil weight of 50000 kg and a water in oil content of 30 ppm, which is a high value, we get a water mass of only 1.5 kg stored in the oil. Thus, the water content in the transformer prior and after the oil exchange remains almost the same. These reflections confirm once more that moisture in a transformer can not be extracted by exchanging the oil. In other words: Drying of the oil during a short period is not an appropriate method for drying the active part of transformers.

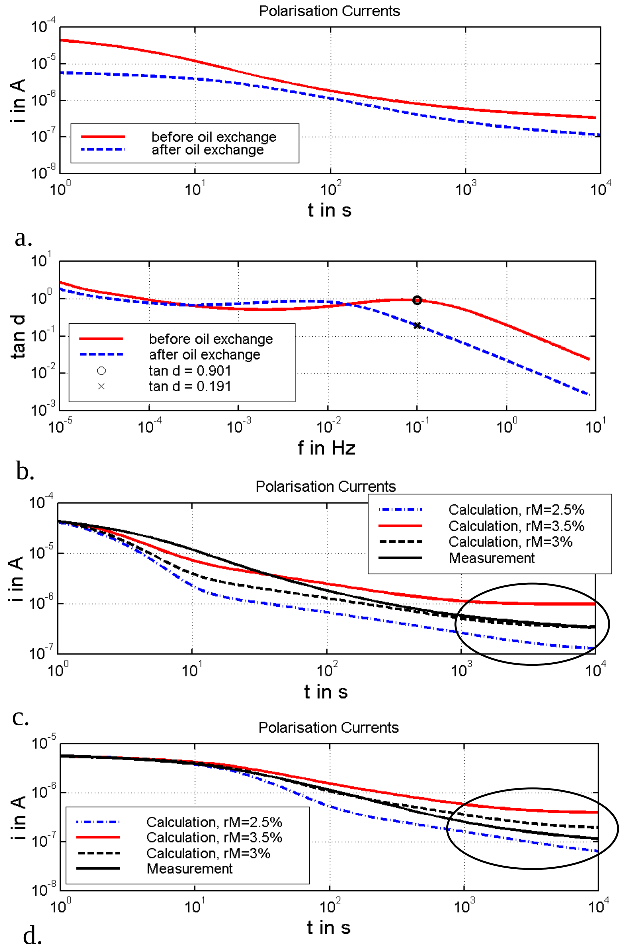

Fig. 7 PDC measurements on a 300 MVA transformer, measured with the PDC-Analyser-3205
a. Polarisation currents measured prior and after the oil change
b. tan δ calculated from measured polarisation currents
Measured and calculated polarisation currents for rM = 2.5 %, rM = 3 % and rM = 3.5 %
c. prior to the oil change
d. after the oil change

Prior to the oil exchange the polarisation index R_{60}/R_{15} is 3.16, which is higher than the value after the oil exchange, which is 2.11. This reduction can be well explained by the shape of polarisation currents before and after the oil exchange (**Fig. 7a**). The difference of the polarisation currents prior and after the oil change decreases continuously in a time range up to 100 s.

Thus, the increase of R_{15} measured before and after the oil change is higher than for the R_{60} values and thus the quotient R_{60}/R_{15} from current measurements after the oil change decreases. Obviously, the polarisation index R_{60}/R_{15} is not only affected by the moisture in the solid insulation but also by the oil conductivity (oil quality) to a certain degree. Therefore, the polarisation index is not a good indicator for the state of the solid insulation.

The polarisation spectrum can also be determined by RVM (Recovery Voltage Measurement). A DC voltage is applied to the dielectric during a certain charging time T_C. After elapsing a period of $0.5 \cdot T_C$ during which the dielectric is short circuited the so-called recovery voltage is measured for such a cycle. The polarisation spectrum is the maximum recovery voltage over the charging time T_C for charging periods from e. g. $T_C = 1$ s up to $T_C = 10000$ s. The same polarisation spectrum can be derived from polarisation and depolarisation current measurements using the R-C model (**Fig. 1f**) for the entire transformer. **Fig. 8** shows the polarisation spectra determined by the RVM method and those calculated from PDC measurements before and after the oil exchange.

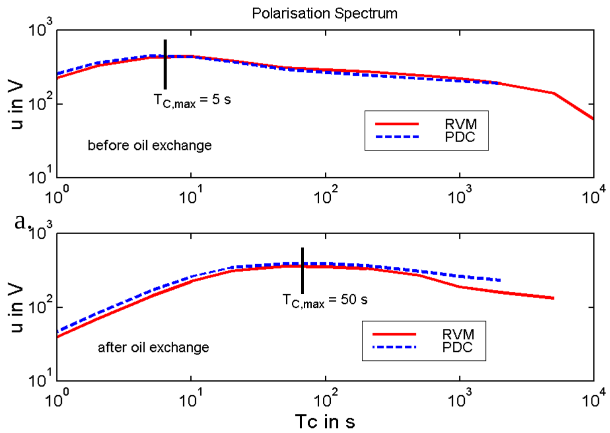

Fig. 8 Polarisation spectra determined by PDC analysis and recovery voltage measurement (RVM) from measurements
a. prior to the oil exchange
b. after the oil exchange

The polarisation spectra determined by PDC analysis and the RVM method are fairly identical. The maximum values occur at $T_{C,max} = 5$ s for the polarisation spectra from measurements prior to the oil change and at $T_{C,max} = 50$ s from measurements after the oil change. This is one more prove that the shift of the polarisation spectrum is not due to different moisture contents in the solid insulation but due to a difference in oil quality (conductivity). From RVM interpretation of the polarisation spectra (based on the position of their maxima) results a big difference of the moisture content in the solid insulation before and after the oil exchange of about 1 % (**Table 2**). The reflection on water content in oil and in solid insulation mentioned above shows that such a big difference is impossible. Obviously, the improved oil quality has a major impact on the results provided by the RVM method. This outcome is in agreement with the recent investigations of CIGRE TF 15.01.01 [6].

6. CONCLUSION

The PDC measuring and analysis system is a non-destructive method which provides reliable information about the condition of a transformer's insulation system, namely the moisture content in the solid insulation material and the conductivity of the oil as well as other quantities like tan δ, polarisation index and polarisation spectra.

Investigations of numerous transformers in new and aged status of different designs, voltage levels and ratings show a good correlation between the PDC results, the results of Karl-Fischer titration and dew point measurements.

Therefore, it may be concluded that the PDC analysis provides a valuable tool to assess the status of power transformer insulation systems.

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