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 is 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 dependent on operational conditions. All these ageing processes lead to the formation of water molecules. Therefore, water plays a key role for the ageing of the oil and 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 depolymerisation. This paper presents the Polarisation and Depolarisation Current 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.

INTRODUCTION

Numerous transformers, which are currently in service, have been installed 30 or even more years ago. They might be close to their nominal 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 with respect to availability and quality of voltage. In addition environmental aspects such as consequential damages, fire and 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, electromechanical and chemical stresses. Dielectric and thermal stresses lead to degradation processes of oil and cellulose. Cellulose consists of molecular chains, which are characterised by their degree of Depolymerisation (DP). The chains of molecules break apart as the cellulose degrades which decreases the 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 degradation or breaking process of cellulose molecule chains produces water in the solid insulation, 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 on-site drying.

The PDC analysis is a non-destructive method for determining the moisture content in the solid insulation material like paper and pressboard [2, 4]. According to Fig. 1a a DC voltage step of 500 V is applied between the insulation system of HV and LV windings during the polarisation duration $T_P$. Thus, a pulse-like polarisation (charging) current of the transformer capacitance flows. The current decreases during the polarisation duration to a final value, which is determined by the conductivity of the insulation system (Fig. 1b). 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, again a pulse-like discharging current of negative polarity flows, which goes gradually towards zero. Usually, the polarisation time $T_P$ and the depolarisation time $T_D$ are equal.

Then, a model, which describes the dielectric behaviour of the transformer’s main insulation system, is parameterised. The behaviour of an arbitrary dielectric can be described by an R-C network model shown in Fig. 1e,
where R and C result from the conductivity and the capacity of the dielectric and the Rp-Cp-series-circuits represent the long term polarisation effects. The complete R-C-model for a transformer (Fig. 1f) can be directly derived from the simplified geometry model of the main insulation system (Fig. 1d) and the knowledge of the model of the used dielectrics. The parameters of this model (Fig. 1f) can be determined using already measured characteristics of pressboard material samples with certain water content, the oil parameters and the geometry of the main insulation system. The “best fit” between calculated relaxation currents for different moisture contents and measured currents provides valuable information about the transformer’s condition such as the moisture content in the solid insulation material, tan δ in a low-frequency range, polarisation index (e.g. R$_{60}$/R$_{15}$) and DC conductivity of the oil.

a. Measurement of the relaxation currents using the Siemens measuring system PDC-Analyser-3205 [2, 3]

b. Principle waveform of relaxation currents

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. Model for the behaviour of a dielectric with arbitrary polarisation characteristic and conductivity

f. Model for the dielectric behaviour of insulation system of power transformers

**FIGURE 1**

**INTERPRETATION OF PDC MEASUREMENTS**

In Fig. 2 the principal effect of different oil conductivities and moisture contents in the solid insulation material on the polarisation current is shown. The conductivity of the oil changes the amplitude of the polarisation current typically in a time range $t < 100$ s, whereby an increasing oil conductivity results in an increasing current. A higher water content in the pressboard and paper insulation affects the polarisation characteristic mainly in the time range $t > 1000$ s as it is clearly visible by an increasing difference of relaxation currents beyond about 100...1000 s. The evaluation of relaxation currents in the time domain allows to use this characteristic of oil-paper insulation systems for separating the effects of oil quality and moisture content in the solid insulation material from each other. Fig. 2b shows the PDC analysis of a new 392 MVA power transformer. The polarisation currents have been calculated for moisture contents of 0.5 % and 1.0 % in the solid insulation material. The measured polarisation current is in the
time range \( t > 1000 \) s in between the calculated currents for moisture contents of \( rM = 0.5 \% \) and \( rM = 1.0 \% \). Thus, the conclusion is: The moisture content in the solid insulation material of this transformer is in between 0.5 \% and 1.0 \%. In the case of new transformers the PDC result can be compared with results of the Karl-Fischer titration and the dew point measurement of the nitrogen filling which allows to determine the moisture in the solid insulation material since these measurements are carried out in the Nuremberg power transformer factory as routine quality checks. For the 392 MVA transformer, the Karl-Fischer result was 0.61 \% and the dew point measurement value is 0.45 \%. Thus, it can be stated that there is a good match between PDC analysis and other moisture determination methods.

![Diagram](image)

**FIGURE 2**

a. Affect of oil conductivity and moisture content in the solid insulation material on the polarisation current \( i_{\text{pol}} \)

b. PDC analysis of a 392 MVA transformer

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

**FIGURE 3**

Such comparisons between the PDC analysis and results from the Karl-Fischer-Titration and the dew-point measurement have been carried out on numerous transformers with different ratings and designs. This proves the applicability and reliability of the PDC method for “determining” the moisture content in the solid insulation material of power transformers (Fig. 3).
ON-SITE PDC MEASUREMENTS ON TRANSFORMERS IN SERVICE

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 1 gives a summary of the results. Furthermore, a paper sample was shaved at a lead of a tap winding. The degree of depolymerization is DP = 352, which indicates a normal thermal ageing of the paper.

<table>
<thead>
<tr>
<th>Measurements</th>
<th>Prior to oil change</th>
<th>After oil change</th>
</tr>
</thead>
<tbody>
<tr>
<td>tan δ at 0.1 Hz, directly measured</td>
<td>0.894</td>
<td>0.1867</td>
</tr>
<tr>
<td>tan δ at 0.1 Hz, from PDC analysis</td>
<td>0.901</td>
<td>0.191</td>
</tr>
<tr>
<td>Conductivity σ_{oil} of the oil, from PDC analysis in 1/Ωm</td>
<td>= 4.5·10^{-11}</td>
<td>= 3.5·10^{-12}</td>
</tr>
<tr>
<td>Moisture in the solid insulation material, from PDC analysis</td>
<td>3 %</td>
<td>2.7 %</td>
</tr>
<tr>
<td>Moisture in the solid insulation material, from RVM measurements</td>
<td>3.45 %</td>
<td>2.48 %</td>
</tr>
<tr>
<td>Polarisation index, R_{60}/R_{15}</td>
<td>3.16</td>
<td>2.11</td>
</tr>
</tbody>
</table>

Table 1: 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}, and the polarisation spectrum and polarisation indexes, e. g. R_{60}/R_{15}. Fig. 4 a/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 1. 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.

![PDC measurements on a 300 MVA transformer, measured with the PDC-Analyser-3205](image1)

- a. Polarisation currents measured prior and after the oil change
- b. tan δ calculated from measured polarisation currents measured and calculated
- c. Polarisation currents for rM = 2.5 %, rM = 3 % and rM = 3.5 %
- d. prior to the oil change
- e. after the oil change

FIGURE 4
Fig. 4c/d shows the PDC analysis of measurements taken prior and after the oil exchange. The results are with $r_M = 3\%$ before the oil change and $r_M = 2.7\%$ 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 moisture content of 3\%, we have total water content of 300 kg. Assuming further an oil weight of 50000 kg and 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.

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. 4a). 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. 5 shows the polarisation spectra determined by the RVM method and those calculated from PDC measurements before and 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

Fig. 5 shows the polarisation spectra determined by PDC analysis and recovery voltage measurement (RVM) from measurements:

- Prior to the oil exchange (Fig. 5a)
- After the oil exchange (Fig. 5b)

**FIGURE 5**

Polarisation spectra determined by PDC analysis and recovery voltage measurement (RVM) from measurements:

- Prior to the oil exchange
- 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 [5].

CONCLUSIONS

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 $\tan \delta$, 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.

REFERENCES


[3] PDC-Analyser-3205, Siemens AG, Transformatorenwerk Nürnberg, Dept. PTD T MCS T, Katzwarnger Strasse 150, 90461 Nürnberg, Germany, contact: Thomas.Leibfried@ptd.siemens.de
