Determining the water content in transformers

Water content influences the life of a transformer in many ways. The obvious and generally known aspect is its direct influence on the dielectric strength of the insulating medium – oil and solid insulation. Furthermore, the accelerated aging of the solid insulation through hydrolysis processes and the resulting loss of mechanical properties, as well as the much feared “bubbling”, i.e. the risk of bubble formation in case of dynamic load changes, are of primary concern.

Many publications focus on indicating the water content of the solid insulation based on the water content of the insulating oil. Electrical measurement procedures (PDC, FDS, RVM) that have reached a stage where they can be safely applied for determining the water content of the solid insulation, as well as experiences gained from drying tests with the use of paper samples, show that in case of aged insulations, the frequently applied equilibrium curves must be reconsidered and amended.

In addition to results from drying tests, this article also presents a solution for assessing aged insulation.

Forms of water in oil

Water is present in the mixed dielectric of a transformer in the following forms:

- **Free water**
  When the absorption limit is exceeded, free water separates from the oil. This can happen when a transformer with moist solid insulation cools down and may affect the cold start behaviour of the transformer.

- **Physically dissolved water (including bound water)**
  In the case of aged insulating oils, the presence of polar oil decay products is not uncommon. These substances behave as solutizers for water and change it to a finely emulsified form. The physically adsorbed water in cellulose fibres leads to a drastic reduction of the dielectric properties of the oil and thus jeopardise the safe operation of the transformer.

- **Chemically bound water**
  Chemically bound water results from reactions between oxidised oil components in strongly aged oils at high temperatures.

Free water and physically dissolved water are measured by means of the Karl-Fischer titration and can be removed with conventional drying methods. Chemically bound water is only released at higher temperatures and is a potential hazard for the dielectric strength. This water cannot be removed with conventional methods. Chemically bound water is usually only found in aged oils (low interfacial tension). The removal of chemically bound water is only possible if the binding substances (acids, carbonyl compounds, surfactants) are removed at the same time or prior to this process. One way to achieve this is for instance oil regeneration before drying.

**Determining the water content in oil with the Karl-Fischer method**

A standardised and reliable method for determining the water content in oil is the Karl-Fischer method [1]. This method can be performed as a direct titration or as a heating method followed by a coulometric titration. Potential interferences might arise from oil or paper aging products, such as aldehydes, ketones, surfactants.

Recently, the reliability of this method has been questioned, because higher water content values could not be confirmed in aged oils through a subsequent water extraction by means of drying. Our experiments, however, have shown that the influence of carbonyl compounds on the Karl-Fischer result is negligible. The analysis of the old oil (example 7.2) through HPLC (high performance liquid chromatography) has indicated a total amount of approximately 2 mg/l carbonyl compounds. In order to simulate the effect of these compounds, 2 mg/l 2-furfural was added to new oil and the water content was measured before and after adding this substance. This has resulted in a significant modification of the water content.
Connection between the breakdown voltage and the water content in oil

The dielectric strength of oil depends on the water saturation in % [2] (see Fig. 1). These curves are not temperature-dependent and apply down to a temperature of minus 30°C. The curve below was recorded for a new oil.

The representation of moisture in oil in % of water saturation has the following advantages:

- Not temperature-dependent
- Not oil or state-of-the-oil dependent

From the curve, it can be seen that the breakdown voltage is within an acceptable range up to a 20% water saturation in oil. At a saturation value of 80%, the insulating oil loses its dielectric strength completely.

Similar curves can be determined and derived in the same way for aged oils by means of laboratory measurements. The problem for practical applications is to classify aged industrial oils, because a large number of parameter combinations (colour, purity, NV, tan delta, interfacial tension) can occur for differently loaded and aged transformers.

Where is the moisture in a transformer [3]?

For the purpose of modelling, solid insulation can be grouped into:

- Thick structures
- Thin cold structures
- Thin hot structures

Thick structures represent about 50% of the entire insulating system – synthetic-resin compressed wood, laminated chipboards, pressure segment chains. These parts have a small surface and, due to the high material thickness, they have very high diffusion constants for moisture. Therefore, their contribution to the moisture distribution during dynamic processes is very low.

Thin cold structures, such as chipboard barriers, shielding caps, represent 20 - 30% of the insulating mass. During dynamic processes – temperature change – areas with higher moisture might result.

Thin hot structures – e.g. winding insulations – are highly exposed to dynamic processes and contribute most to the moisture distribution between oil and solid insulation. Past-mortem moisture profiles, such as for the example in Fig. 2, clearly show a significant moisture profile for the winding.

Effect of the water content on paper aging [5]

Aging of the paper is directly proportional to the water content. Water decomposes the cellulose structure hydrolytically, whereby the long cellulose molecule (degree of polymerisation – DP approximately 1000) is separated into smaller sections as if cut with scissors. At a degree of polymerisation of 200, cellulose has almost no mechanical resistance, i.e. the transformer is no longer short-circuit-proof. Experiments show that the decrease of the degree of polymerisation is higher if the initial moisture of the paper is higher, i.e. its mechanical properties are reduced proportionally – see Fig. 3. It must be noted that this effect is auto-catalytic, i.e. during the aging of cellulose more water is formed, which thus accelerates the decomposition.

Application of moisture distribution curves for estimating moisture in the solid insulation

It is intended to come to a conclusion regarding the water content in the solid insulation based on the water content in oil, using the so-called moisture curves. These curves were determined for new oil and new paper [6] by means of a

- Direct method: storing the paper and oil at various moisture values and measuring the moisture in paper and oil, e.g. Fabre-Richon curves
- Indirect method: combination of two curves – paper and air % saturation with oil and air % saturation. A combination of these curves results in a representation (Oommen curves, Fig. 4) of moisture in paper (%) versus moisture in oil (ppm).

Conditions and error sources for moisture distribution curves

Both methods for drawing up moisture curves require the following conditions to be met:

- Same solubility of water in new and aged oils – however, experience shows that aged oils can absorb up to three times as much water as new oils – see example 7.2
- Equilibrium state of oil and solid insulation (no dynamic processes) – this equilibrium is rare in a real transformer, see example 7.3
- Negligible diffusion constants (only the thin insulation is taken into consideration)
- Constant distribution of moisture in the solid insulation (temperature differences lead to moisture differences)
- Absorption and desorption of water from the paper follows the same process (no “hysteresis behaviour”)

All these conditions represent a largely simplified model that does not apply to real transformers.

An example for the effect of oil aging on moisture curves 31.5 MVA, 110 kV power transformer, date of construction 1957 [4]

A model analysis between EON/Weidmann/Siemens was intended to determine the moisture distribution in the winding insulation, as well as the efficiency of the LH3 drying and its effect on the DP value.

Through a defined load and cooling, the temperature of the transformer was maintained on-site at a medium level (approximately 50°C) for about 3 months, in order to achieve a stable moisture distribution. The moisture in oil (Table 1), as
Table 1: Oil analysis before and after on-site simulation.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>16.01.03 Start</th>
<th>03.03.03 End</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colour</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Appearance</td>
<td>clear</td>
<td>clear</td>
</tr>
<tr>
<td>Neutralisation value (mg/kg oil)</td>
<td>0.22</td>
<td>0.22</td>
</tr>
<tr>
<td>Tangent delta 90°C</td>
<td>3.58</td>
<td>3.61</td>
</tr>
<tr>
<td>Water (mg/kg oil)</td>
<td>23</td>
<td>33</td>
</tr>
<tr>
<td>Temperature °C</td>
<td>28</td>
<td>54</td>
</tr>
<tr>
<td>% water saturation in oil</td>
<td>9</td>
<td>5.5</td>
</tr>
</tbody>
</table>

Table 2: Comparison between the saturation of new and old oil.

<table>
<thead>
<tr>
<th>Temperature °C</th>
<th>Saturation of new oil (ppm)</th>
<th>Saturation of old oil (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>51</td>
<td>175</td>
</tr>
<tr>
<td>40</td>
<td>126</td>
<td>360</td>
</tr>
<tr>
<td>60</td>
<td>254</td>
<td>711</td>
</tr>
</tbody>
</table>

well as the moisture in the solid insulation after the oil drain, were determined by means of the Karl-Fischer titration. The water saturation profile of this aged oil was determined in the laboratory in relation to the new oil [7] (Table 2).

Based on that profile, the familiar Oommen curves (Fig. 5) for a new oil continuous lines) were supplemented by the curves for the analysed, aged oil (dashed line). The use of the Oommen curves for a new oil result in moisture values in the solid insulation between 3 and 4.7% (red dots, values from Table 1), which would indicate a wet transformer. However, by considering the water saturation of aged oil, the resulting values in the solid insulation were only 1.5 – 2.5% (dashed points, values from Table 1), which were later confirmed by direct measurements on paper.

An example for transient phenomena between oil and solid insulation [8]

The test object was a 16 MVA, 25 kV transformer, year of construction 1953. The drying process involved a stationary bypass drying installation. The normal drying process can be divided into two phases (phase 1 and 2, Fig. 6).

During the first phase (18.07.2003 – 31.07.2003), a quick reduction of the water content in the oil was achieved (in the example this took approximately 14 days). Along with it, a visible improvement of the breakdown voltage could be observed.

Phase 2 (30.07.2003 – 14.08.2003) shows an equal input of moisture with the output moisture, i.e. an almost stable state between the moisture from the solid insulation and the moisture taken up by the adsorbent.

Low load phases (phase 3) show that the drying efficiency at low oil temperatures decreases significantly.

In a later part of the experiment (phase 4), the adsorbent was taken out of the circuit and the sensor technology remained operational. For conditions similar to those at the beginning of the experiment (load, oil temperature), the build up of oil moisture was observed until a stable state was reached. This state was reached after approximately 28 days.

This experiment provided striking evidence about the temperature-dependent nature of transition processes between oil and solid insulation as well as the duration until these processes are nearly completed.

Application of moisture distribution curves for estimating moisture in solid insulations

The following procedure is necessary to ensure a reliable estimation of the moisture in solid insulation by means of moisture distribution curves:

- Stable operation for at least 1 month
- Temperatures > 30°C (below 30°C there is almost no moisture exchange between cellulose and oil)
- At least 2 samples taken at different temperatures
- Determining the percentage of water saturation of the oil in a laboratory
- Application of corrected moisture distribution curves for aged oils
- Determining the water content at different operating temperatures under stable conditions
- An important factor is the sampling temperature (measured in the oil jet). It is recommended to use further dielectric methods (PDC, FDS).

Summary

The basic tool for determining the moisture content in transformers is still the oil analysis. The application of the Karl-Fischer titration as a chemical analysis method raises no questions. Deviations of the actual water content in the solid insulation that were observed in practice are a result of an erroneous interpretation when applying the well-known moisture distribution curves.

In the future, a classification of aged oils must be in place and the corresponding curve shapes have to be drawn for this classification. For transformers considered to be critical, there are electrical measurements to confirm the results of the oil analysis. Continuing the experiments already started in collaboration with transformer manufacturers and users could provide the basic material for drawing up a family of curves.

Bibliography


[7] BS 6522, Method for Determination of percentage Water Saturation of Insulating Oil