Breakdown and flashover phenomena related to the presence of high absolute water contents in clean and carbonized transformer oil

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Abstract: This paper reports on experimental investigations dealing with the impact of dissolved and disperse water on the breakdown strength of open oil gaps and the flashover behavior of solid/liquid interfaces in a uniform electrical AC field using clean as well as carbonized transformer oils. The measurements reveal that in technically clean oil with disperse water at small gap distances the breakdown strength can for subsequent voltage stresses be significantly higher after the first initiation of a breakdown than during the first readings while for larger gap spacings this effect cannot be noticed. Moreover, it is shown in this contribution that especially for practically relevant long gap distances carbonized oils can exhibit a better electrical strength in the presence of high absolute water contents than clean oil. This finding applies to the breakdown voltage of open oil gaps as well as to the flashover behavior of solid/liquid interfaces.

Introduction

The electrical insulation of modern on-load tap changers (OLTC) consists of a combination of mineral based transformer oil and solid materials, like for example glass-fiber reinforced epoxy resin (FRP) which is used for the switching tube. Consequently, the electrical strength of an OLTC is not only determined by the breakdown strength of the oil gaps but also by the flashover behavior of the existing solid/liquid interfaces which are contingent on constructional constraints and often considered to be a weak point in an insulation system.

Besides this, the electrical strength of an OLTC is also to a high extent governed by the presence of carbon particles which are produced during the normal switching operations in the diverter switch compartment.

A third factor which has a strong impact on the electrical strength of oil insulated high voltage devices is the oil humidity. Especially high water contents or even the formation of disperse water are considered to have a severe detrimental effect. The formation of disperse water might for instance result from a damaged gasket at the oil expansion tank. Thus humidity can penetrate into the warm oil during normal load conditions and will partly precipitate when the oil cools down during no-load or part-load operation as the water solubility of the oil decreases with declining temperature.

With regard to the outlined problem the scope of this paper is to provide scientific knowledge concerning the combined impact of high absolute water contents and carbon particles on the breakdown strength of open oil gaps and the flashover behavior of solid/liquid interfaces being oriented parallel to the electrical field.

Investigated liquid and solid dielectrics

The investigations were performed on three naphthenic mineral based transformer oils of the same type. One was a technically clean oil while the two others were derived from OLTC after a high number of switching operations in the laboratory. Their carbon contents amounted to \( c = 40 \) and 416 mg/l, respectively. The humidity of the oils was adjusted for the test series to levels of 10, 20, 40 and 80 ppm and was controlled by the help of a coulometric Karl-Fischer-titration device. With regard to the water solubility of the oils at 20 °C the first three water contents lead to dissolved water-in-oil-emulsions while the latter represents for technically clean oil the state of disperse water (Tab. 1).

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative permittivity ( \varepsilon ) at 20 °C</td>
<td>2.2</td>
</tr>
<tr>
<td>Loss factor tan ( \delta ) at 20 °C</td>
<td>2.4 ( 10^{-3} )</td>
</tr>
<tr>
<td>Water solubility ( w_S ) at 20 °C</td>
<td>44 ppm</td>
</tr>
<tr>
<td></td>
<td>400 ppm</td>
</tr>
</tbody>
</table>

The experiments related to the flashover behavior of a solid/liquid interface were performed on commercially available FRP-rods with an outer diameter of 10 mm (Tab. 2).

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative permittivity ( \varepsilon )</td>
<td>5.3</td>
</tr>
<tr>
<td>Arithmetic mean surface roughness ( R_a )</td>
<td>2.6 µm</td>
</tr>
<tr>
<td>Maximum surface roughness ( R_m )</td>
<td>20.0 µm</td>
</tr>
<tr>
<td>Glass-fiber content</td>
<td>65.73 %</td>
</tr>
</tbody>
</table>

The glass-fibers were oriented parallel to the axis of the rods so that these specimens should only be
regarded as a model of the switching tube of OLTC were the winding of the glass-fibers is realized under a certain angle to the axis. Moreover the surface roughness of the investigated spacers was significantly higher than the respective values of the tubes applied in OLTC.

**Electrode configuration and test procedure**

The investigations were performed in a uniform electrode configuration which is illustrated in Fig. 1. It consisted of two Rogowski-shaped copper electrodes which should simulate the grading rings in OLTC. In each of the electrodes a hole of 10 mm diameter with rounded off edges was drilled in the middle to fix the spacers representing the switching tube for the experiments with a solid/liquid interface.

![Figure 1: Applied electrode configuration](attachment:image)

The breakdown and flashover behavior was determined at room temperature in a ramp-test using AC voltage with a voltage rising rate of 1 kV/s. The gap distance was varied between 5 and 50 mm and had in some cases to be limited to smaller gap spacings with respect to the maximum output voltage of the applied high voltage devices.

In the following diagrams the arithmetic means and the standard deviations of the obtained results are presented. The statistical analysis of the recorded readings is described in [1, 2].

**Results and discussion**

In Fig. 2 the impact of different water contents on the electrical strength of oil gaps without and with a spacer is displayed for technically clean oil and gap distances up to 50 mm. It can be derived from Fig. 2a that for the oil gap without a spacer an increase of the oil humidity from 10 over 20 to 40 ppm leads to a significant reduction of the breakdown strength. The reason for this behavior is the lower boiling point of water compared to pure oil. As with rising water content these areas of reduced oil density grow the electrical strength declines. Additionally, an increase of the water content is combined with an enhanced drift of water molecules and water clusters into the inner electrode gap resulting from dielectrophoretic forces due to the high relative permittivity of water ($\varepsilon_r,_{\text{water}} = 80$) compared to oil ($\varepsilon_r,_{\text{oil}} = 2.2$). This leads to an accumulation of water molecules in the high field region. As due to the permittivity mismatch between oil and water field enhancements emerge in the vicinity of water molecules an increased amount of water in the high field region facilitates the initiation of a breakdown at low voltages [3].

Moreover, it can be taken from Fig. 2a that the initial breakdown values for a humidity of 80 ppm are only slightly lower than for 40 ppm. This can be attributed to the fact that at 20 °C the water solubility of clean oil amounts only to 44 ppm. Thus for a water content of 40 ppm, equaling a relative humidity of 91 %, the breakdown strength is already almost exclusively governed by the high amount of water-clusters and not by the hydrocarbon compounds of the oil as beyond a relative humidity of 80 % there are always enough water clusters present in the oil bulk to cause a breakdown at nearly constant electrical field strength more or less independent of the absolute or relative humidity. So an elevation of the humidity to 80 ppm, equaling a relative humidity of 182 % and being even entailed by the formation of disperse water in case of clean oil, does not yield to a pronounced further reduction of the breakdown strength.

This behavior can also be deduced from Fig. 3 where the medium breakdown field strength of clean oil.

![Figure 2: Breakdown voltage $U_B$ of the oil gap and flashover voltage $U_F$ of epoxy resin spacers vs. gap distance $s$ with the water content as parameter (clean oil, $c = 0$ mg/l)](attachment:image)

a) without spacer (for 80 ppm initial breakdown values are displayed)

b) with spacer
oil without a spacer is illustrated in dependence on the relative humidity. Furthermore, the diagram shows that the initial breakdown strength at small gap distances is more affected by the occurrence of high relative humidities than in case of larger gap spacings. The reason for this is that at small gap distances the field enhancements caused by the water molecules are comparatively higher than at larger gap spacings.

During the investigations on the breakdown behavior of technically clean oil without a spacer an interesting phenomenon could be observed for a water content of 80 ppm at small gap distances. After filling the test vessel with new oil and waiting for approx. 15 min. the precipitation of disperse water in form of single droplets was noticed on the bottom electrode. After the first breakdown test these droplets vanished and the oil became extensively turbid. Moreover, the bottom electrode was now covered with a sort of thin water film. As can be taken from Fig. 4 the following recorded breakdown values were for a gap distance of 5 mm now all significantly higher than the first reading. For a gap spacing of 10 mm this effect could also be observed but was less pronounced while for larger gap distances this effect did not occur.

For the interpretation of the described behavior it has to be considered that under an applied electrical field water drops often break into smaller droplets and can form a cloud between the electrodes as is reported in [3, 4]. The droplets in the cloud repel each other and may drift away from the high field region. Thus the breakdown strength can be higher after the first “conditioning” voltage application especially when the size of the drops is relatively large with respect to the gap spacing as is the case for gap distances of 5 and 10 mm.

For the configuration with a solid/liquid interface it can be deduced from Fig. 2b that a variation of the oil humidity between 10 and 40 ppm has a similar but less pronounced impact on the electrical strength compared to the open oil gap. A reason for this behavior can be seen in the fact that the flashover strength of the spacers is not only determined by the condition of the oil but also by the field enhancements at the solid/liquid interface resulting from the rough surface structure of the rods (Tab. 2) in combination with the permittivity mismatch between the solid material ($\varepsilon_{\text{FRP}} = 5.3$) and the oil ($\varepsilon_{\text{oil}} = 2.2$). Compared to the strong impact of these field distortions the humidity’s influence on the electrical strength is slightly receded [2].

A further increase of the oil humidity from 40 to 80 ppm leads for the configuration with a solid/liquid interface to a completely different behavior compared to the open oil gap. For gap distances up to 20 mm the electrical strength is for both water contents nearly identical, i.e. the flashover behavior seems to be determined by the field distortions at the interface. For larger gaps the presence of disperse water is entailed by a significant rise of the flashover values compared to 40 ppm. In addition, for gap distances above 20 mm prior to flashover sporadic sparks could be observed at the interface as is also reported in [3]. Moreover, the oil became extensively turbid due to the spraying of water drops into very fine droplets combined with the onset of an electro-hydrodynamic motion. Hence, the improved electrical strength can be explained by a drift of water molecules away from the high field region. Additionally, during the pre-discharges resulting from field enhancements at the spacer’s surface where water droplets exist volume charges can be established at the interface leading to a field homogenization and thus to a higher flashover strength than for 40 ppm.

In Fig. 5 the impact of the oil humidity on the electrical strength is illustrated for a highly carbonized oil. It can be taken from the diagrams that the breakdown and flashover strength is for all gap distances less affected by a variation of the oil humidity between 10 and 40 ppm compared to clean oil. This behavior can be attributed to an approx. 165 % higher water solubility of the carbonized oil relative to clean oil and the high amount of carbon that governs the electrical strength especially in the range of small gap lengths more than the oil humidity.

Moreover, Fig. 5a reveals that for the open oil gap without a spacer an increase of the water content from 40 to 80 ppm is combined with a significant improve-
ment of the breakdown voltage in the whole scrutinized gap distance range. To explain this behavior it has to be considered that because of the high water solubility of the carbonized oil an absolute humidity of 80 ppm is still below the saturation limit, i.e., no disperse water is present in the oil. Due to the hydrophilous character of the carbon particles the presence of a high amount of water facilitates the growth of the particle size by forming carbon/water complexes. This results in the first stage in field enhancements and invisible pre-discharges at these particles which is in turn entailed by the formation of volume charges that account for a field homogenization and lead to the improved breakdown strength relative to a water content of 40 ppm.

For the configuration with an inserted spacer this effect is concealed by the strength determining impact of the solid/liquid interface so that a variation of the water content between 40 and 80 ppm leads to the same flashover strength for all investigated gap distances.

The impact of different carbon contents on the electrical strength is displayed in Fig. 6 for an oil humidity of 80 ppm. It can be taken from the upper diagram that an increase of the carbon content is especially for larger gap distances combined with an improvement of the breakdown values. The main reason for this behavior is that in the scrutinized range of carbon contents the water solubility rises with increasing degree of carbonization. This strength increasing effect obviously overcompensates the strength reducing field enhancements at the conductive carbon particles.

Fig. 6b shows that for the configuration with a solid/liquid interface the flashover strength at 80 ppm is nearly independent of the carbon content for gap distances up to 20 mm. For larger gaps the carbonized oils exhibit a better flashover behavior than clean oil. Driven by the electrical field the carbon particles settle at sites on the spacers where local field enhancements prevail which results in a reduction of the tangential field component and leads to an improved flashover strength [1].

Conclusions
The investigations have revealed that for long gap distances carbonized oils can exhibit a better electrical strength in the presence of high absolute water contents than clean oil. This result applies to the breakdown voltage of open oil gaps and to the flashover behavior of solid/liquid interfaces.

References

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