VAISALA / WHITE PAPER

The Effect of Moisture on the Breakdown Voltage of Transformer Oil

Power transformers utilize oil as a heat transfer medium and a dielectric material, together with cellulose. Breakdown voltage (dielectric strength) is one of the most important parameters of transformer oil. It is measured when the transformer is taken into use and typically monitored by sampling during its operational lifetime.

It has been reported that breakdown voltage is affected by several factors, such as moisture, particles, acidity, and pressure [3,4,5,6]. The objective of this study is to investigate the dependency of the breakdown voltage on moisture using a representative set of oil samples and to point out the advantages of online moisture measurement.

Materials and methods

The transformer oil samples used in this study (Table 1) were three mineral oils, one synthetic ester-based oil, and two mineral oil samples taken from transformers in operation. In addition, aging of the transformer oil was simulated for two of the mineral oils by using an oxidation treatment. This was done by feeding air into the oil vessel at 150 °C, catalyzed with a piece of copper. After a few days the oil color had changed to dark brown and the TAN value had increased to about 1.6.

The breakdown voltage of the oil samples was measured at room temperature according to the IEC 60156 standard using a BA100 Breakdown Analyzer (b2 electronic GmbH). The measurement sequence (6 breakdowns) was typically repeated a few times at each moisture level. The moisture level of the oil relative to saturation (water activity in oil) was determined using a Vaisala MMT330 transmitter with the probe installed in the test cell of the breakdown analyzer. The transmitter has a capacitive sensor in which the capacitance is affected by the amount of water molecules that penetrate the sensor polymer, which in turn depends on the water activity in the surrounding oil.

The methods for determining the breakdown voltage of oil are described in the IEC 60156 [1] standard, and guidelines for interpreting the results in terms of transformer maintenance are presented in the IEC 60422 [2] standard.
For example, for new transformers above 170 kV the recommended lower limit is 60 kV, whereas breakdown voltages below 50 kV indicate a need for oil reconditioning [2].

Table 1. Oil samples used in the study

Sample 1	Mineral transformer oil 1, new
Sample 2	Mineral transformer oil 1, aged
Sample 3	Mineral transformer oil 2, new
Sample 4	Mineral transformer oil 2, aged
Sample 5	Mineral transformer oil 3, new
Sample 6	Synthetic ester-based transformer oil, new
Sample 7	Transformer 1 (in operation since 2001, sample taken 09/2011)
Sample 8	Transformer 2 (in operation since 1972, oil regeneration 1993, sample taken 09/2011)

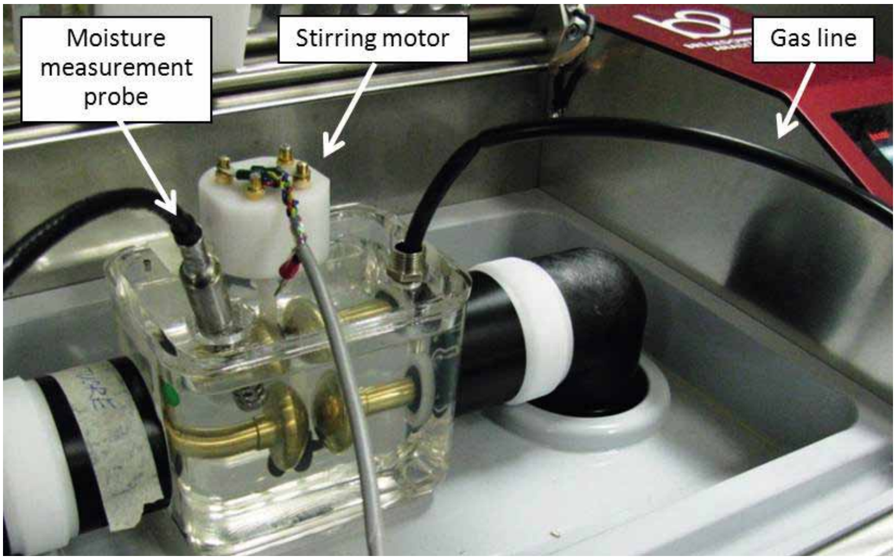

Figure 1. The breakdown voltage analyzer test cell equipped with a moisture measurement probe and a gas line for feeding humid nitrogen.

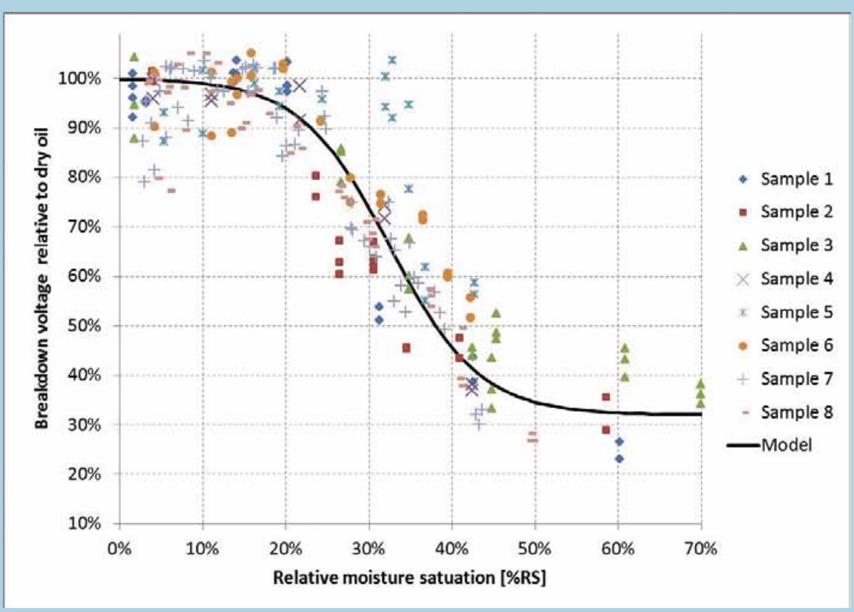

Figure 2. Measured dependency of the breakdown voltage on the relative moisture saturation with an approximative model fitted to the data. Each point corresponds to the average of six breakdown voltage measurements performed according to the IEC 60156 standard.

In order to vary the moisture level of the oil, saturated nitrogen flow was fed into the oil under constant stirring. A saturator cell, immersed in a temperature-controlled bath, was used to control the humidity of the nitrogen flow and thereby the moisture in the oil sample. The flow was stopped before the breakdown voltage measurement sequence was started. The test cell, equipped with the probe and gas line, is shown in Figure 1.

Results and discussion

The results of the breakdown voltage as a function of the relative saturation of moisture in oil are presented in Figure 2. Each point represents the average of six breakdowns. The breakdown voltages for each oil sample were normalized with the corresponding dry oil value to account for the variation between different oil samples (60…88 kV). It is observed that the breakdown voltage remains almost unchanged when the relative moisture saturation is below 20%. Above that it decreases rapidly. This behavior seems to be similar for all the oil samples tested. One explanation for the unexpected similarity between the new and aged samples could be that according to Ref. [4] it is the low molecular acids, rather than TAN, that contribute to the breakdown voltage.

Figure 2 also includes a model function fitted to the measured data. Although approximative, such a model can be used to interpret the changes in the oil moisture in terms of the breakdown voltage.

It should be noted that the moisture level of the oil in the above breakdown voltage model is expressed as relative saturation rather than moisture content in ppm. This is important because the water solubility, i.e. the ppm value corresponding to a given relative

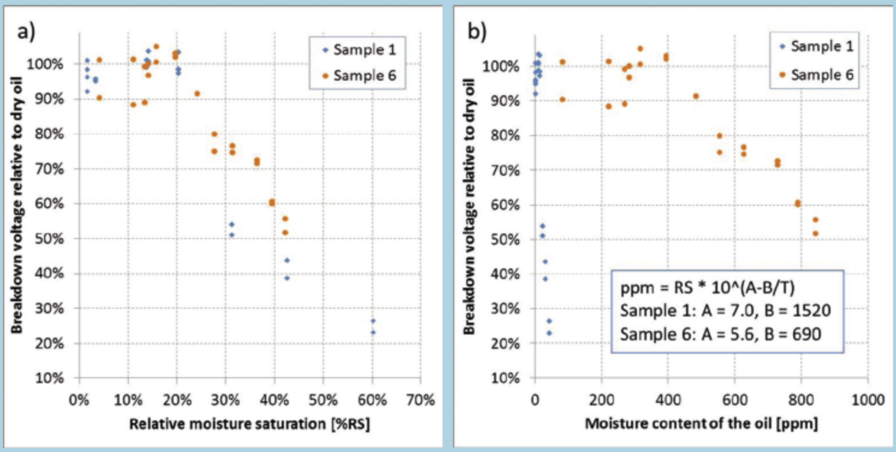

Figure 3. *Comparison between the dependency of the breakdown voltage on relative moisture saturation (a) and moisture content in ppm (b). Oil sample 1 is a typical mineral oil whereas oil sample 6 is a synthetic ester-based oil with very high water solubility. The oil-specific solubility coefficients are shown in the inset.*

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saturation, can vary significantly between different oils and is also affected by the oil temperature and age [7]. Figure 3 illustrates the difference between relative saturation and ppm for two oil samples with very different water solubility. For both samples the two solubility coefficients required for the ppm calculation were determined by coulometric titration and temperature variation, as described in Ref. [8]. The comparison in Figure 3 shows that measuring moisture relative to saturation rather than in ppm is more informative regarding the breakdown voltage. This is also reported in Refs. [3,4].

In a typical transformer maintenance routine the breakdown voltage is monitored by taking an oil sample for laboratory analysis, for example every two years. It has been reported, however, that in addition to slow moisture change processes such as cellulose degradation, there may also be considerable short-term variation in the moisture level of the transformer oil due to changes in the transformer loading and ambient temperature [9].

The change in relative moisture saturation can be caused either by migration of moisture between the oil and cellulose insulator or the temperature-dependency of water solubility. Taking into account the above breakdown voltage results, this indicates that breakdown voltage may fluctuate during transformer operation; this is also pointed out in Ref. [10]. Knowing the moisture-induced momentary change in breakdown voltage could be useful for transformer operation and maintenance. This can be achieved with online measurement of relative moisture saturation.

Conclusions

The effect of moisture on the breakdown voltage of transformer oil was investigated using a set of eight oil samples comprising both new and aged oils. The results were very similar for all the oils tested when moisture is expressed relative to saturation: the breakdown voltage remains high when moisture saturation is below 20% but then decreases significantly as relative moisture saturation increases.

In order to provide a convenient interpretation of moisture changes in terms of breakdown voltage, a model function was fitted to the data. This is considered to be particularly useful for online moisture measurement, which allows the detection of short-term breakdown voltage changes and reliable monitoring of trends, as well as elimination of the measurement errors that can result from improper oil sampling.

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