

Analysing laboratory results for transformer oil breakdown voltage

The key role of oil relative humidity in BDV estimation and interpretation

ABSTRACT

The article proposes a method to interpret the results of the Breakdown Voltage (BDV) test performed on transformer mineral oil, which is highly influenced by the relative humidity of the oil sample. Generally, the temperature of the oil at the moment of sampling is different from that at the moment

the test is performed in the laboratory. While this temperature difference does not affect the absolute amount of water (ppm) in the oil sample, relative humidity is affected, and, as a result, the final BDV result is affected, producing misleading results. In this article, a method to incorporate the water content and the oil sampling temperature is proposed in order to improve the

interpretation of the results and avoid false diagnostic oil condition assessments. The method results have been validated by multiple testing laboratories and by using real field data.

KEYWORDS:

dielectric breakdown voltage, relative humidity, water, temperature, mineral oil

The BDV level of insulating fluid is influenced primarily by its relative humidity and particles, and minor factors affecting oil BDV can include the type of oil and ageing sub-products

Laboratory BDV results can be affected by the differences of the temperature and thus of the oil relative humidity between the sampling and testing time

Sampling temperature can vary greatly, from relatively low temperatures up to 60 °C or higher, whereas when oil is tested in a laboratory, oil temperature is typically close to 20 °C

Introduction

The dielectric breakdown voltage of insulating liquid is a measure of its ability to withstand voltage stress without failure [1]. This parameter is tested in laboratories in the form of a routine test to examine the capability of the oil to provide the required insulation level [1, 2]. The test is performed according to ASTM [3] and IEC standards [4].

The BDV level of insulating fluid is influenced primarily by its relative humidity and particles [5,6]. Some secondary, minor factors affecting oil BDV can include the type of oil and ageing sub-products; however, most of these factors slowly change over the oil's lifetime. Humidity, on the other hand, can change rapidly inside the transformer, as well as in the oil sample itself. While the amount of absolute water content, expressed in ppm, remains the same, as it is independent of the sample's temperature, relative humidity varies depending on the temperature change be-

tween the sampling and testing time. Such a change in relative humidity can heavily influence the laboratory's BDV result, leading to uncertainties in understanding whether the tested sample really is a good representation of the transformer's oil and, consequently, possible misinterpretation of the results. By knowing the initial relative humidity of the oil at the moment of sampling and comparing it with relative humidity at the moment of performing the laboratory test, it becomes possible to estimate BDV more accurately and avoid any unnecessary concerns.

Background on laboratory tests and related challenges

The BDV test is carried out by taking an oil sample, bringing it to a laboratory, preparing the sample, and following the standard test procedure of reporting the mean value from several breakdown measurements. However, the mean value must be accompanied with the standard deviation, and if the scattering of results

is spread over too large a range, the sequence of the tests must be repeated.

Over the years, the results can show quite high variability due to the deviations during the sampling, handling, and testing stages. A typical example is shown in Figure 1, reporting the historical data of a transformer, where we can observe a swing in the 40–90 kV range, corresponding to a range from a very bad condition up to a very good condition.

In addition to all those factors that can influence the accuracy and repeatability of data over time, the most influential factor is the relative humidity of the oil. Indeed, the breakdown voltage of the same oil sample can change depending on its relative humidity, as shown in the Figure 2 curves.

This leads to an important consideration: whenever oil is sampled from a transformer, sampling temperature can vary greatly, from relatively low temperatures up to 60 °C or higher, whereas when oil

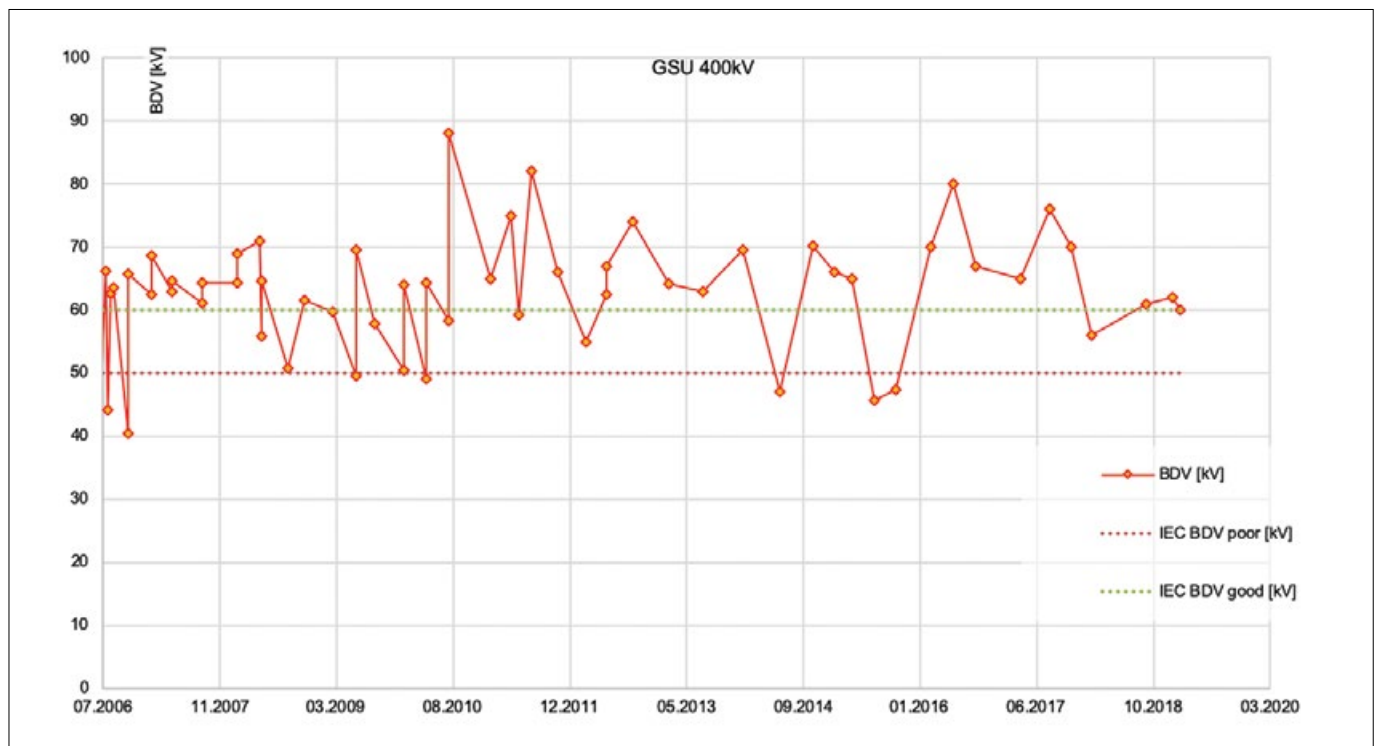


Figure 1. Example of a lab BDV test results trend

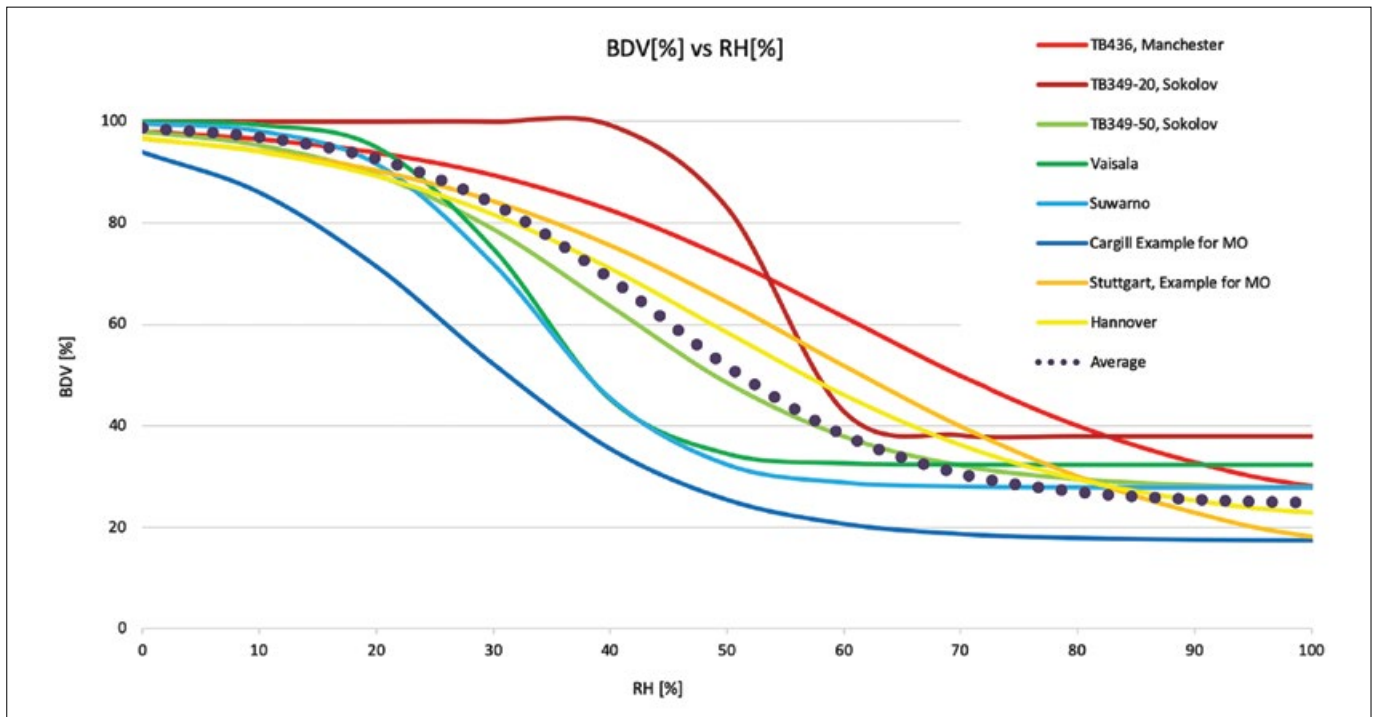


Figure 2. Transformer oil BDV [%] vs RH [%] in different studies

is tested in a laboratory, oil temperature is typically close to 20 °C.

The absolute water content (WCO) of an oil sample, expressed in ppm, does not change between the moment of sampling and the moment of performing a test in the laboratory; however, relative humidity does. If the relative humidity of the oil sample in

the laboratory is different from the one of that same oil inside the transformer, the BDV result will be different and no longer representative of the real BDV condition inside the transformer while in operation.

The following two examples demonstrate the influence of RH on laboratory BDV results.

Example 1

Figure 3 shows the historical results of BDV measurement on a 132 kV transformer, plotted together with the oil sampling temperature and water content (WCO), which was measured in ppm. IEC acceptance limits [2] have been added as a reference.

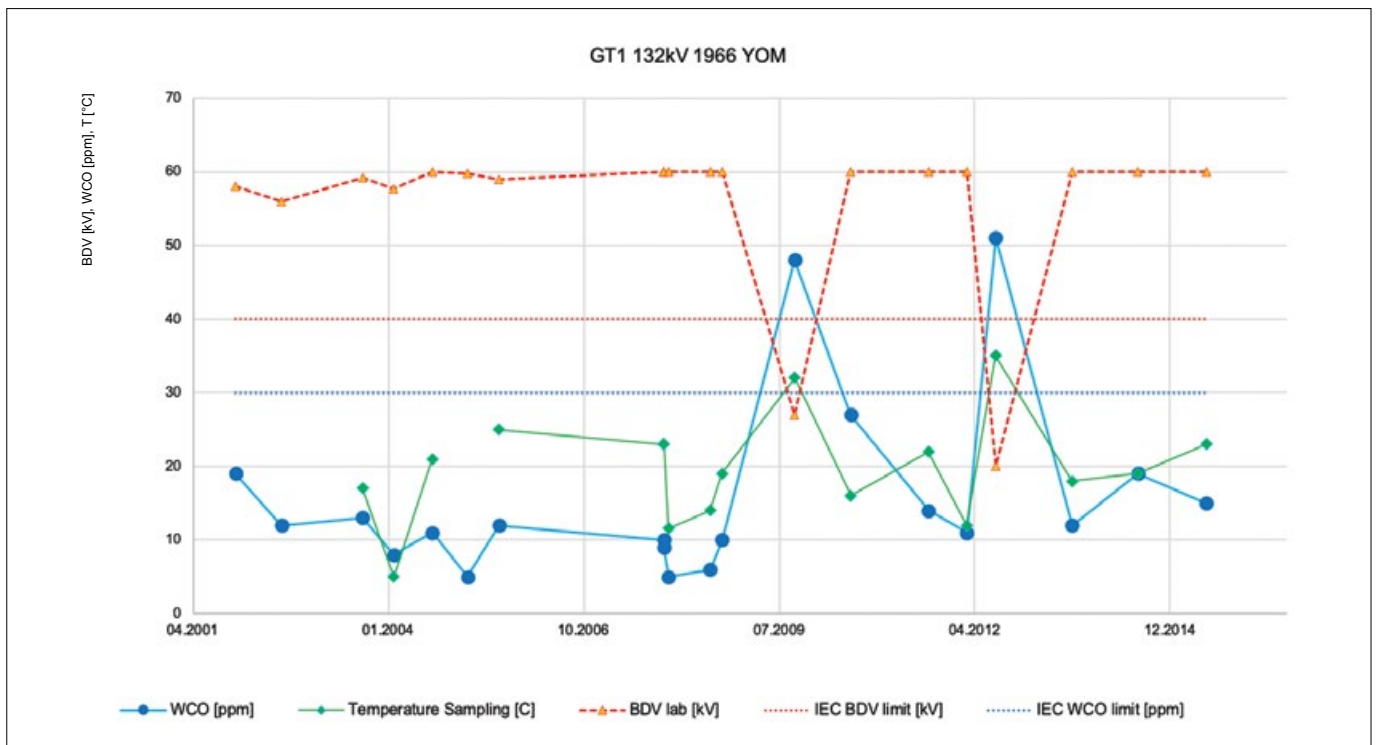


Figure 3. Timeline of laboratory BDV and WCO results for a wet 132 kV transformer.

Since the RH of the oil at the moment of the test was not the same as that of the oil at the moment of sampling, we can say that the sample was not representative of the transformer’s oil during the BDV test

Out of the data collected, most BDV results (red dashed line) have been above the IEC limits of 40 kV for this class of transformer, except for two instances in 2009 and 2012, when BDV reached critical levels of around 30 kV. This result could have caused concern to the transformer’s owner, leading to extra maintenance costs of performing an investigation on the moisture content of the insulation and, potentially, oil regeneration or insulation drying. However, subsequent measurements once again demonstrated acceptable BDV results, thus bringing the low BDV results into question. Looking at water content, it can be observed that there is a dependency between the measured low BDV values and the high WCO. Furthermore, there is also a direct dependency between the moisture and the temperature increase during sampling.

Most of the samples were collected from the transformer at relatively low oil temperatures due to the either low load or cold ambient conditions. Only two samples, taken in 2009 and 2012, had hotter temperatures.

Thus, it can be reasoned that

- due to the higher oil temperature, moisture has migrated from the transformer’s paper insulation to the oil, causing a temporary excess of moisture in the oil;
- at the moment of oil sampling, the WCO was higher than in other cases;
- the sample has then been shipped to the laboratory, and the temperature was stabilised at the laboratory temperature level, lower than that of the transformer at the moment of sampling;
- the combination of the high amount of absolute water at a lower temperature in the lab resulted in a higher RH during the lab test, affecting the BDV test and causing lower values to be reported;

Since the RH of the oil at the moment of the test was not the same as that of the oil at the moment of sampling, we can say that the sample was not representative of the transformer’s oil during the BDV test.

Example 2

Figure 4 shows the laboratory results for BDV and WCO in the mineral oil from 1700 samples made available by the ZTZ-Service laboratory, along with the oil sampling temperature. The linear fit of the data highlights that lower BDV results can be observed for those samples that had a higher temperature and WCO at the moment of sampling.

The same behaviour can be seen in Figure 5, where the WCO values have been converted into RH, considering the laboratory temperature. This relationship coincides with what is expected when one is aware of the BDV–RH relationship (see Figure 2).

Further on, WCO has been converted to RH at the temperature that was current at the moment of sampling (RH_{sampling}) and has been plotted together with RH at the laboratory (RH_{lab}) (see Figure 6).

As expected, RH values are very close to each other whenever the sampling temperature and laboratory temperature are

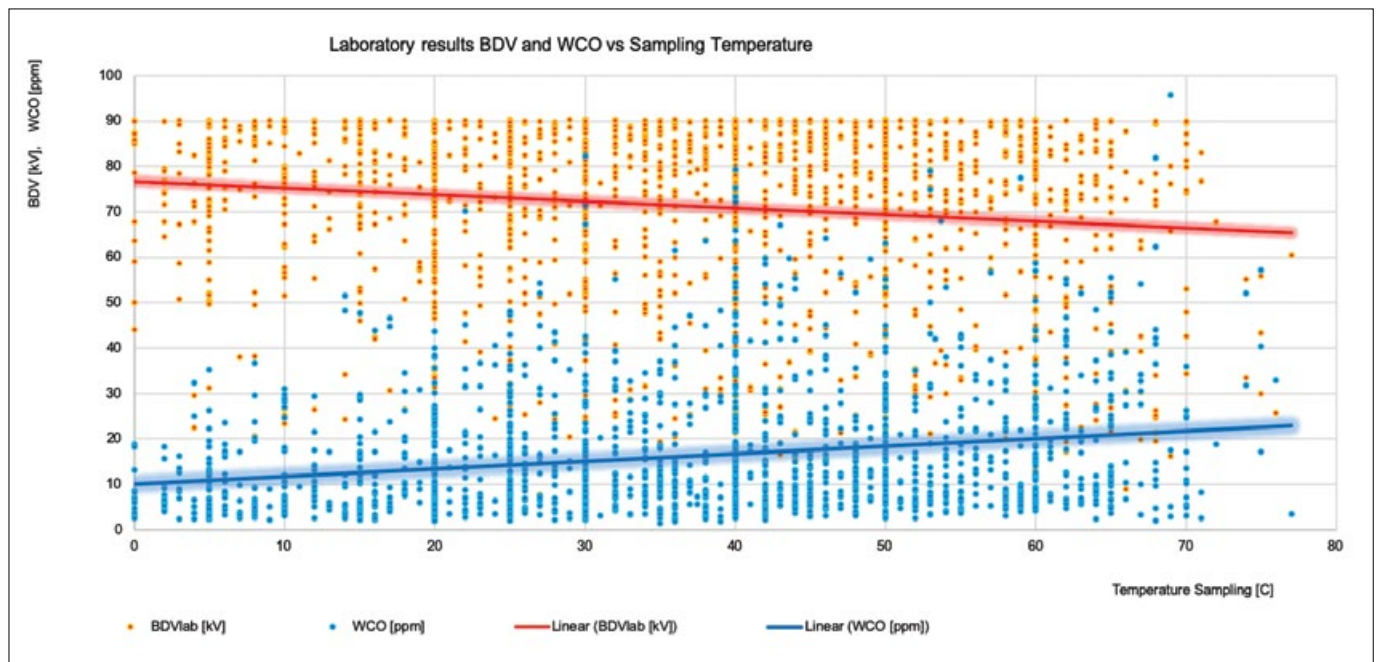


Figure 4. ZTZ-Service database for oil BDV and WCO vs sampling temperature

similar, while they diverge significantly when the two temperatures are different. In particular, when the transformer oil temperature is high, the difference in RH is evident. Interestingly, the transformers for which lower BDV was reported are the ones with lower RH, meaning those with drier oil. The explanation for this contradiction is that the BDV test has been done on a sample with a relative humidity higher than the one existing inside the transformer. This phenomenon is caused by the decrease in temperature from the sampling conditions at the transformer

The oil at the moment of the test may not be representative of the oil condition inside the transformer anymore due to the differences in relative humidity

site versus the temperature in the lab where the testing has been performed.

This highlights a critical factor in the assessment of the oil BDV test:

the oil at the moment of the test may not be representative of the oil condition inside the transformer anymore due to the differences in relative humidity.

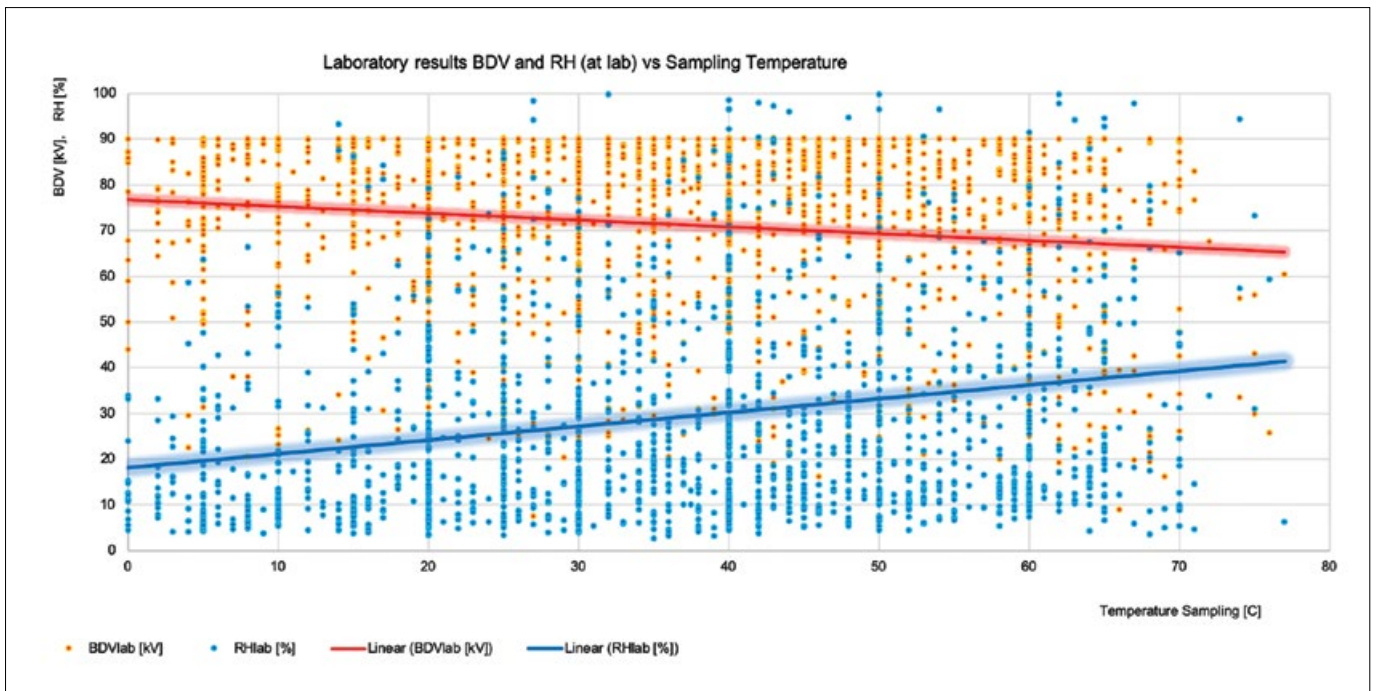


Figure 5. BDV and laboratory RH vs sampling temperature

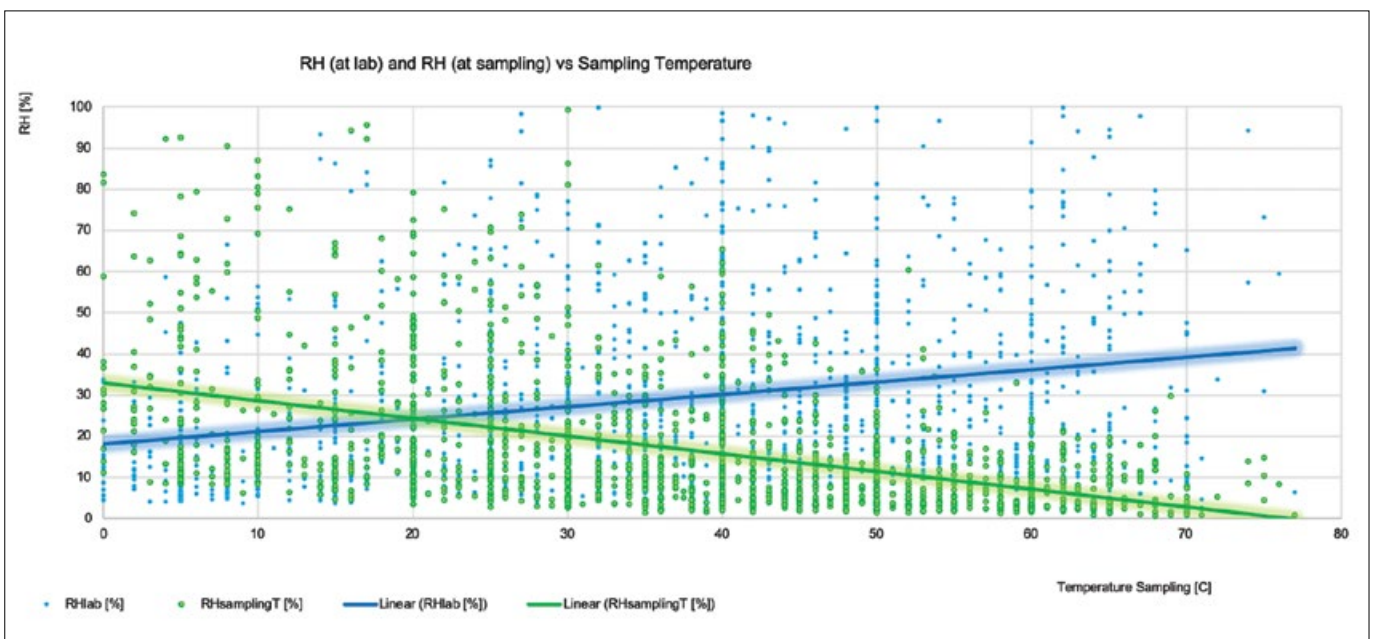


Figure 6. Oil RH at sampling and oil RH in laboratory vs sampling temperature

By knowing the RH at the moment of sampling, it is possible to determine a second point on the curve, which is the estimated BDV in the transformer

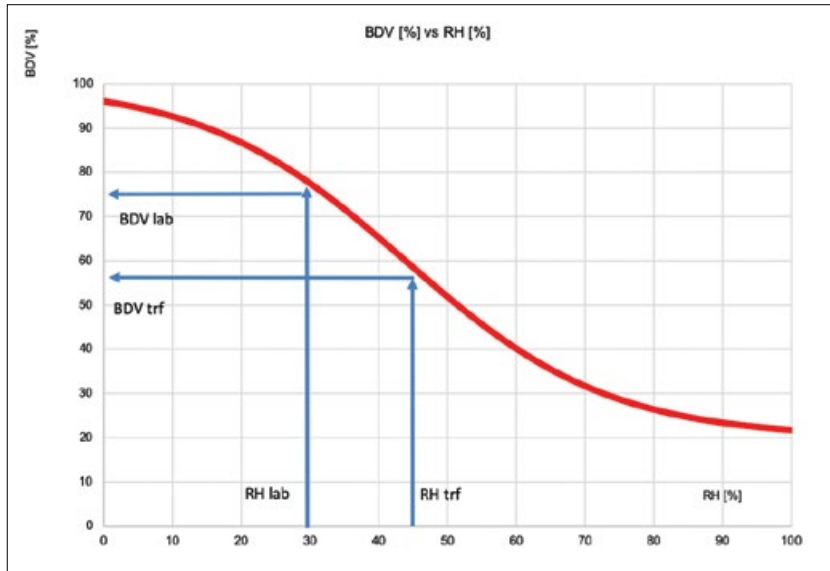


Figure 7. Laboratory BDV results in interpretation to different sampling RH condition

How to interpret BDV results better

Analytical method

The proposed method consists of calculating the RH of the oil at two temperatures — the temperature at the moment of sampling and the laboratory temperature — in order to estimate oil BDV in both situations. As shown in [5, 7], BDV can be better expressed in [%] instead of [kV]. In this format, 100 % represents the ideal

oil BDV in dry condition, with respect to the specific oil type and to the BDV test method used. The correction procedure concept is based on the non-linear relationship between RH and BDV, as shown in the curves from Figure 2. Whenever oil is tested in a laboratory, the measured BDV and RH% represent one point on the curve (RHlab vs BDV(%))lab). By knowing the RH at the moment of sampling (RHtrf), it is possible to determine a second point on the curve, which is the estimated BDV in the transformer (BDV(%))trf).

The sequence of steps to define the BDV of the oil at the moment of sampling is given in Figure 7 and Figure 8.

The real oil BDV at sampling moment BDV_{trf} can be found by (1):

$$BDV_{trf} = BDV_{lab} * k_{BDV}, [kV] \quad (1)$$

where k_{BDV} is the BDV correction factor and can be found as

$$k_{BDV} = BDV(\%)_{trf} / BDV(\%)_{lab} \quad (2)$$

where $BDV(\%)_{trf}$ and $BDV(\%)_{lab}$ are the expected oil BDV at the moment of sampling and testing in lab conditions. Both $BDV(\%)$ values are expressed as a percentage of the maximum achievable BDVdry (“dry” oil BDV). Both $BDV(\%)$ can be obtained via the equations published in studies [1, 7] if oil RHlab and oil RHtrf are known.

Both RH can be calculated as follows:

$$RH = WCO * 100 / W_s, [%] \quad (3)$$

where W_s is the oil saturation level at a given temperature, calculated as:

$$W_s = 10 * exp(A - B / T), [ppm] \quad (4)$$

where A, B are constants specific to oil type and their ageing [5]. The parameter T is the oil temperature in Kelvins for the laboratory (20 °C) and sample at the sampling origin.

It must be pointed out that, in an ideal scenario, both the oil type and the age should be considered whenever WCO is converted

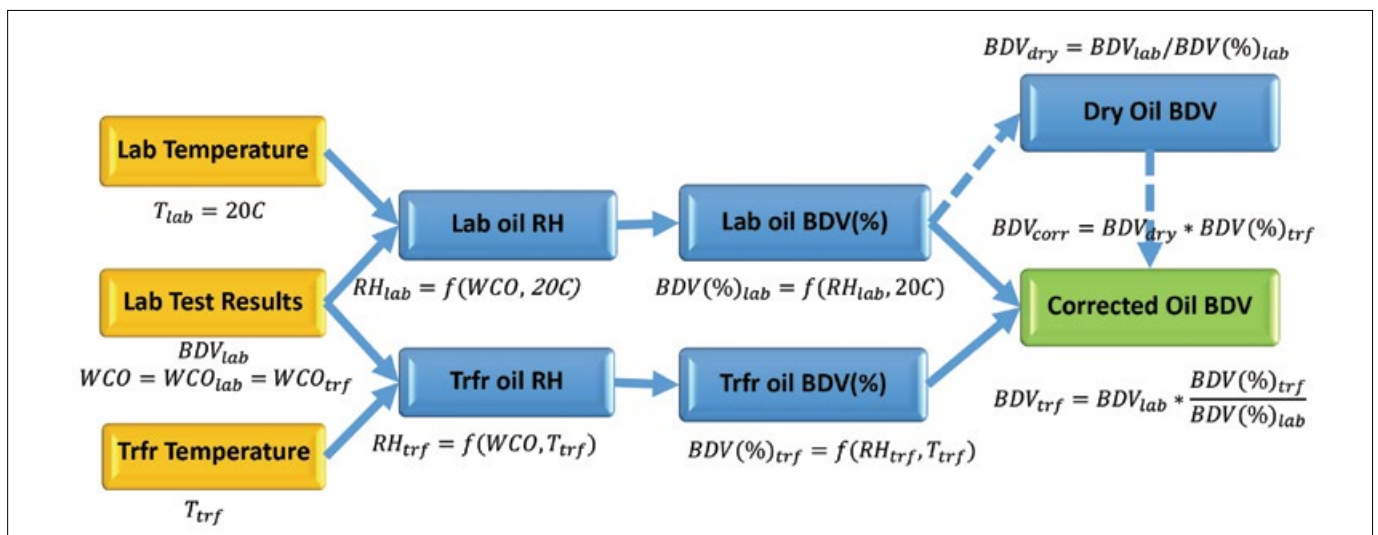


Figure 8. Flow chart for BDV lab results interpretation

Table 1. BDV correction factor for the range of oil sampling temperatures and lab WCO results

Sampling temperature, C		Lab moisture test result (WCO), ppm															
		New oil (A=7.09, B=1567) (4)								Old oil Acidity=0.3 (A=8.42, B=1921) (4)							
		2	5	10	15	20	30	40	2	5	10	15	20	30	40		
0		0.99	0.95	0.76	0.48	0.33			0.99	0.95	0.79	0.52	0.33				
10		1.00	0.98	0.94	0.84	0.69	0.50		1.00	0.99	0.95	0.88	0.77	0.52	0.44		
20		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00		
30		1.00	1.01	1.02	1.06	1.12	1.39	1.80	1.00	1.01	1.02	1.04	1.07	1.20	1.46		
40		1.00	1.01	1.04	1.08	1.17	1.56	2.28	1.00	1.01	1.02	1.05	1.09	1.26	1.61		
50		1.00	1.01	1.04	1.10	1.19	1.62	2.48	1.00	1.01	1.03	1.06	1.10	1.28	1.66		
60		1.00	1.02	1.05	1.10	1.20	1.66	2.57	1.00	1.01	1.03	1.06	1.11	1.29	1.69		
70		1.01	1.02	1.05	1.11	1.21	1.67	2.61	1.00	1.01	1.03	1.06	1.11	1.30	1.70		

to RH [5], while temperature should be used for the BDV–RH conversion [8, 9]. However, the analysis of the influence of those factors on BDV correction has shown that they have a small influence (see Table 1 for the oil age influence).

To simplify the correction process, Table 1 was proposed, showing BDV correction factors as a function of discrete inputs of WCO and sampling temperature



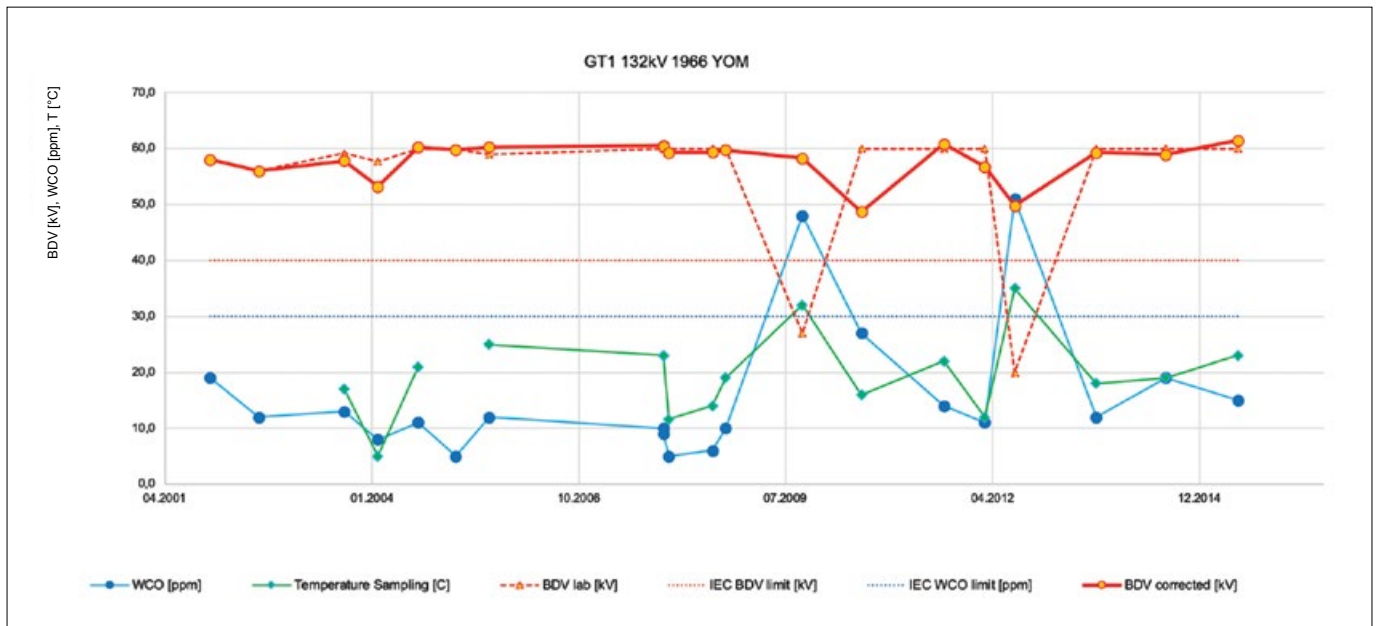


Figure 9. Old wet 132 kV transformer. Corrected BDV.

By using correction formulas or coefficients, the measured BDV had been reported within normal values, closer to 50 kV, thus eliminating any concern

Simplified method using correction factors

To simplify the correction process, the following table was proposed, showing BDV correction factors as a function of discrete inputs of WCO and sampling temperature (assuming the laboratory temperature to be 20 °C). The table also takes into account whether the oil is new or old, “old” meaning Acidity >= 0.3.

The cells of Table 1 have been coloured to enable the correction factor entity to be perceived more intuitively, in the following manner:

- minor correction (within 10 %): green
- moderate correction (10 % – 2 times): yellow
- major correction (2 times and above): orange

By applying the correction factors from Table 1, BDV was corrected to 54.4 kV, thus very close to the original value

Real cases

Case 1: false positive on a 132 kV transformer from 1966

The following case shows the correction applied to the data previously mentioned in Example 1 (Figure 3).

The two suspicious BDV values reported below the IEC limits by the laboratory have been corrected using moisture and temperature values (Figure 9). As expected, those values were underestimated, creating unnecessary concerns due to the higher RH at the moment of performing the test, caused by the decrease of temperature between sampling (above 30 °C) and testing (20 °C) in combination with a temporarily elevated amount of absolute water content.

Case 2: false positive on a 132 kV transformer from 1968

Figure 10 presents a report on a case similar to Case 1: BDV was reported to be low in 2001 (38 kV) and 2004 (20 kV). In particular, the 2004 value had an elevated water content (50 ppm) and a hot sampling temperature (40 °C). By using correction formulas or coefficients, the measured BDV had been reported within normal values, closer to 50 kV, thus eliminating any concern.

Case 3: Laboratory test

The correction factors were also tested by performing a test in a laboratory, simulating a possible real condition (see Table 2 for results). The moisture content in the sample was 21 ppm, measured using the Karl-Fischer method.

In the first simulation, the oil temperature was cooled down to 15 °C, simulating the oil’s condition at a relatively cold temperature. The moisture was measured again and reported to be 21 ppm (as expected), and BDV was tested and reported to be 55 kV. The oil was then left at laboratory temperature (20 °C) to test the BDV in laboratory temperature conditions. The purpose of this was to observe what would normally happen when testing any field sample. The BDV test result in lab conditions was 62 kV, which constitutes an overestimation of 7 kV compared to the BDV measured at transformer temperature. By applying the

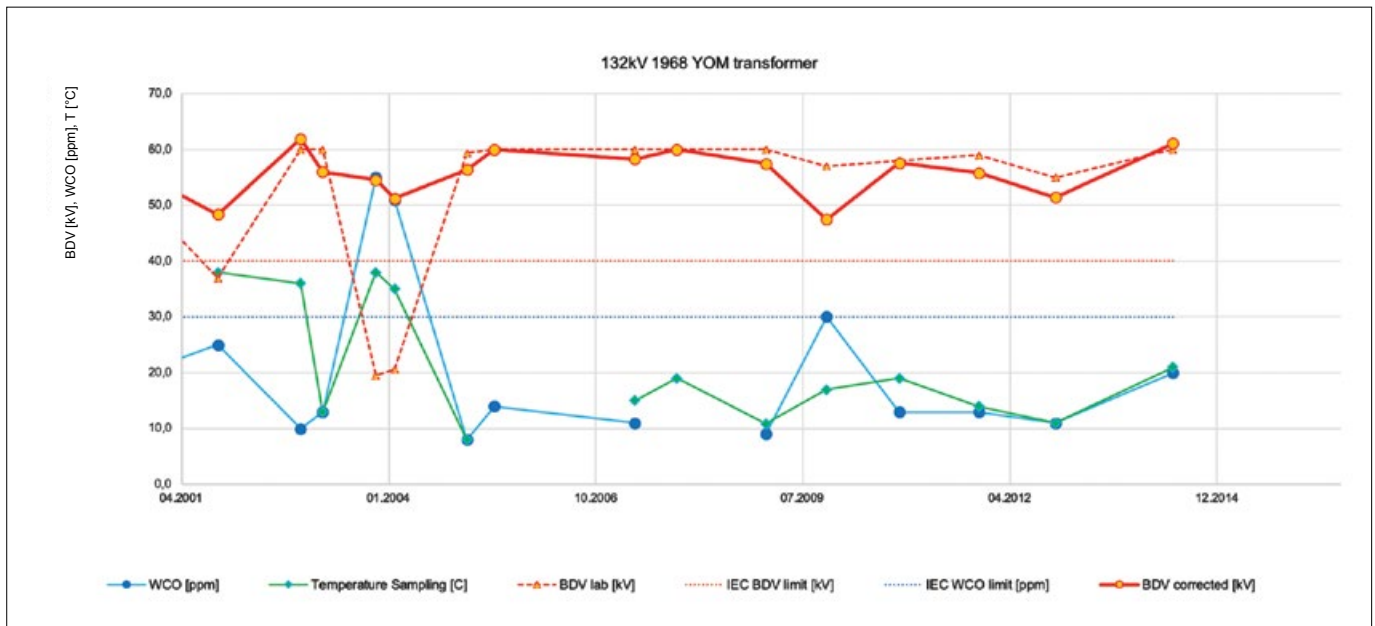


Figure 10. Old wet 132 kV transformer. Corrected BDV.

The method is advantageous in reducing the number of false positive and negative results, providing better trending over time and enabling asset managers to plan proper maintenance based on the real condition of the oil

correction factors from Table 1, BDV was corrected to 54.4 kV, thus very close to the original value.

In the second simulation, oil was heated to reach 33.3 °C. When WCO was measured again at 21 ppm, the measured BDV at that temperature was 83 kV, showing a 20 kV difference when compared to the test at 20 °C (the laboratory temperature). By applying the correction factors from Table 1, the laboratory BDV was corrected to 72.9 °C, which is still underestimated but much closer to the original value.

Conclusion

Oil BDV laboratory results can have a high variability due to the difference between the oil temperature from the mo-

ment of sampling at the transformer site and the temperature during lab testing. In particular, the results belonging to samples taken at cold oil conditions (below lab temperature) may be overestimated, while those relevant to samples at a higher oil temperature may be underestimated, causing unnecessary concerns regarding the transformer's condition.

An analytical method for the correction of laboratory BDV results has been proposed, which takes into account both the oil temperature at the moment of sampling and the sample moisture content (WCO tested for the same sample). The procedure requires knowing the curves describing the dependency of WCO and BDV on the relative humidity RH% for a specific oil.

In case the curves are unavailable, a simplified method has been proposed, which uses a table of correction factors dependent on sampling temperature, WCO, and oil age. The method has been successfully tested on real-field and laboratory database cases.

The application of the analytical method using real-world example cases demonstrates that it has been possible to correct BDV results reported as critically low, making them a reason of concern for the end user, and to bring them back to normal, acceptable levels. Laboratory measurement led to the underreporting of BDV values due to the higher relative humidity of the sample, caused by the decrease of the oil temperature from the field to the laboratory.

Table 2. Laboratory test concerning the oil temperature effect on the BDV and analytical correction

Simulated transformer temperature	Moisture (ppm)	BDV measured at the sample temperature	BDV measured at 20 °C	Correction factor as for Table 1	BDV analytically corrected
14.9 °C	21	55 kV	62 kV	0.88	54.4 °C
33.3 °C	21	83 kV	62 kV	1.17	72.9 °C



An analytical method for the correction of laboratory BDV results has been proposed, which takes into account both the oil temperature at the moment of sampling and the sample moisture content

The method is advantageous in reducing the number of false positive and negative results, providing better trending over time and enabling asset managers to plan proper maintenance based on the real condition of the oil.

It is recommended that the standards working groups of IEC and IEEE adopt this concept and method of correcting BDV in their respective standards and guides.

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