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Development and Verification of an Online Method for Determining the Oil Condition of On-load Tap-changers and Transformers

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SUMMARY

Modern on-load tap-changers (OLTC) are mostly maintenance free, inspections and revisions are only necessary when a specific number of switching operation, or a time-based interval has been reached. Depending on the application, taking an oil probe is required at several years. However, this can lead to the risk of changes in the oil not being recognized for a long time. Even when on-load tap-changers are produced and tested with highest quality standards, their installation, maintenance and also the installation of related piping to the conservator and filtering units can enable the possibility of failures, such as a loose flange or a damaged seal, in this critical component, with a negative impact to its insulating oil.

Consequently, corrosion as well as a decreased dielectric strength of the insulating oil may occur, leading to costly outages of power transformers. Monitoring the oil quality can help to indicate several failures long before severe and expensive consequences will occur.
Laboratory analytics define the quality of the insulating oil by its dielectric properties, using breakdown voltage tests as well as measuring tests for the dissipation factor, the specific resistance, the conductivity, the permittivity, and the moisture in oil. Unfortunately, investigations in the laboratory are not continuously available and cost intensive because skilled personal is required for taking the oil sample. If the oil samples are not taken in the correct manner, the results of the analyses can be greatly distorted, so that an interpretation cannot be made correctly, and the wrong decisions are made with regard to asset management.

Therefore, within this paper we developed and validated an innovative and cost-efficient method to continuously monitor one of the most decisive parameters of the insulating oil, the dielectric strength.

A correlation analysis related to the breakdown voltage (BDV) is conducted considering the influence of different parameters. Furthermore, different types of oil such as mineral oils and ester fluids where investigated. It is shown that the developed method can guarantee an accuracy of ± 10 kV for the qualities of oils used in this investigation.

Since an OLTC is a very specific device, and the evaluation of the determined oil quality always depends on the OLTC type with its specific properties, a three-stage evaluation scheme (poor, medium, good) is applied to provide users with simple recommendation for action.

To describe the benefits of the method and its stability in the field, a sensor optimized for use in OLTCs is developed and put into service. This ensures that, despite the complex options for installation, safe and reliable operation is always guaranteed, and interoperability is ensured.

Due to missing failure cases during on site measurements, the method is additionally validated against historical data.

Thus, it can be summarized that the described method basically can indicate faults after maintenance measures and, due to the knowledge of the oil quality, the maintenance intervals can also be enlarged to reduce costs.

KEYWORDS

Breakdown – Voltage – On-load – Tap-changer – Oil – Quality – Moisture

1. Introduction

The requirements for insulating liquids encompass basic dielectric and physico-chemical properties necessary for insulation, heat transport and cooling, long-term stability, and arc extinguishing capability (depending on the equipment). Although in our days the proportion of natural or synthetic esters is currently increasing, mineral oils remain the most widely used type of insulating liquid.

Insulating fluids must fulfill several functions, including dissipating the heat generated, lubricating moving parts of the device, and ensuring electrical insulation. Consequently, insulating oils require high dielectric strength, good thermal conductivity, and long-term chemical stability [1,2]. They must maintain these properties over a long service life and at high temperatures [3,4]. As part of the condition assessment, it is a central task to continuously monitor these properties. This publication initially focuses on the dielectric strength of the insulating liquid. As state of the art, a standardized offline oil breakdown voltage (BDV) test is used to evaluate this property [5].

However, these methods are based on taking oil samples and therefore have two major disadvantages. Firstly, it is always only a snapshot of the condition. Many faults that arise during commissioning, for example, develop over a relatively short period of time.

In one specific case of the operator involved, for example, a faulty assembly was only detected after the routine oil sampling. During the time without monitoring, corrosion damage occurred that could have been significantly minimized with the use of a suitable sensor that continuously measures moisture and breakdown voltage (see also Figure 1).

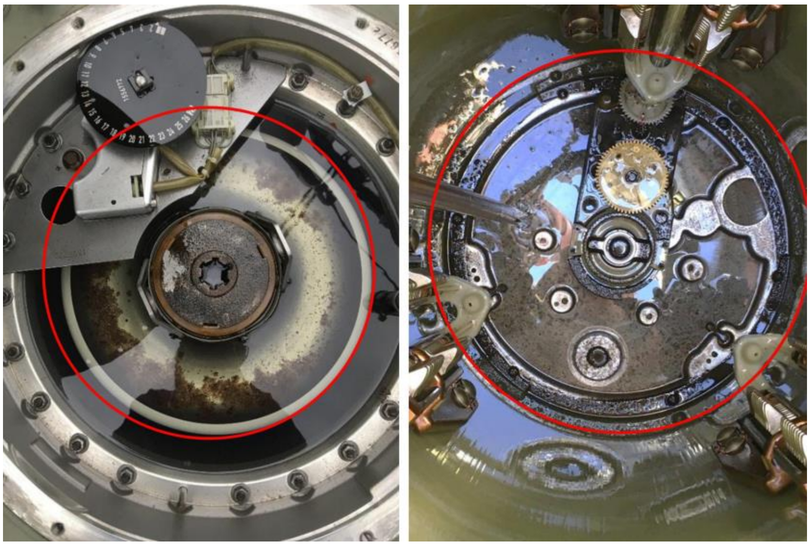

Figure 1: Damage patterns due to corrosion that were only detected during routine oil inspections

Therefore, achieving the necessary certainty for detecting a potential fault requires numerous inspections in a short period, resulting in high costs. This error could have been determined by a sensor proposed here with a suitable moisture measurement analogous to [6] and a corresponding determination of the breakdown voltage. The second major drawback is the sampling process itself, because this process is very error prone. The analysis and the handling of the oil in the laboratory are also subject to error, which is why it is advisable to use a sensor for on-line determination or indication of the BDV. The breakdown process is a highly complex process influenced by many parameters [7,8]. Hence, it's crucial to minimize the number of parameters to achieve a cost-optimized sensor system for online monitoring. However, care must also be taken to ensure that the sensor can later be used in relevant equipment, such as an on-load tap-changer (OLTC). Unlike integrating the sensor into a transformer, integrating it into an OLTC poses a high risk of mechanical collision with the drive. In addition, access via the head cover of the OLTC is severely limited, particularly in the event of retrofitting, as there is usually only access for a temperature sensor. Therefore, this publication presents a simplified sensor system able to indicate numerous faults while meeting mechanical and design requirements at minimal cost.

2. Methods

2.1 Parameters influencing the breakdown voltage

The parameters influencing the breakdown voltage have been extensively investigated in the past [9]. Generally, these can be categorized into oil type-dependent parameters and oil quality parameters. Oil type-dependent parameters include density, viscosity, conductivity, and saturation moisture. While oil quality parameters encompass relative humidity and the type and number of particles.

As a part of the following investigations and to record the S-curves required for modeling, four different types of oil are examined as examples. Specifically, two mineral oils (mineral oil type A and type B) as well as two ester-based oils (ester oil type A and type B) are utilized. Different ageing states are examined to cover the aforementioned influencing factors. The oils were artificially, i.e. thermally aged. Both new oil samples and a heavily aged oil samples are considered below for the mineral oil types A and B. However, for the two ester type samples, only new oil is considered as a reference in this publication.
Since reference measurements in the laboratory analysis are always carried out at room temperature, i.e. at approx. 20 °C, the temperature of the operating fluid is also factored in as a parameter. In the case of an OLTC, sensor access is highly limited. As the sensor is fitted beneath the cover of the on-load tap-changer, temperatures up to 125 °C must be considered. This upper temperature limit thus determines the sensor’s upper operating point. Temperature variations are conducted as part of this investigation using a modified and heatable test cup as well as the setup illustrated in Figure 2, which can be integrated into a climate chamber.

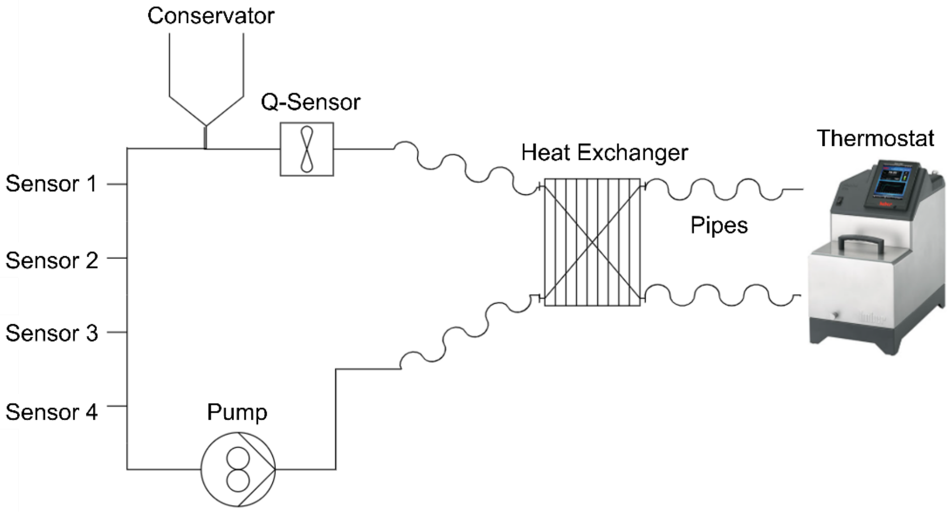

Figure 2: Sketch of the test setup

This means that the ambient temperature and the oil temperature can be modified as shown in *Table 1*. In addition, the flow rate of the oil can also be varied in the test setup described above. Oil temperatures below 0 °C are not investigated in this study.

Table 1: Variation of the oil temperature (T_{Oil}), the ambient temperature (T_{Oam}) and the flow rate of the oil (v_{Oil})

Parameter	Min	Max
T_{Oil}	0 °C	125 °C
T_{am}	– 20 °C	100 °C
v_{Oil}	0.1 m/s	0.8 m/s

2.2 Preparation of oil samples

To create the required set of data, laboratory tests are carried out. This means that the values of the breakdown voltage for the different moisture values are determined experimentally, taking into account the parameters to be varied (e.g. the type of oil, the different temperatures). For this purpose, it is necessary to prepare samples with different moisture contents for the different types of oil. To be able to adjust the oil moisture dry and moist stock solutions are used, which are mixed together in a suitable ratio to cover the full range of moisture. Moist oil is produced by heating water in a round bottom flask and passing water vapor through the oil. The respective oil moisture is determined using a capacitive moisture sensor on the one hand and a Karl Fischer titration on the other.

2.3 Measuring the breakdown voltage

Breakdown voltages are required to establish reference curves. Therefore, a commercially available test device is utilized. For the measurement, the test protocol according to IEC 60156:2018 is adhered to. The alternating voltage is incrementally increased from 0 kV to 10 kV at a rate of 2 kV/s under constant stirring. Subsequently, this voltage is maintained 10 s before further increased at a rate of 2 kV/s until a breakdown occurs. Ten consecutive breakdowns are measured in succession, with a pause of one minute after each breakdown. Finally, an average value is calculated from the individual measurements excluding the highest and lowest two measured values. These measurements were carried out within an oil laboratory that adheres the processes of an accredited laboratory and participates annually in interlaboratory tests to validate the quality of the analysis.

2.4 Deriving the model functions

As already described, the fundamental relationship between the breakdown voltage and the moisture in the oil can be described by an S-curve. These S-curves only represent empirical relationships, and there exists a variety of S or sigmoid functions capable of describing such curves. Table 2 lists nine of them. Initially, these functions are considered to be equivalent in their ability to fit the S-curve.

As part of the modeling process, consideration is also given to meta-parameters and aging effects. Predefined fitting parameters, depending on the type of the oil or the aging status, can be selected manually or through the use of machine learning algorithms. It is assumed that metadata, such as the type of on-load tap-changer and the number of switching operations, is available to a higher-level monitoring system.

Table 2: Overview of various possible fit functions

Function	Definition
Logistical function	$f(x) = \frac{a}{1 + e^{-b\cdot(x-c)}} + d$
Tangent Hyperbolicus	$f(x) = a \tanh\left[b \cdot (x - c)\right] + d$
Arkus tangent	$f(x) = a \cdot \arctan\left[b \cdot (x - c)\right] + d$
Error function	$f(x) = a \cdot \mathrm{erf}[b \cdot (x - c)] + d$
Gundermann	$f(x) = a \cdot \arctan\left[e^{-b\cdot(x-c)}\right] + d$
Gompertz	$f(x) = a \cdot e^{-b\cdot e^{-g\cdot(x-c)}} + d$
Algebraic 1	$f(x) = \frac{a \cdot (x - c)}{\sqrt{b + (x - c)^2}} + d$
Algebraic 2	$f(x) = \frac{a \cdot (x - c)}{b + \lvert x - c\rvert} + d$
4th order polynomial	$f(x) = ax + bx^2 + cx^3 + dx^4 + g$

A standard algorithm is employed to assesses the quality of the standard error for the fitting parameters, enabling the calculation of a prediction interval (coded as prediction interval). This interval delineates the range of values within which future measurements can be expected with a specified probability. These intervals differ from confidence intervals, which describe the range of values of already measured data with a fixed probability. In the subsequent figures, the 95 % prediction interval is consistently provided.

The assumption here is that the breakdown follows a normal distribution and can be approximated by the t-distribution.

In this study, the logistical function exhibited the best agreement. The optimum S-curve was found using the orthogonal distance regression (ODR) algorithm of the python library SciPy. ODR allows the consideration of measurement uncertainties of the training data in both the x- and y-dimensions. The fitting proved to be robust against the variation of the initial parameters.

2.5 Sensor requirements

The sensor to indicate the breakdown voltage must fulfill various criteria, especially, for application in a tap-changer. It is crucial to consider that the available access points for sensors in OLTC's are very limited, and the sensor may have to be able to cover multiple functions. The installation requirements in an on-load tap-changer can be summarized as follows:

- Compliance with the maximum installation space above the cover of the on-load tap-changer to prevent possible collisions with the drive linkage or the gearbox

- Compliance with the maximum installation space below the cover of the on-load tap-changer, negative dielectric influences must be prevented - the sensor may therefore only be installed inside field shadowing of the protective electrodes

- Compatibility with the user guidelines - these can be very individual and require, for example, redundant temperature measurement and an operating temperature of at least 125 °C

- As a low-cost sensor, as few physical variables as possible should be detected that are easy to record; to ensure multifunctionality, the sensor should have active and passive temperature measurement sensors

- The variables to be measured must be guaranteed with sufficient accuracy in a wide range of possible oil temperatures and ambient temperatures

The sensor presented here therefore has a redundant temperature measurement (active and passive) and a capacitive moisture sensor to determine the oil moisture. Figure 3 shows a 3D sketch of the sensor (left), a drawing of the sensor (center) and a picture of the sensor in its installed state (right). The housing shape is selected in such a way that on the one hand a collision with the drive linkage can be ruled out and the sensors cannot have a detrimental dielectric effect.

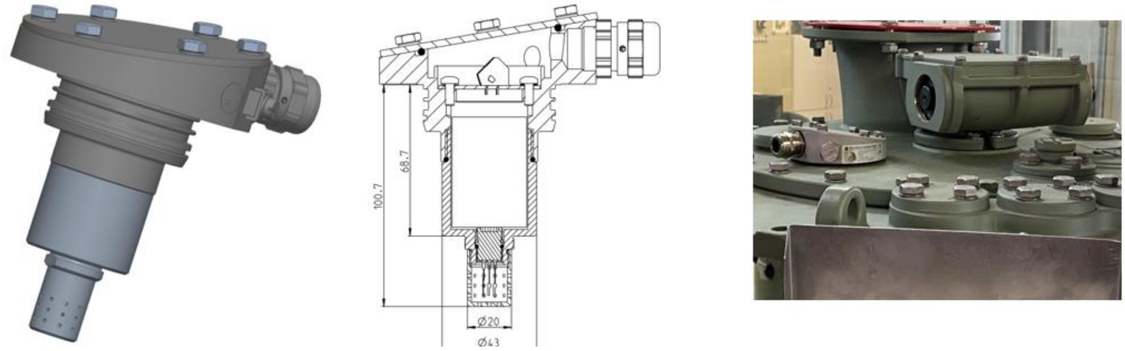

Figure 3: Sensor 3D sketch of the sensor (left), a drawing of the sensor (center) and a picture of the sensor installed (right)

3. Results and Discussion

3.1 General results

As described, there are numerous factors influencing the breakdown voltage of insulating oils, with some even interact. Oil type, oil age and relative humidity have been identified as particularly important. The results for six different oil samples (referenced above) are described and discussed below. Relative humidity is systematically varied for each oil sample, and the resulting breakdown voltage is measured, with an individual S-curve is recorded. Moisture reference values are recorded in the test cup or via a capacitive moisture sensor integrated into the test setup, while breakdown voltage reference values are recorded in the previously described breakdown voltage device. Since breakdown voltage depends on the relative humidity, which is in turn is a function of the oil temperature, the breakdown voltage is also temperature dependent. The question arises whether a change in temperature has an effect beyond the change in relative humidity. On the one hand, an increase in temperature theoretically leads to a reduction in density and viscosity, which should reduce the breakdown voltage. On the other hand, the scatter of the breakdowns is very high, so that the effect may be obscured within the error bars of the standard measurement and may only be discernible with a significantly higher number of breakdowns. Using mineral oil type A as an example, the S-curves at 25 °C, 40 °C, 60 °C and 80 °C are recorded and compared with the aid of the heated test cup. It's important to note that no effects of paper insulation are considered in the arrangement due to its negligible relevance in modern OLTC designs. The results are depicted in Figure 4, where the logistic function is employed for fitting.

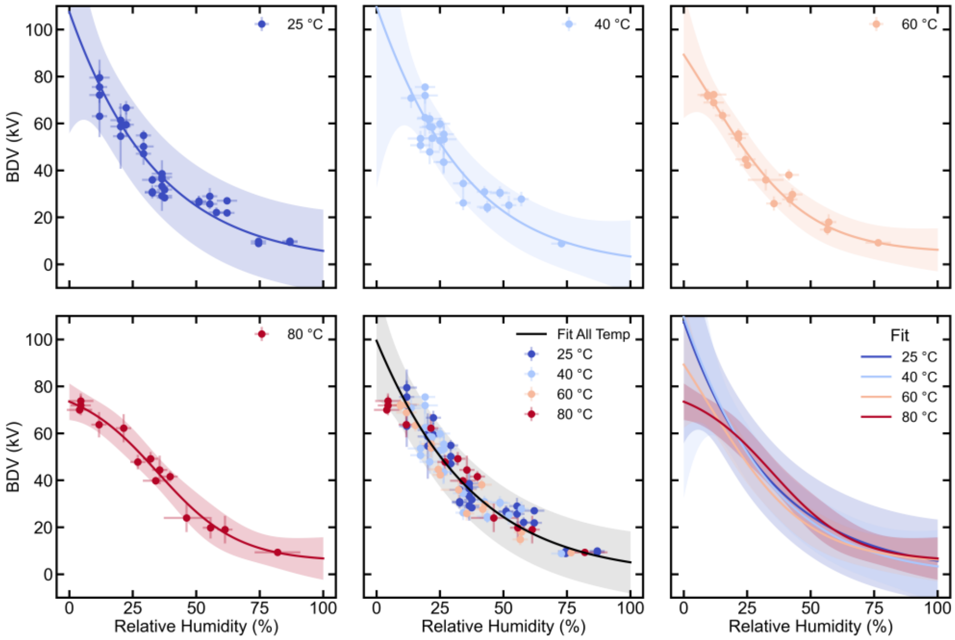

Figure 4: Breakdown voltage as a function of relative humidity for fresh mineral oil Type A at different (elevated) temperatures.

Within the scope of the measurement inaccuracy, no influence of the temperature beyond the change in relative humidity can be recognized.

The scenario of cooling to low oil temperatures is particularly critical, as the relative humidity rises sharply due to the exponential saturation behavior. Hence, the scenario of cooling is also considered. The results are shown in Figure 5. A direct comparison of the recorded points shows that the values for 5 °C align well with those at elevated temperatures. In fact, they fall perfectly within the range predicted by a fit using only the data for the high temperatures. Moreover, incorporating the measured values at 5 °C results to an almost negligible change in the fitted curve.

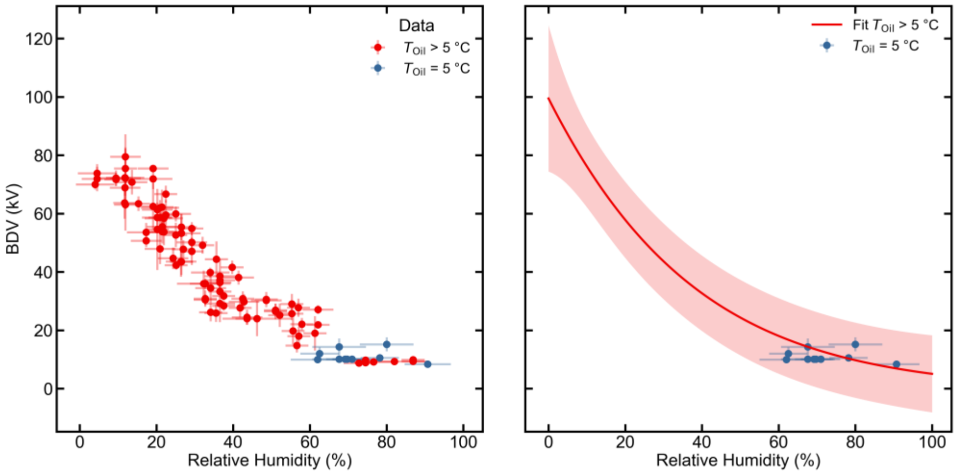

Figure 5: Breakdown voltage as a function of relative humidity for fresh mineral oil type A with cooling oil

An overview of the breakdown voltage values collected for the individual oil samples is shown in Figure 6. Three recognitions become clear at first glance. Firstly, the point curves differ greatly, confirming the expectation that the type of oil has a major influence on the breakdown voltage.

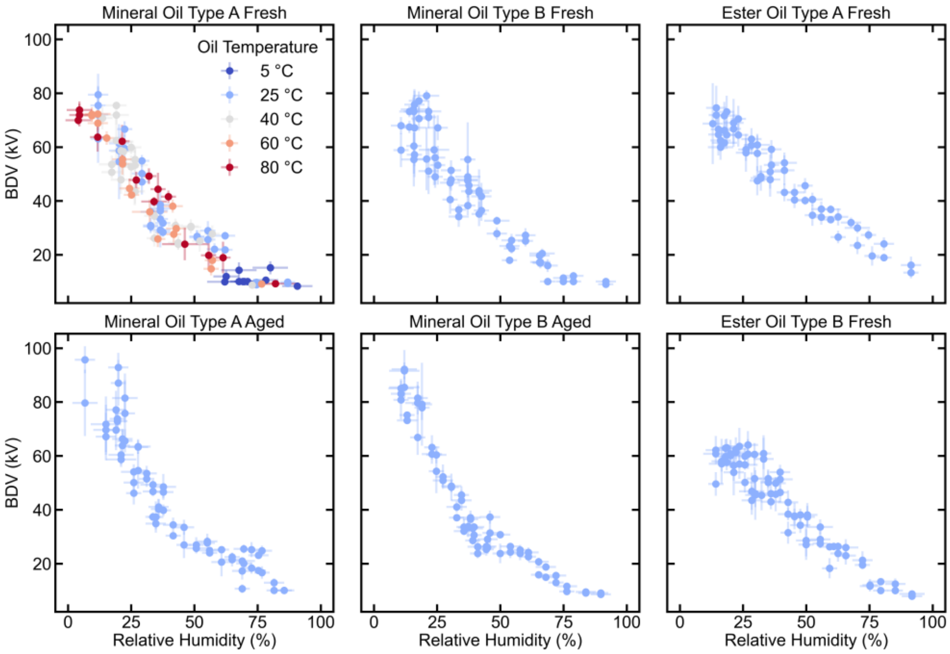

Figure 6: Overview of all measured breakdown voltage data.

Secondly, the large scattering of the breakdown voltage at the same relative humidity is striking. This uncertainty is taken into account in the adjustment process through the use of prediction bands. Thirdly, it is worth noting that no saturation was observed at low relative humidities. Stagnation at low moisture levels can be expected based on the investigations in the past and has also been confirmed in the context of preliminary investigations for this publication [10]. Up to a relative oil moisture content of around 15 %, the breakdown voltage decreases only minimally. This can be attributed to the fact that very dry oils absorb moisture from the environment during the experiment. For this reason, the lowest moisture levels achieved were typically between 10 % and 15 %, just above the range where saturation is expected. As a consequence, the fitted curves (presented similarly) resemble an exponential decay rather than an S-curve. This effect can be explained as already done above. Each of the oils investigated reaches at least 60 kV at the lowest relative humidities. Therefore, a decision making between good and poor quality in terms of the breakdown voltage is possible at any time.

The effect of oil ageing is examined subsequently. For mineral oil type A and B, the tests are therefore carried out for both aged and fresh oils.

The graph (Figure 7) on the left clearly shows that for mineral oil type B there is only a marginal difference between aged and fresh oil in terms of the scattering of the breakdown voltage. Oil ageing is a complex process that simultaneously alters many oil properties with an influence on the breakdown voltage. However, the breakdown voltage tends to decrease.

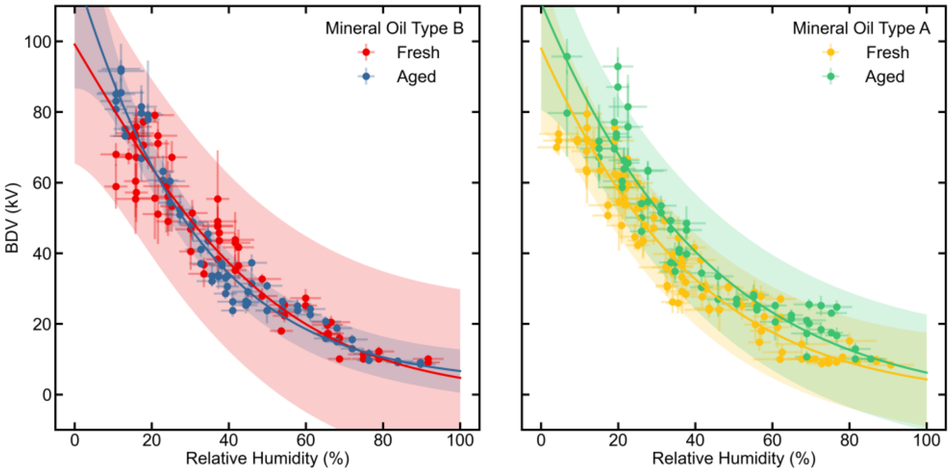

Figure 7: Comparison of the breakdown voltage for new and aged mineral oil type B (left) and type A (right)

A lack of clear visibility of the effects can be caused by the test method according to IEC 60156:2018. Due to the duration of the standard measurement of 30 seconds, particles cannot always align themselves in the field and therefore cannot always influence the breakdown process. The results for mineral oil type A, on the other hand, show that there is a slight shift in the two curves. Unexpectedly, the curve for used oil is higher than that for fresh mineral oil type A. Considering the above remarks on mineral oil type B, it seems completely implausible that ageing actually leads to an increase in breakdown voltage. The suspicion therefore arises that the mineral oil mixture, which is supposed to be representative of aged mineral oil type A, contains additives from another type of oil. The samples examined were taken directly from the field and for historical reasons not all oil handling activities were documented. The operator is therefore unable to rule out a mixture of oil types. To investigate this, the density of the two mineral oil samples (type A oil samples) are determined. As it can be seen in Figure 8, the used oil sample has a significantly reduced density. This suggests an admixture of a GTL oil with a lower density, such as the mineral oil of type B (see dashed lines in Figure 8 for the densities according to the manufacturers' data sheets). This assumption also corresponds well with the observation of the higher breakdown voltage of the used oil sample of type A, because type B has a slightly higher breakdown voltage (Figure 9).

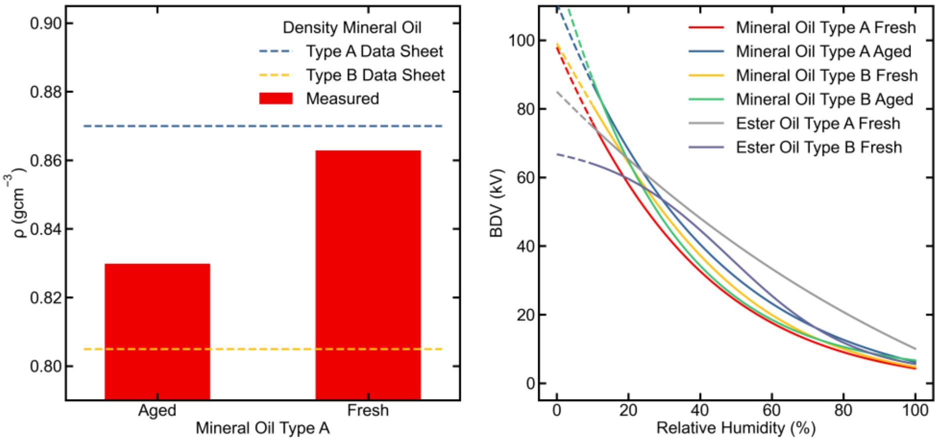

Figure 8: Density measurement of the oil samples (left) and comparison of the fitted logistic functions for the six oil samples analyzed (right)

In order to be able to evaluate an influence independent of the naturally aged oils, an additional investigation is carried out with artificially aged, i.e., oils subjected to thermal aging. The results of the test series for three types of oil are depicted in the following Figure 9.

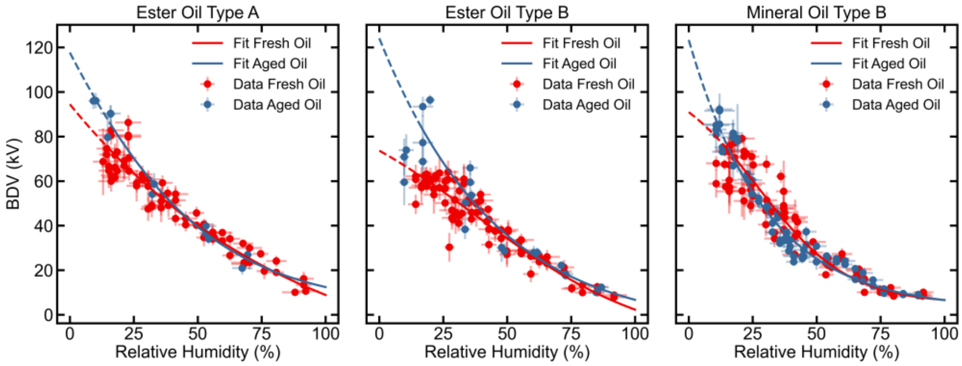

Figure 9: Results for artificial aged oil samples

In summary, based on a comparison of the measurement results according to IEC 60156:2018, a dependency based on the oil age can initially be disagreed, whereas an influence of the oil type can be clearly confirmed. Furthermore, it can be recognized that this dependence is usually expressed by a shift in the S-curves. An adjustment of the respective curves and thus the determined breakdown stress can therefore be made by adjusting the parameter “d” within the formulas from Table 2.

If a measured value of the breakdown voltage is inputted to the algorithm within the higher-level monitoring system, the parameter “d” can be adjusted automatically to the value of the respective oil grade. This adjustment is unnecessary for pure, known oils, but the accuracy is increased if unknown oils are used. Generally, however, the type of oil used is known and a pure mixture can be assumed, so that this adjustment is unnecessary.

3.2 Model accuracy

To determine the accuracy, the accuracy of the reference measurement is initially determined. For this purpose, an oil sample is extracted from an oil volume of approximately 200 l and measured 50 times.

As depicted in the boxplots in Figure 10, breakdown voltages between 50 and 100 kV are measured, with the medians of the measurements clustering around 80 kV. The distribution of the breakdown voltage of the individual breakdowns is shown in the diagram in *Figure 10* on the right. Due to the distribution, the fitting of a normal distribution and a Weibull distribution yield very similar results.

The standard deviation of the fitted normal distribution is approximately 10 kV and can be considered as an estimate for the dispersion of the breakdown voltage. Initially, this value corresponds to the maximum accuracy or error permitted by the fit function. All measured reference points are utilized to assess the forecast bands. For a normal distribution, the range of $\mu \pm \sigma$ encompasses 68% of the measured values. Therefore, the 68% prediction band is considered to estimate the accuracy of the fit.

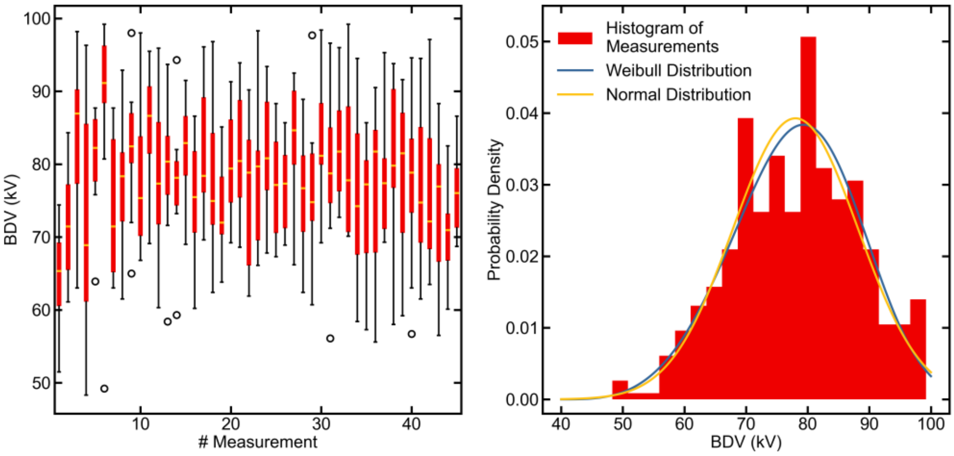

Figure 10: Box plots and distribution

As the prediction band depends on the relative humidity, its values differ at different points on the S-curve. It can be observed that the mean error of the fit is between 3 kV for old and 13 kV for new mineral oil of type B. For new mineral oil of type A, the fitting error of around 7 kV is even slightly below the standard deviation of the individual breakdowns. Therefore, the average fitting error is within the range of the natural dispersion of the breakdown voltage measurement according to IEC 60156:2018, which shows the quality of the fitting.

3.3 Accuracy and comparison with field data

Firstly, the accuracy of the simplified model is discussed. The deviation from the respective final BDV curve is determined for each of the breakdown voltages measured in the laboratory tests. The distribution of the deviation for the critical range below 60 kV is shown in Figure 11 as a histogram for the respective oil types. It is noticeable that the accuracies for the different oil types differ slightly. While 98% of the deviations for ester oil of type A are below 10 kV, the figure for the ester oil of type B is only 83%.

To better evaluate this deviation, the expected deviations from standard laboratory analyses should be taken into account. Each laboratory ensures its analysis capability and quality by participating in round robin tests. An identical partial sample is sent to the participating laboratories and the results are compared. An evaluation of a series of round robin tests shows that deviations of 12 kV can occur between the laboratories. This illustrates the statistical nature of the breakdown voltage.

As shown in Figure 11 , the deviations for all oils are below this 12 kV threshold in 95 % of cases, which must be evaluated taking into account the sensitivity of the sensor. To obtain a comprehensive picture the sensor shown in Figure 3 is implemented in a real arrangement and continuous comparative measurements are conducted regarding variables such as temperature, oil moisture and the derived breakdown voltage.

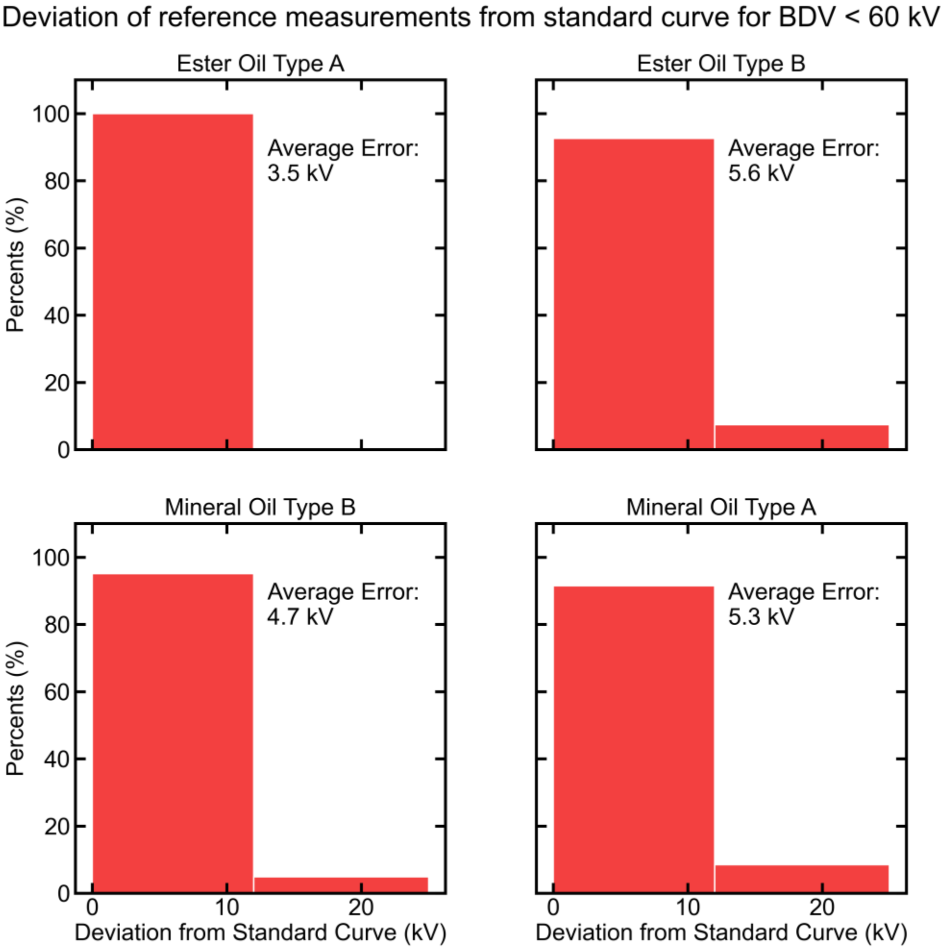

Figure 11: Accuracy

As not enough data were available for evaluation at the time the paper was completed, the model approach is evaluated using historical data. The available measured moisture values of a transformer are utilized in the model. Since the moisture values provided originate from analyses conducted by different laboratories and over a period of several years, the values shown in blue in Figure 12 show wide scattering. Therefore, based on IEC 60422 or TB 761, a deviation into three different areas is conducted out (red < 40 kV; yellow 40 to 50 kV; green > 60 kV). It can be observed that despite the large scatter and the existing deviation of the fit and the available data, the indication, i.e. the classification into the three ranges, was consistently maintained (Figure 12).

In summary, the results demonstrate sufficiently good accuracy based on the use of a low-cost sensor. By employing the simple model approach and the knowledge of temperature and moisture, the operator can reliably and promptly detect serious errors and thus achieve significant added value compared to the current evaluations in the laboratory.

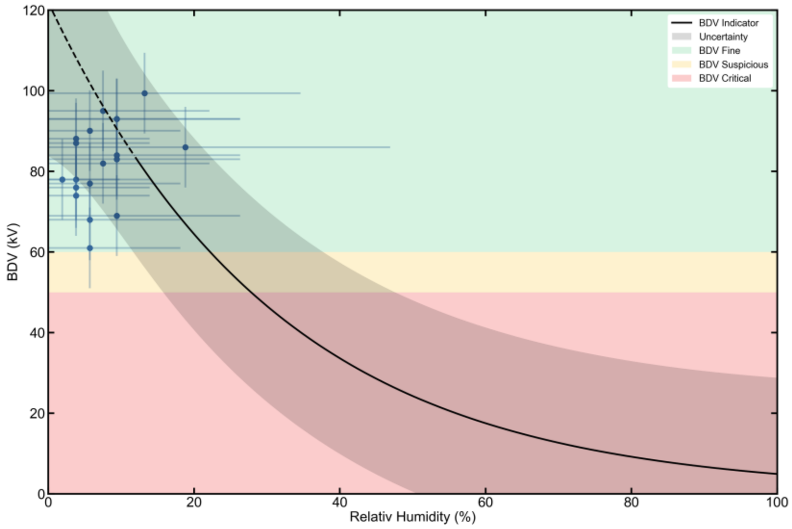

Figure 12: Application of field data

Outlook

To further validate the approach, not only the current field test will be followed up, but additional tests will also be conducted in OLTCs and transformers. Furthermore, the mentioned effect of saturation at very low moisture values of less than 10 % is also investigated in an extended and specialized test setup. These results will be published soon.

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