Online Monitoring of Transformer Oil Breakdown Voltage

Applying laboratory BDV test results to transformer operation in real-time

ABSTRACT

The standard oil BDV test is performed on oil samples removed from the transformer and is representative only for the oil condition during the laboratory test due to changes in the oil sample's relative humidity between the time of sampling and the time of the test. The water content in oil is continuously changing during transformer operation due to moisture migrating to and from the cellulose. Furthermore, an oil temperature gradient exists inside the transformer from top to bottom, and variations in loading and active cooling during operation dynamically change the oil's relative humidity, and thus change the BDV depending on internal location and time. To provide an accurate assessment of oil dielectric condition under a range of operating conditions, an online estimation for the oil BDV is needed. In this paper, an online BDV calculation methodology is proposed.

KEYWORDS:

Dielectric breakdown voltage; BDV; relative humidity; temperature; transformer; online monitoring

Day-to-day changes in the oil temperature and moisture content lead to dynamic changes in oil BDV

1. Introduction

The standard oil breakdown voltage (BDV) test is used to evaluate the ability of insulating oil to sustain electric stress. Excessive moisture or particles in oil will reduce its electrical insulating properties, which could result in electrical faults producing electrical discharges and/or arcing inside the transformer. The oil BDV test is performed on oil samples removed from a transformer using the methods defined in the industry standards [1, 2].

A significant issue concerning laboratory BDV test results is that the results are representative only for the oil condition at the time of the laboratory test. Although BDV may be influenced by the presence of particles and some other factors, for most transformers, BDV is mainly dependent on the oil's relative humidity (RH). However, because the sample temperature of the oil during the BDV test differs from its original temperature inside the transformer, the RH will change. Therefore, the BDV result will not be representative of the actual condition of oil inside the transformer [3]. Furthermore, the dynamic thermal conditions, in which the oil temperature is higher at the top of the tank and lower at the bottom, will produce different oil RH and, thus, different BDV by internal location. Furthermore, the water content in oil (WCO) is continuously changing during transformer operation due to moisture migrating to and from the cellulose as the transformer windings and oil temperatures increase and cool down with changes in loading and ambient temperature.

Laboratory BDV test results are representative only for the oil condition at the time during the laboratory test and can differ from the actual condition in the transformer

For these reasons, the oil BDV test performed on samples removed from the transformer fails to provide a correct assessment of the oil condition in the operational transformer and is not representative of associated risks from potential electrical faults inside the transformer.

To provide a more accurate assessment of the oil BDV and the transformer condition under a range of operating conditions, online measurement or estimation of the oil BDV is needed. In this paper, an online BDV calculation model is proposed. Similar analytical models are applied in transformer online monitoring, such as for determining the 'bubbling temperature' at the transformer rapid heating or condensing free water in oil ('rain in oil') as oil quickly cools down. Both conditions could result in oil breakdown and transformer failure if they occur. However, these extremes reaching bubbling temperature or free water in oil are rare occurrences, whereas oil breakdown may occur within a range of operating conditions between these extreme conditions. Therefore, an oil BDV model can fill an important gap in online monitoring models and condition assessment of transformer oil by identifying potentially dangerous operating conditions during thermal changes inside the transformer.

2. Online BDV model

Multiple studies in the industry have shown a correlation between oil BDV and RH, as shown by the graphical models. In the publications [4] and [5] the following equations (1) and (2) are proposed for the laboratory BDV test results as empirical models:

$$BDV_{pu} = BDV_{min} + \frac{BDV_{max}-BDV_{min}}{1+e^{\frac{RH-RH_{midspan}}{RH_{timeconstant}}}} \quad (1)$$

$$BDV_{pu} = 95 * e^{-\left(\frac{RH}{63.15}\right)^2} + 5 \quad (2)$$

The constant terms in equation (1) are given in [4], The BDV vs RH relationships described by equations (1) and (2) can be seen in Figure 1.

The results of equations (1) and (2) are expressed as % of the maximum BDV of dry oil. Equation (3) is used to convert BDVpu to the actual BDV value in kV:

$$BDV_{kV} = BDV_{pu} * BDV_{dry} \quad , \quad (3)$$

where BDV_{dry} is the virtual oil BDV [kV] of dry oil when the oil has an RH = 0%. Evaluating BDV_{dry} will require laboratory test results of WCO and BDV available for the same oil sample by the procedure shown in Figure 2:

The set of equations (1-3), together with the procedure of the dry oil BDV estimation (Figure 2), form the basis of the online BDV estimation model.

3. The effects of temperature and RH distribution in the transformer on BDV

The RH in transformer oil may be directly measured online using capacitive sensors in the transformer. However, one problem is that the RH of oil will vary throughout the transformer, and therefore, the online estimation of BDV by online monitoring will be dependent on the sensor location.

To overcome this limitation, oil RH may be calculated at any region inside the transformer tank where WCO and temperature are known according to equation (4):

$$RH = \frac{WCO*100}{W_s} \quad (4)$$

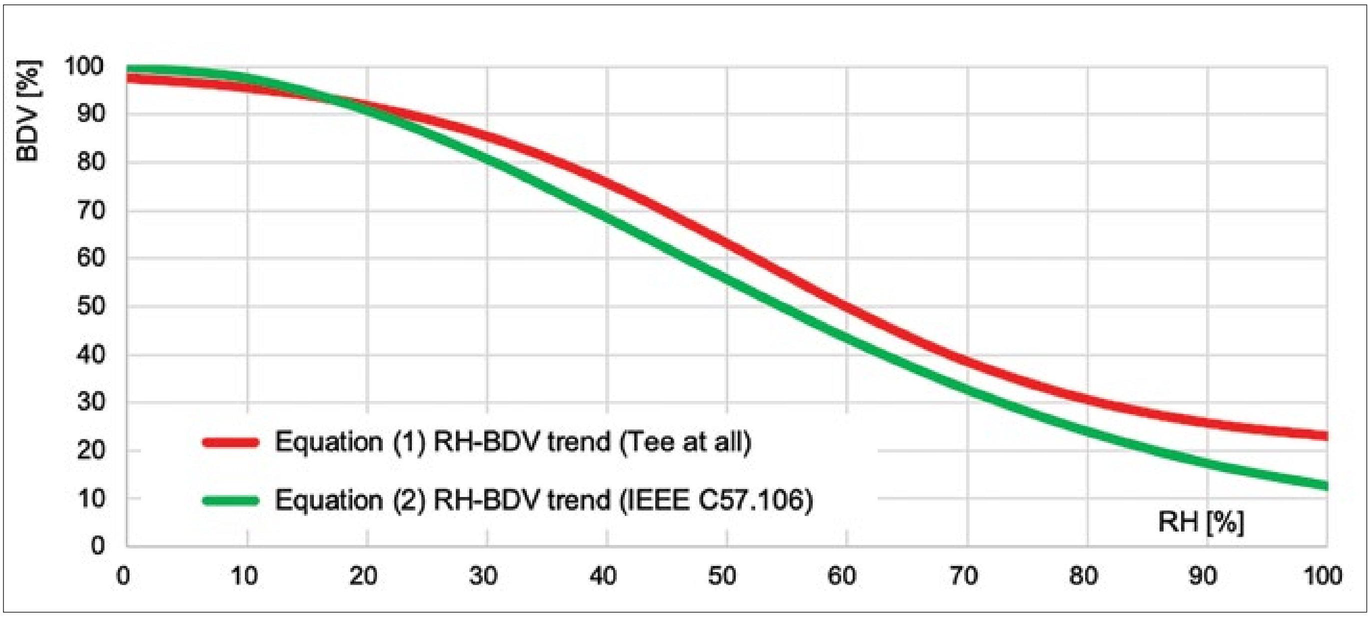

Figure 1. BDV(%) versus RH by equations (1) and (2)

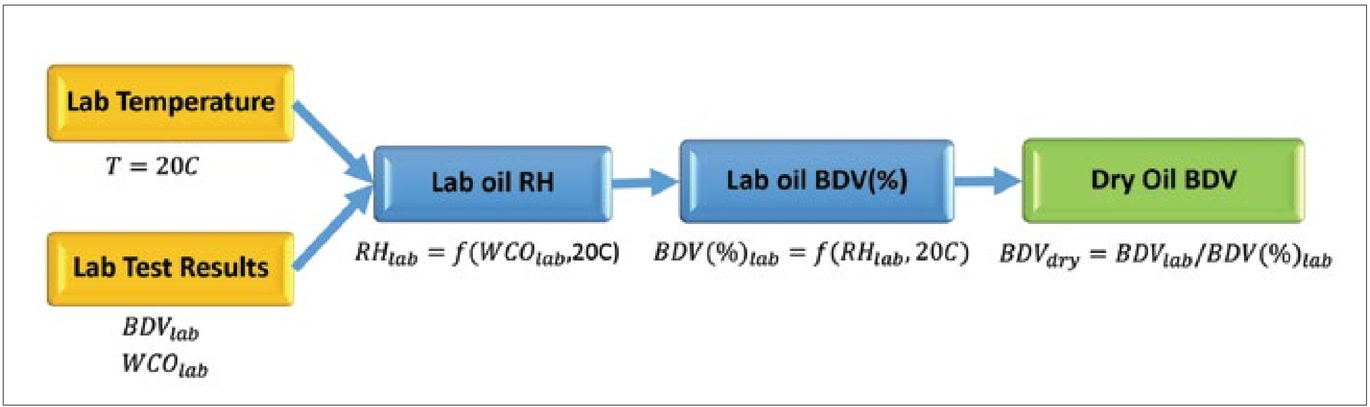

Figure 2. Procedure for Dry oil BDV estimation from lab test results.

The relationship between water content, temperature, relative saturation and BDV may be used for the online estimation of BDV at different locations inside the transformer

where Ws is the transformer oil saturation moisture limit and can be determined from equation (5):

$$W_s = 10^{\left(A - \frac{B}{T}\right)} \quad (5)$$

where A and B are constants whose values are dependent on the type of oil and its ageing state, and T is transformer oil temperature in Kelvins.

Although the RH and temperature vary within the transformer oil volume, the WCO may generally be considered uniform throughout the transformer [6]. This uniformity can also be verified by testing for WCO using Karl Fisher titration on two independent oil samples retrieved from a sampling point near the top of the tank and at the bottom. Because the WCO can be assumed uniform, the further RH estimation can be simplified as just a function of oil temperature at all locations in the transformer tank. Thus, oil RH distribution through the transformer can then be evaluated by following these two methods:

1) Determine the WCO at a single location inside the transformer. It can be equally evaluated by an online monitoring system from simultaneous measurement of the oil RH and the temperature at the same location.

2) Define oil RH for all points within transformers where temperature sensors are installed or where thermal models can predict temperature. The oil temperature may be directly measured at the top and bottom parts of the transformer by externally mounted or inserted in thermowells temperature sensors, while the temperature in internal parts, even under high voltage, may be measured by fibre optic temperature sensors. Alternatively, internal temperature distribution can be estimated based on methods described in IEC 60076-7 [7] using a transformer thermal model (see Figure 3) or other models.

Figure 3 shows that oil RH distribution in a transformer is opposite to the distribution of temperature. As oil BDV is inversely proportional to oil RH, the transformer bottom oil is expected to have the lowest BDV (parts of the main insulation and winding bottom part) and the area around the windings hot spot is expected to have the highest oil BDV.

Due to the non-linear BDV vs. RH relationship (see Figure 1), the BDV properties may be highly sensitive to temperature distribution within the transformer. BDV can be uniformly good or poor within all regions of the transformer, or there may be very localized regions where the BDV properties have a sharp transition from good to poor.

In summary, the relationships WCO-to-RH and RH-to-BDV may be used for online estimation of BDV at different locations inside the transformer. If an online monitoring system is capable of continuous measurement of WCO at any single location and temperatures at multiple locations inside the transformer, then by having laboratory results for BDV and WCO from the same sample as the base point, the real-time BDV can be estimated at all these regions inside the transformer.

4. The effect of temperature variation during transformer operation on BDV

Previously, we established that WCO is approximately uniform in all regions of the transformer, while oil RH can vary between regions as a function of temperature. However, the WCO in transformer oil is not constant over time due to moisture migrating in-and-out of the

Although the RH and temperature vary within the transformer oil volume, the WCO may generally be considered uniform throughout the transformer

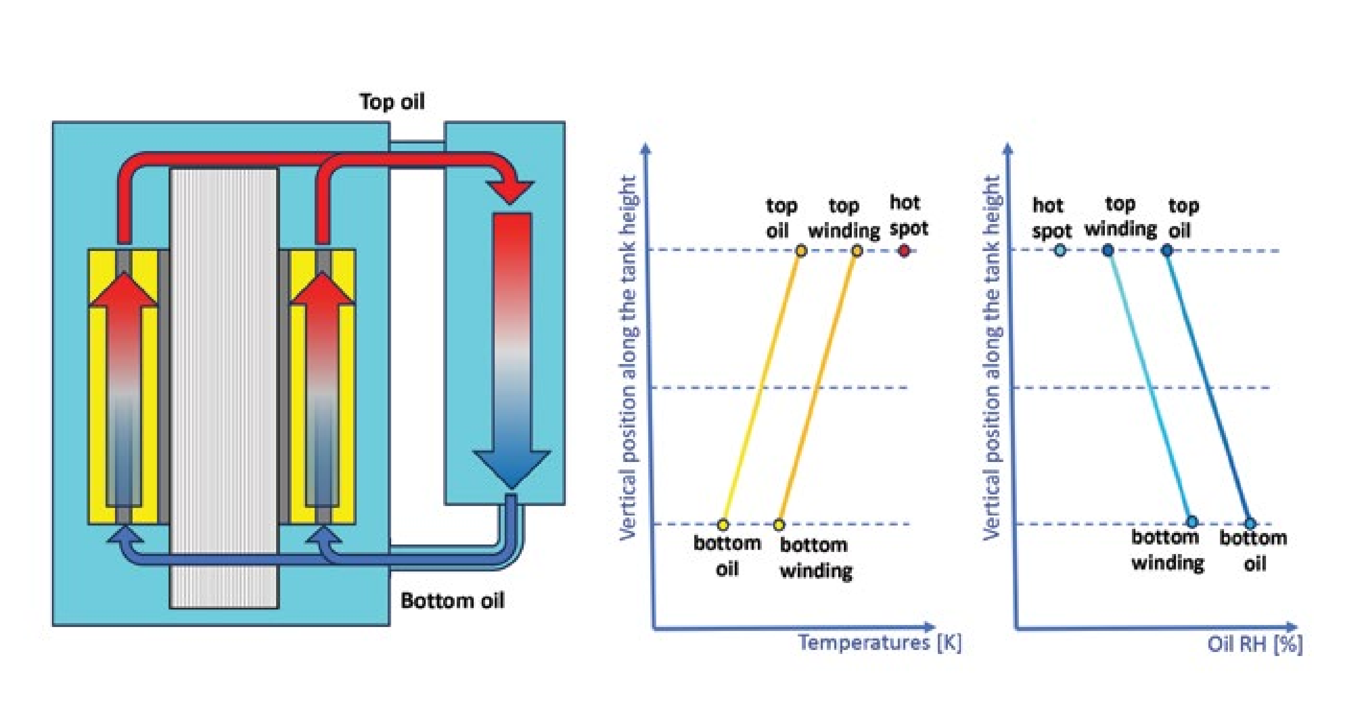

Figure 3. Temperature distribution by an IEC model from [7] and oil RH distribution by the transformer height

Rapid temperature decrease can lead to the increase of the oil Relative Humidity above the equilibrium condition, resulting in a temporary reduction of the oil BDV

transformer cellulose insulation driven by temperature changes in the active part. Dynamic changes in transformer loading, resulting in oil temperature variation, can lead to scenarios where oil BDV is reduced. In this section, the phenomenon of intermittent reduced BDV is discussed.

Most of the moisture in a power transformer is stored in the cellulose insulation. The moisture migrates between cellulose and oil when thermal equilibrium conditions change following temperature variations. The speed of the moisture migration between oil and cellulose is temperature-dependent. For example, because the speed of the establishment of equilibrium is based on diffusion time constants (see Table 1), the equilibrium will happen much faster at 70°C than at 20°C.

The transformer thermal time constant is in the range of 1.5-3.5 hours [7], which is approximately equal to the moisture diffusion time constant at high temperatures. In turn, at low temperatures, the change in oil temperature happens much earlier than a new moisture equilibrium can be reached.

At a fast temperature decrease, moisture migrates from the oil back to the cellulose but requires more time for equilibrium due to larger diffusion time constants. As a result, while there is a slow reduction of the WCO, the oil RH at such moments is increased over the expected for equilibrium conditions, resulting in a temporary reduction of the oil BDV (see example in Figure 4). This problem of potential BDV reduction when transformers are subjected to a fast temperature decrease is mentioned in [10] and addressed in detail in [11].

Routine maintenance, where oil samples are retrieved from the transformer for condition evaluation of WCO and BDV, is unlikely to coincide with these dynamic loading/temperature change periods. In the case of online monitoring, it is possible to continuously track the variation in RH and thus calculate the change of real-time oil BDV by applying the model described above.

Table 1. Diffusion time constants for oil-impregnated pressboard by Foss [8] and Guidi [9]

Oil-impregnated pressboard by 1mm thickness				
Temperature, °C	**20**		**70**	
Author	Foss	Guidi	Foss	Guidi
Diffusion time constant (hours)	333	678	6	15

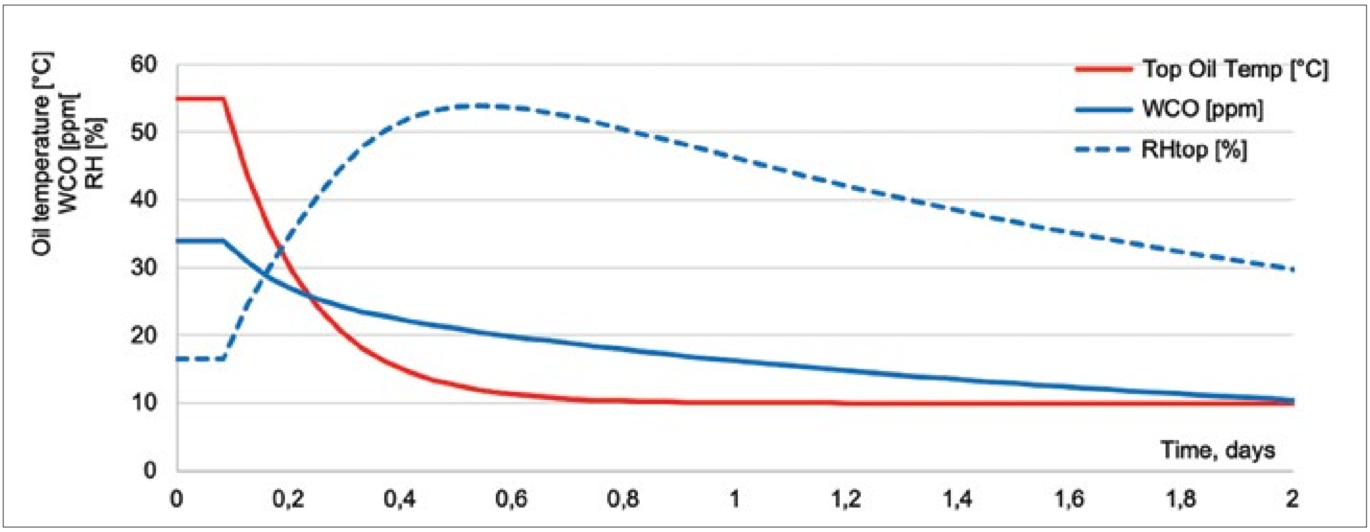

Figure 4. Modelled temperature and moisture trends of the de-energizing event of the ONxx-cooled transformer with 4% of the moisture in cellulose. The drop of the top oil temperature from arbitrary 55°C to 10°C of the ambient temperature causes the temporary increase of oil RH.

5. The example of BDV evaluation of a real transformer

The minimum BDV value does not coincide with the moment of the load increase but occurs about half a day after the transformer returns to the normal regime

In this example, online monitoring data from a transformer has been used to evaluate real-time oil BDV in post-analysis. The following data were available for the analysis:

- online oil temperature data from the top and the bottom of the transformer tank
- online water content in oil (WCO) from a single location
- laboratory measurements for WCO and BDV from the same oil sample

The condition of the transformer was examined over a specific period where the transformer was subjected to overloading (approximately triple load over its typical routine level) for the duration of 5 days, followed by a return to typical loading. The loading profile, temperatures and WCO are shown in Figure 5.

Upon returning to normal load, the BDV was reduced due to the phenomenon of temporary oil RH increase at fast oil temperature drop.

The steps for online BDV evaluation are:

- laboratory tests results WCO = 22 ppm, and BDV = 53 kV
- conversion of laboratory BDV to BDVdry (see Figure 2 for procedure)
- either equation (1) or (2) can be used for BDV modelling

In Figure 6, equation (2)-based model results for the real-time bottom and top oil BDV are shown.

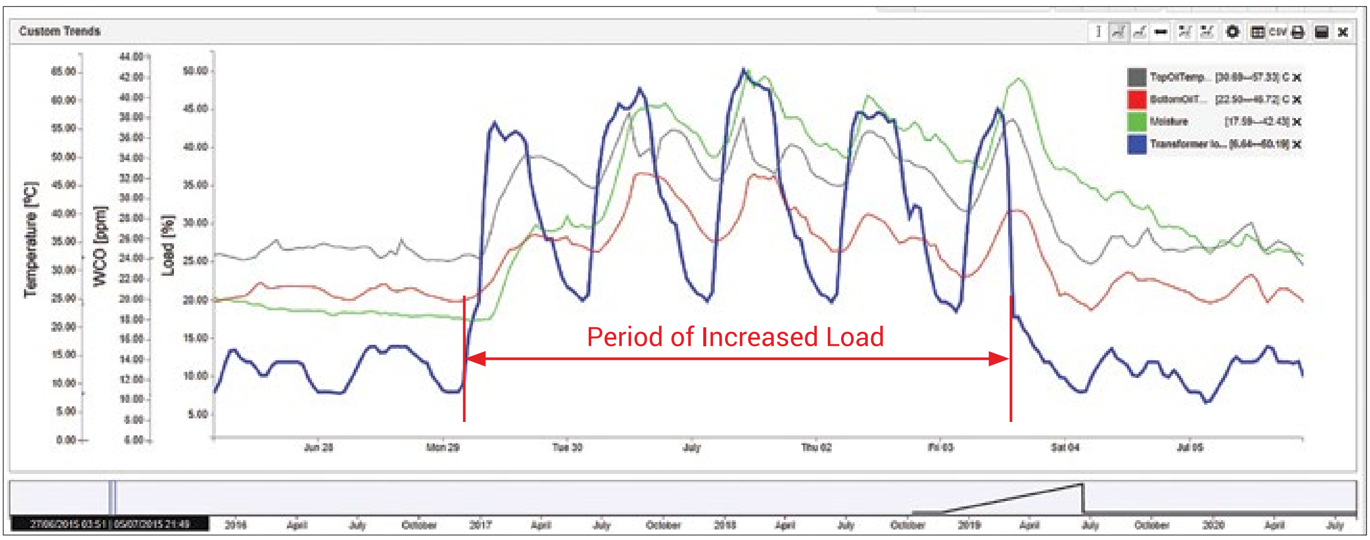

Figure 5. Load, Top/Bottom oil temperature and WCO profiles of a wet distribution transformer during temporary operation with an increased load.

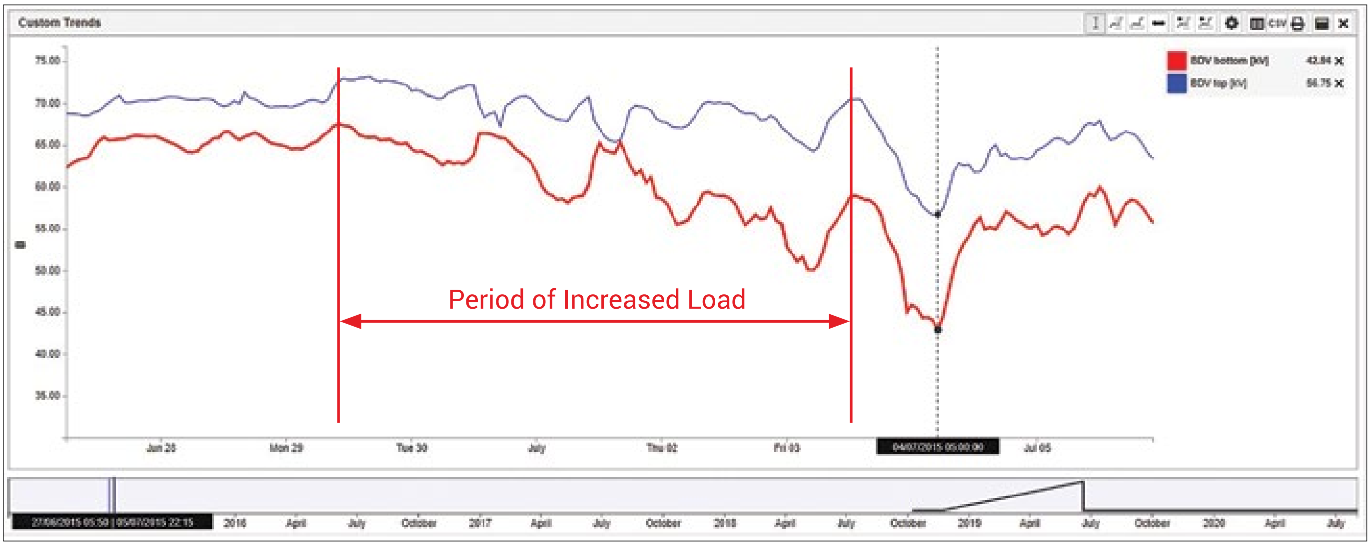

Figure 6. Modelled real-time oil BDV

With the proposed method, oil BDV values reaching critically low levels can be identified online and in different loading conditions, even if these critical levels are only intermittent

An analysis of the online BDV behaviour in Figure 6 suggests the following:

- The minimum BDV value does not occur during the period of increased load but about half a day after the transformer returns to normal regime.
- There is a clear difference in real-time BDV at the top and bottom of the transformer.
- The online data show that, while the laboratory test was showing BDVs of 53kV at 22ppm WCO, the transformer normally operates with real-time BDV in the range 60-70kV for top and bottom oil.
- A case was previously reported in [11] where, based on a study in [12], the bottom oil BDV reduction was estimated at 33% from the laboratory results. The modelled process reveals very similar results, with bottom oil BDV dropping by 35% from its typical values before the event.
- Continuous evaluation clarifies that there are no other dangerous periods that could be potentially overlooked by manual analysis for specific moments of time.

A deeper diagnostic value can be obtained by using the oil temperature together with the WCO and BDV. In Figure 7, the WCO and oil temperature results are plotted on a map with the oil BDV indicated by a colour-mapped histogram (BDV map) for the same transformer modelled for a longer period of its operation.

The regions indicated by blue boxes in Figure 7 indicate the following sequential operating conditions for the transformer:

1. Normal transformer operation
2. Period of increased load (with the min-

imum BDV during return to normal operation)
3. Transformer de-energized for online oil processing equipment connection (second reduced BDV period)
4. Transformer oil treatment period
5. Transformer operation after oil treatment

The BDV Map can display the online data in a two-dimensional graph showing the dependency of the oil BDV with the real operating onditions in terms of temperature and moisture

One can clearly see that, for the majority of transformer operations, the oil BDV is at a safe operating condition (>50kV for this transformer voltage class). However, at two moments, the first one right after the period of the increased load and the second one after the transformer is de-energized for oil processing equipment connection, the reduction in temperature and the delayed moisture distribution equilibrium resulted in increased oil RH and thus finally in a reduced real-time BDV. After the transformer oil treatment is performed, it reduces the moisture content and oil BDV stays in a safe operating condition.

6. Conclusion

The analytical model for BDV calculation defined in equations (1)-(3), along with the application of online monitoring for WCO and temperature at multiple locations inside the transformer, provides the required data for the calculation of RH and estimation of BDV under sudden temperature changes. In scenarios of slow or sudden temperature variations, this online monitoring estimation can determine the RH and the BDV at multiple locations inside the transformer in real-time. By using this methodology, the oil BDV values reaching critically low levels can be identified, even if these critical levels are only intermittent, under certain loading variations.

This paper has demonstrated that the modelling of BDV utilizing online monitoring data for moisture in oil and temperature monitoring is feasible. The online method enables the detection of phenomena which cause reduced oil BDV due to sudden changes in the operating conditions, such as a reduction in loading or a change in the cooling conditions. The information can also be used to inform when oil reconditioning is recommended to remove moisture from the transformer.

A representation of the real-time BDV model trended with other online data provides valuable diagnostic information. BDV information can be visualized as a new proposed chart type called “BDV map”. The BDV map can display the online data in a two-dimensional graph with oil BDV values colour-mapped, providing the relationship of BDV change to operation conditions such as oil temperature and moisture content. This visualization informs operators which operating regimes for loading and temperature changes expose the transformer to risk due to dynamic changes in WCO and temperature.

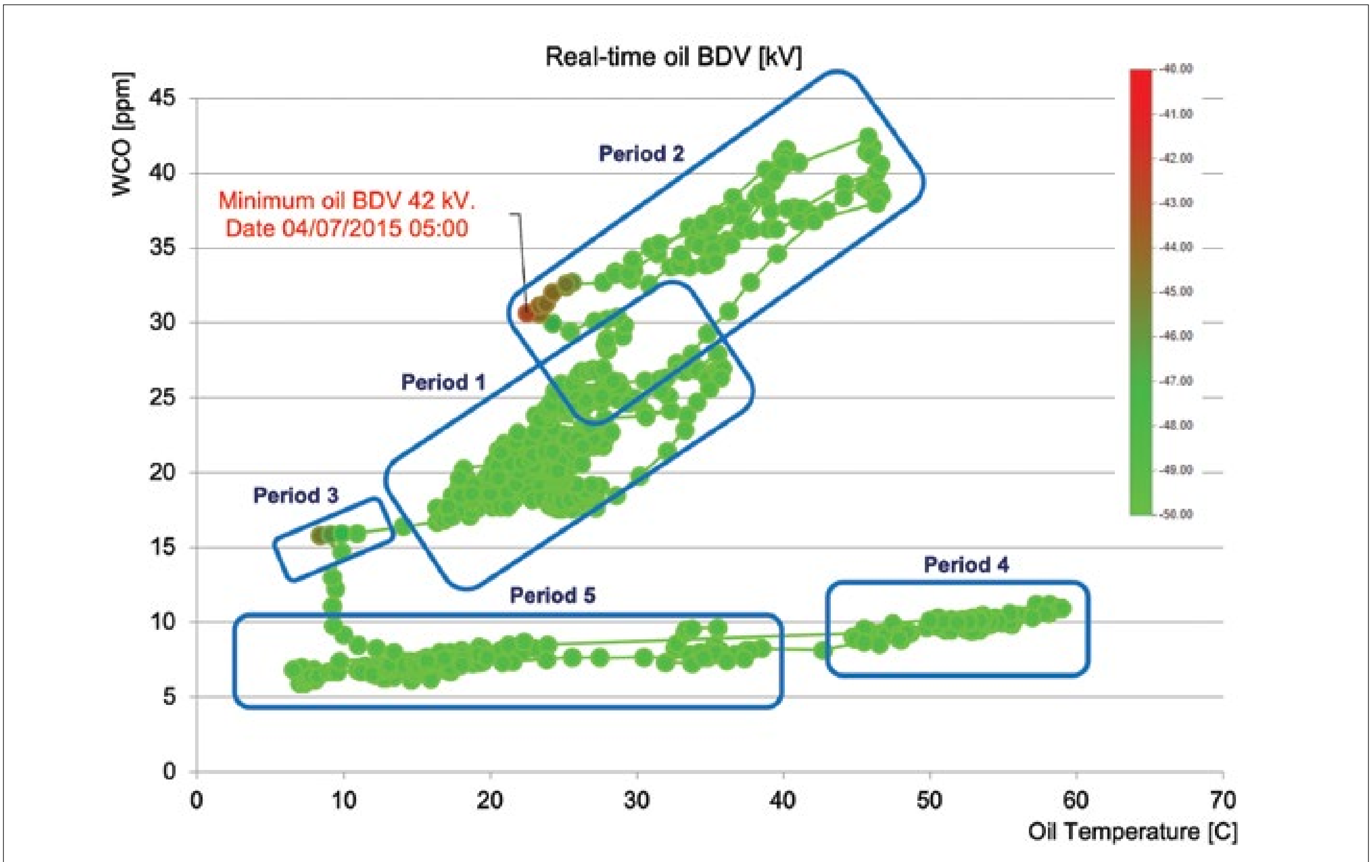

Figure 7. Real-time BDV map modelled by IEEE [5] equation (2)

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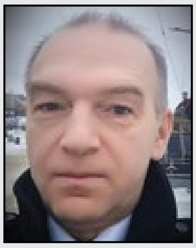
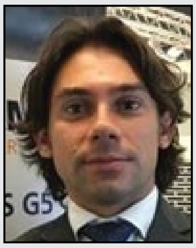
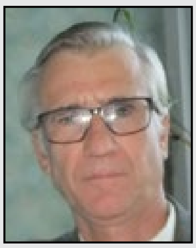


Anatoliy Mudryk, Ukraine. He received his Engineer's degree in Electrical and Mechanical Engineering from the Technical University of Zaporizhzhya in 1996. During his professional life, Anatoliy occupied leading engineering positions at ZTZ-Service and GE Kelman. Currently, he is the Transformer Expert at Camlin Energy. His main areas of activity include transformer design, diagnostics, and reliability. Anatoliy was a member of CIGRE and IEEE transformers committee WGs.



Marco Tozzi received his MS degree in Electrical Engineering from the University of Trieste in 2005 and his PhD degree in Electrical Engineering in 2010 from the University of Bologna. From 2007 to 2011, he was a Project Manager and Technical Advisor at Techimp, Italy, where he was involved in research on the diagnostic of insulating systems by PD analysis. In 2011, he joined Camlin Energy, where he led the development of PD monitoring systems for transformers and held the position of a Senior Product Manager. In January 2022, he became a Sr. Technical Advisor. He is the author or co-author of more than 50 technical and scientific papers.

Nathan Jacob received his MSc and PhD in Electrical engineering from the University of Manitoba in 2005 and 2018, respectively. Nathan has more than 16 years of industry experience in high-voltage testing and condition assessment and was the former Senior Test Engineer at Manitoba Hydro's High Voltage Test Facility. Since 2021, he has been employed as a Technical Solutions Manager at Camlin Energy.



Viktor Berezhny, Ukraine. He received his Engineer's degree in Electrical Engineering from the Technical University of Zaporizhzhya in 1981. In 1992, he joined ZTZ-SERVICE Co, where he was the Head of the Insulating Oil Test Lab and currently occupies the position of a Technical Director. Viktor is the co-author of the Ukrainian Standard Guide on the Interpretation of DGA Results and the Guide on Transformer Oil Acceptance and Maintenance. Viktor is the author of several technical articles and conference presentations.