Water promotes the degradation reactions of the insulating paper and damages the oil-paper insulating system, therefore it shortens the lifespan of a transformer, and also reduces the breakdown voltage of the tap-changer oil.

BENEFITS OF A BDV INDICATOR

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Water and moisture are omnipresent in our environment. We encounter it in the form of rain or moist air. In the insulation systems of electrical equipment, however, moisture is undesirable. Excessive moisture in the insulating oil or insulating paper affects their insulation strength. Water promotes the degradation reactions of the insulating paper and damages the oil-paper insulating system, therefore it shortens the lifespan of a transformer, and also reduces the breakdown voltage of the tap-changer oil.

Figure 1: Deterioration of insulating materials because of water

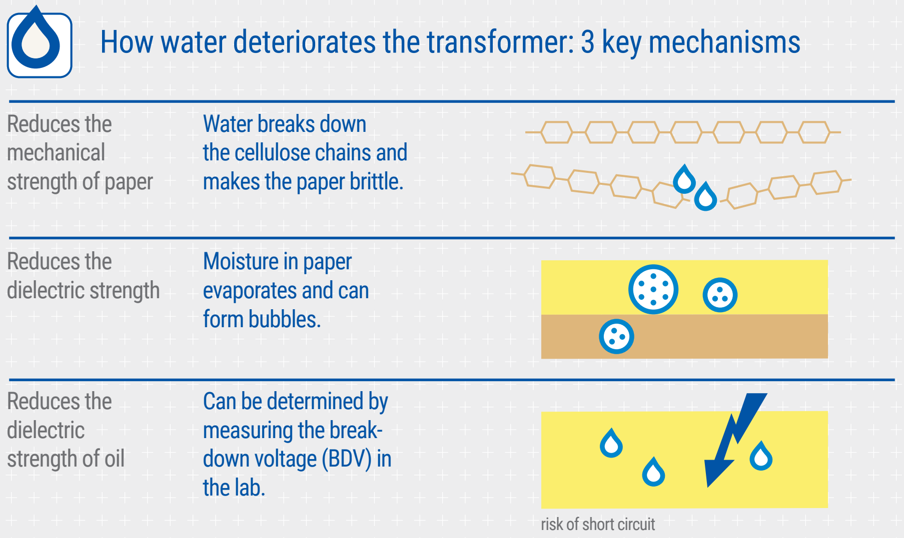
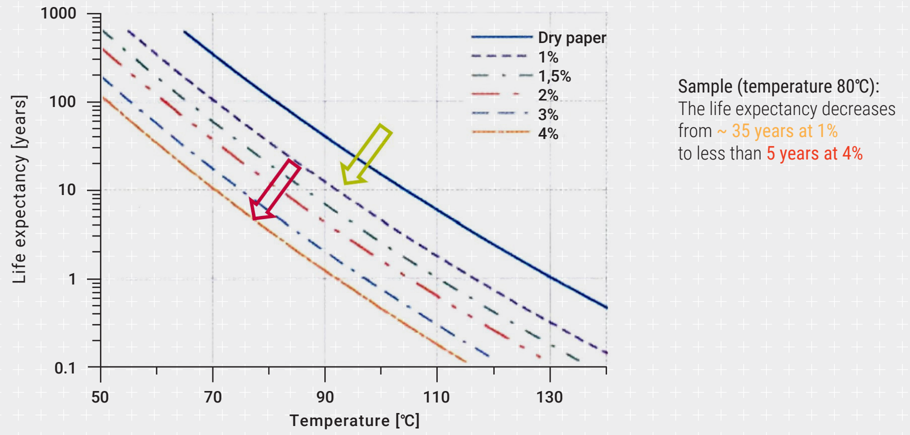


Figure 2: Loss of lifetime because of increased water content

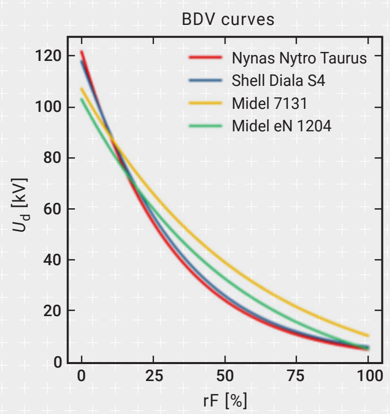


This results in two important aspects regarding moisture:

a. On the one hand, the penetration of moisture into the transformer or tap-changer should be avoided. This is done on the one hand by appropriate handling of the insulating materials and by using dehumidifiers to dry the air inhaled by the transformer or tap-changer.

b. On the other hand, the moisture content of the insulating oil should be continuously monitored. Since it is not possible to directly monitor the moisture content of the insulating paper during ongoing operation of a transformer, this is also done indirectly via the moisture content of the insulating oil.

Figure 3: Resulting BDV models for different oil types



The relationship between relative oil moisture, oil temperature and breakdown voltage can be described using statistical methods from the machine learning toolbox.

A relatively simple way to implement online monitoring of the breakdown voltage is to use the influence of moisture in the insulating oil on the breakdown voltage. The relationship between relative oil moisture, oil temperature and breakdown voltage can be described using statistical methods from the machine learning toolbox. Here, the breakdown voltage data at different oil temperatures and humidity are determined experimentally using a reference method, e.g., IEC 60156. A mathematical model is trained with this data. The model is validated and optimized using test data that is independent of the training data.

Since the test standard used to determine breakdown voltage in the laboratory already has a large measurement uncertainty, it is recommended to divide the results of the BDV calculation into classes based on the IEC 60422[5] standard and the information in the form of a traffic light to represent. This is considered sufficient for long-term trend monitoring.

The advantages of an online moisture sensor with calculation of the breakdown voltage are:

- Continuous monitoring of the moisture content of the insulating oil.
- Continuous monitoring of the insulation strength is possible by calculating the breakdown voltage.
- Calculation of the paper moisture.
- Elimination of the need for regular oil sampling to determine the oil moisture content and the breakdown voltage.
- Timely detection of deviations from the normal or target condition of the transformer and on-load tap-changer.
- Increased operational reliability.

Benefits of a DGA sensor

Evaluation of electrical equipment is an essential but complex process for any asset operator to ensure both operational safety and economic efficiency. As described in detail in CIGRÉ TB 761 [1], the condition of the individual components of the transformer system must be assessed regarding the following aspects:

- Replacement
- Safety
- Maintenance
- Refurbishment / upgrading and
- Oil treatment

This information is condensed, usually in the form of condition indices, and presented for the entire fleet of equipment for decision-making. Over the last 30 years, a very useful method for condition assessment has been the analysis of dissolved gases in the insulating oil. This has been used to evaluate the condition of the active part of a transformer, the tap-changer, and the bushings [6].

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Interpretation of the gas patterns for mineral oil-based insulating oils is described for instance in [7, 8], for ester-based insulating oils in [9]. These interpretation approaches found their way into relevant standards [10, 11]. After the establishment of the method in laboratories, more and more online DGA systems of various types appeared on the market – starting from the sum gas sensor system to multigas sensor systems with 8, 9 or more gases [12, 13]. Essentially, available online DGA systems can be divided into two categories:

a. Systems for fault indication and trend analysis.
b. Systems for fault diagnosis as described in [13].

Fault diagnosis is the interpretation of gas patterns according to the methods described in [10, 11]. Usually, gas concentrations are related to each other and assigned to corresponding fault classes. To form different gas ratios, the respective gas components are required as listed in Table 1.

Table 1: Required gas components for formation of the gas ratios according to different interpretation approaches.

Interpretation according to	Gas Components								
	H_2	O_2	N_2	CO	CO_2	CH_4	C_2H_6	C_2H_4	C_2H_2
Rogers	X					X	X	X	X
Doernenburg	X					X	X	X	X
Duval Dreieck						X		X	X
Duval Pentagon	X					X	X	X	X
CO_2 / CO				X	X				
O_2 / N_2		X	X						
IEC 60599	X					X	X	X	X

Basically, faults are divided into the following classes according to IEC 60599 [10]:

- PD Partial Discharge
- D1 Low energy discharges
- D2 High energy discharges
- T1 Thermal fault with T < 300°C
- T2 Thermal fault 300°C <= T < 700°C
- T3 Thermal fault 700°C <= T

These classical interpretation approaches show several problems:

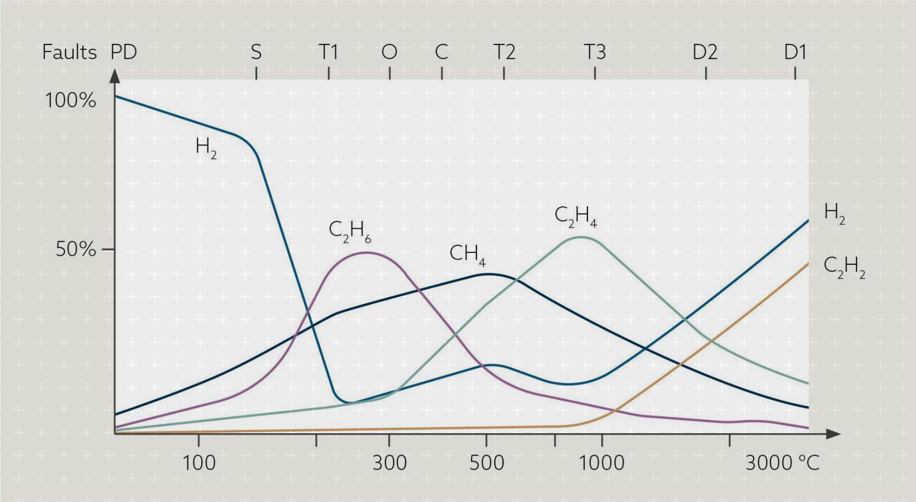
- There is – except for Rogers' gas ratios – no normal range. The gas ratios always indicate a fault.
- The interpretation should be applied only when certain limit concentrations of the gases are exceeded.
- The superposition of different types of faults, which is often the case, is not correctly detected [14].

In recent years, attempts have been made to counteract these disadvantages and improve the reliability of the interpretation results by applying statistical methods from the Artificial Intelligence (AI) toolbox [14-17].

For fault diagnosis, multi-gas online DGA systems are used, which can usually detect > 4 gases and are based on principles of optical spectroscopy (IR or photo-acoustic spectroscopy) or gas chromatography.

Fault indication and trend analysis focus on the relative change of a few gas concentrations. The aim here is to obtain an early indication of deviations from normal or desired operation. Fault classification, as described in the previous chapter, is not the focus. If a corresponding indication is obtained, appropriate measures can be initiated promptly, such as oil sampling with subsequent analysis of various parameters or electrical measurements on site.

Figure 4. Gas formation pattern as a function of temperature [3].



If we look at the development of various gases as a function of temperature and assign them to the typical fault classes as shown in Fig. 4, we can see:

- Hydrogen is present in varying proportions over the entire temperature range.
- The proportion of hydrogen increases sharply during high-energy events (very high temperatures).
- The proportion of acetylene increases sharply during high-energy events (very high temperatures).
- Methane is present in appreciable proportions early in thermally induced faults.

Furthermore, present proportions of carbon monoxide and carbon dioxide indicate possible degradation reactions of the insulating paper, with carbon monoxide forming the precursor to carbon dioxide during paper degradation.

Thus, even with only a few gases, a trend analysis and an early fault indication can be carried out. As shown in Fig. 4, a DGA system detecting the gases hydrogen and carbon monoxide as well as oil moisture can be used for reliable early fault indication and trend analysis. In combination with an extraction unit based on membrane technology, such systems are usually robustly designed and inexpensive, and thus quite suitable for fleet monitoring. The monitoring approach here is rather the large-scale monitoring of the equipment to get a continuous overview of its condition and its development rather than the detailed fault diagnosis of a few critical pieces of equipment.

The advantages of an online DGA sensor with only a few gases for early fault detection are:

- Robust and inexpensive systems.
- Simple handling.
- Early detection of deviations from normal operation.
- Monitoring of a fleet is possible and affordable.

The advantages of a multigas online DGA sensor for fault identification are:

- Fault diagnosis is possible.
- Monitoring of all dissolved gases in critical equipment.
- Gaining knowledge about new and unfamiliar operating equipment.

General advantages of online DGA:

- Continuous monitoring of the oil condition and thus the condition of a transformer and on-load tap-changer.
- Early detection of deviations from normal operation.
- Reduction of regular oil sampling.
- Increased operational reliability (compared to laboratory analysis, the probability of detecting a fault in good time is twice as high [13]).
- Increased predictability of maintenance measures.
- Optimization of operating costs.

Photo: MR

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