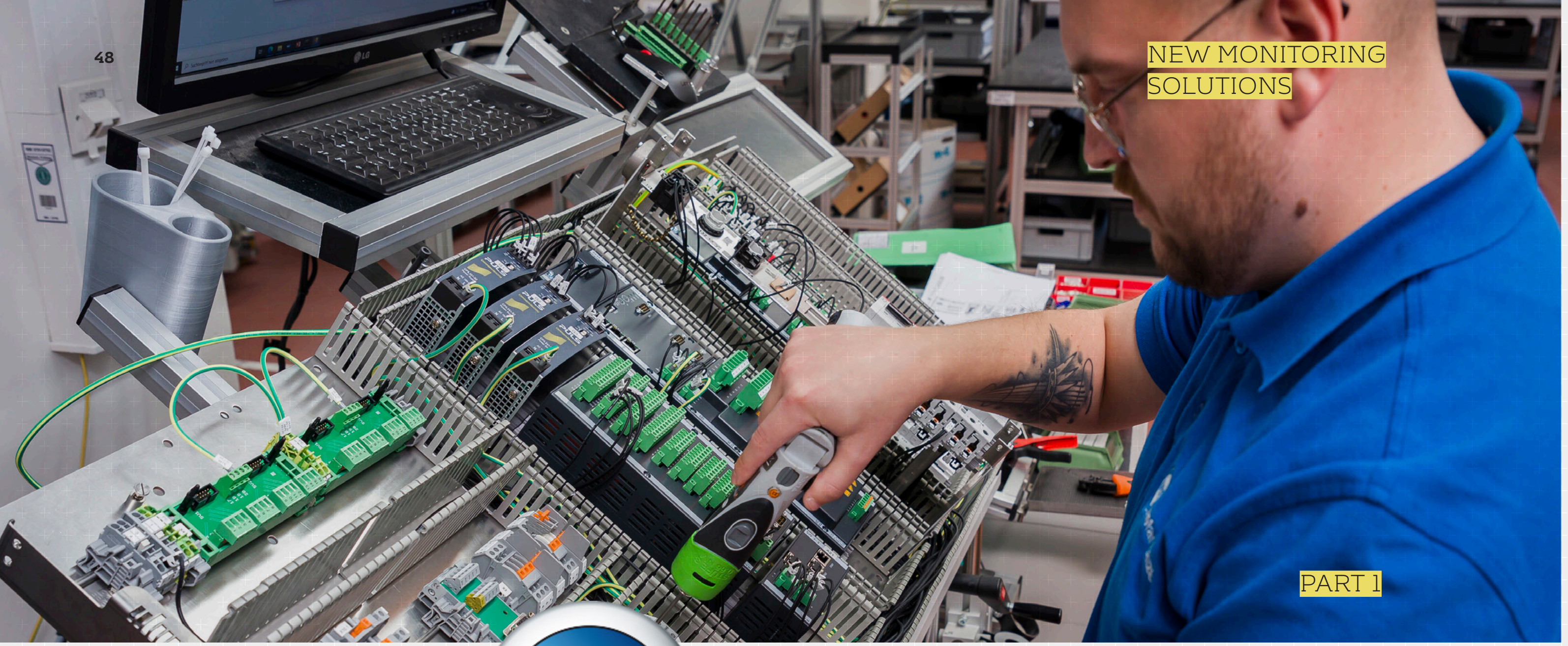


NEW MONITORING SOLUTIONS

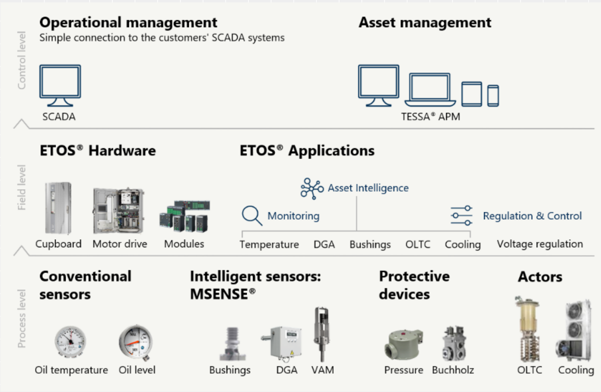
PART 1

NEW TECHNOLOGIES CAN HELP COMPENSATE FOR THE LOSS OF PERSONNEL KNOWLEDGE AND THE INCREASED DEMANDS ON OPERATING EQUIPMENT

New technologies in monitoring and diagnostics help compensate for the loss of personnel knowledge and the increased demands on operating equipment. Also, energy transition is posing enormous challenges for the power supply: Infrastructure conceived decades ago suddenly must transport electricity in a different way. Power grids are aging, and with maintenance strategies that have been the norm up to now, there is an increasing need for renewal, entailing further expense. One solution lies in intelligent, data-driven utilization concepts that enables the use existing infrastructure more efficiently and extend the lifetime.

To achieve this, a balanced portfolio for the different automation levels is necessary (see Figure 1).

Sensors continuously record the signals at the process level. All measured data is then communicated to a central communication node in the field level for further processing and enrichment. Thus, fail-safe and centralized information on maintenance and health status is resiliently available on site. On the control level a global classification can be carried out and risk-based maintenance strategies are enabled. For a holistic system for the diagnosis of power transformers, modular and manufacturer-independent solutions must be found to ensure the best possible application.



Open for third-party devices and data

- Professional know-how
- Holistic advice
- Customised services

Figure 1:
MR's System solution for maximum operational reliability

How these solutions can look in practice is demonstrated by the following applications.

Simplifying and enriching sensors in their use on transformers

To make the best possible conclusions about the health of transformers, it is useful to work on accuracy and reliability of data sources (sensors). The following examples show how this has been done for monitoring the various components on the transformer.

DGA – Dissolved Gas Analysis

The analysis of dissolved gases in the insulating oil in the gas phase is carried out using various analysis approaches: semiconductor sensors, electrochemical sensors, infrared spectroscopy, or gas chromatography. An extraction of the gases from the insulating oil takes place prior to the actual analysis for all methods. These two essential processes are influenced by external factors such as oil and ambient temperature, humidity, air pressure, and other chemical components, which often lead to very high measurement uncertainties and incorrect analysis results. One method for counteracting this is to keep the conditions of gas extraction and detection constant. Detection can also be improved by separating interfering components from the actual target gases. All of these measures require additional components in a DGA analysis system, which significantly increases both its cost and complexity.

Another approach includes mathematical-statistical methods from the toolbox of machine learning or artificial intelligence. The correlation between the actual target variable (in the case of a DGA – the gas concentrations in the insulating oil), the sensor signal, and the disturbing influences is determined using a training data set. The training data set should represent the entire data space of the application to the greatest extent possible. For a DGA, this means recording the temperature range of the insulating oil and the environment, the humidity range, the ambient pressure, and all relevant chemical disturbance components, and thus taking their influences into account as completely as possible in the mathematical model. Other methods such as support vector regression (SVR) are also conceivable. The advantage of this approach, as implemented in the MSENSE® DGA 2/3, is a much simpler and less expensive design of the measurement system. While more effort is needed in the development phase, the customer receives a robust, easy-to-operate, and more cost-effective analysis system.

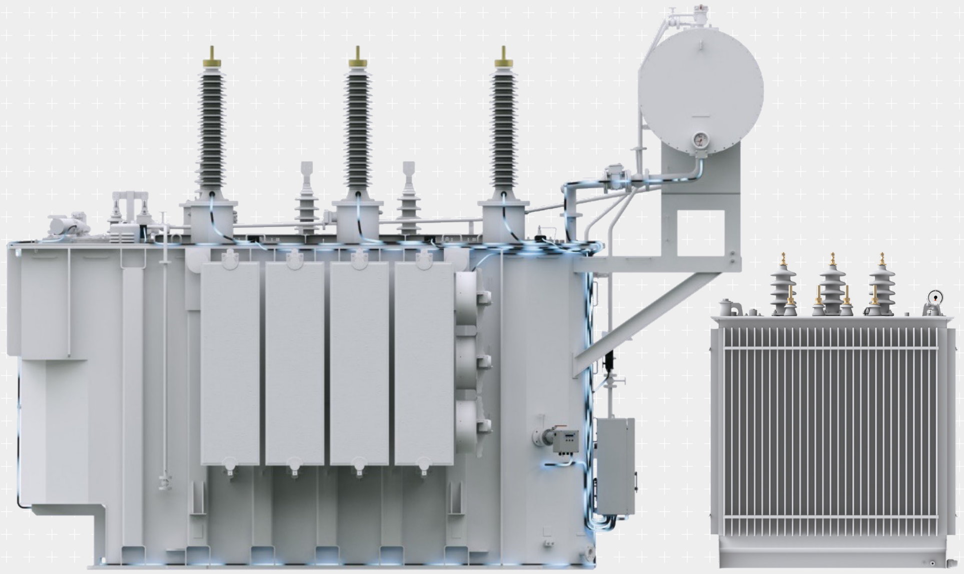


Photo: MR

Another advantage of this approach is the possibility of self-adjustment of the analysis system during operation. With the aid of a reference point, the analysis system can auto-calibrate using machine learning methods and existing measurement (measured-data memory of the analysis system) in order to adapt to the individual conditions on site. In this way, effects such as sensor drift, aging of the insulating oil and the like can be compensated for and consistent measurement repeatability can be ensured.

OLTC DGA

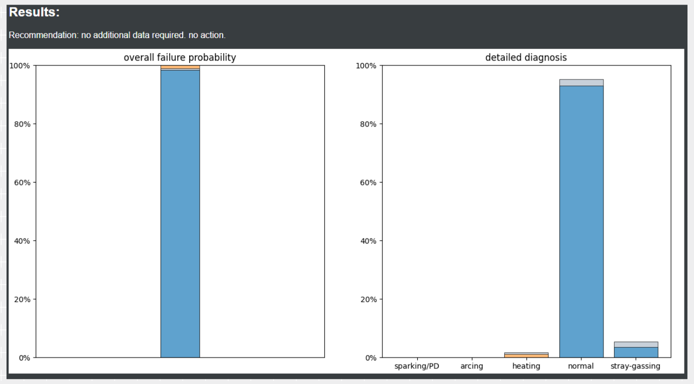
In the CIGRÉ publications CIGRÉ Technical Brochure 443 and CIGRÉ Technical Brochure 771, the gas patterns of on-load tap-changers are interpreted using the gas ratios of methane, ethylene and acetylene according to Duval (Duval triangles) and classified into fault classes or normal operation.

The interpretation of gas patterns of tap changers remains difficult compared to transformers and requires expert knowledge about the functionality of the respective tap changer type and its mode of operation. Nevertheless, the condition assessment of a tap changer by means of DGA is a powerful tool and helps to optimize maintenance measures within the framework of condition-based maintenance and to indicate deviations from normal operation in good time.

For continuous online monitoring, as with transformers, the use of multi-gas online DGA sensors for fault diagnosis is usually not necessary. Often, trend analysis of a few key gases such as hydrogen, carbon monoxide or acetylene/methane is sufficient to detect deviations from normal operation at an early stage. Our investigations showed that with vacuum tap changers of the built-on more than 80% of the deviations from normal operation could already be detected with the monitoring of hydrogen.

The interpretation of DGA data from on-load tap-changers remains difficult, since further information on the operation and function of the on-load tap-changer is required. Therefore, deviating from the previously known approaches, an interpretation approach is proposed, which uses statistical-mathematical algorithms. In addition to the gas concentrations, information on the tap changer is used as input variables, such as tap changer type, number of switch operations, and more. As a result, a diagnosis with an indication of the probability is obtained (see Figure 2).

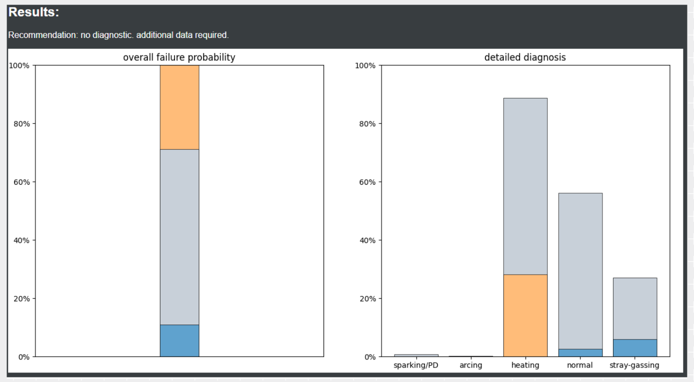
In the example shown (Fig. 2), normal operation is assumed with a high degree of probability (the greater the proportion of the gray area, the greater the uncertainty of the statement made). Here, it was possible to provide a lot of supplementary information on the tap changer, so that the reliability of the statement is high.



Results:

Recommendation: no additional data required. no action.

Figure 2:
Example of a DGA interpretation of a vacuum tap changer based on a statistical approach.



Results:

Recommendation: no diagnostic. additional data required.

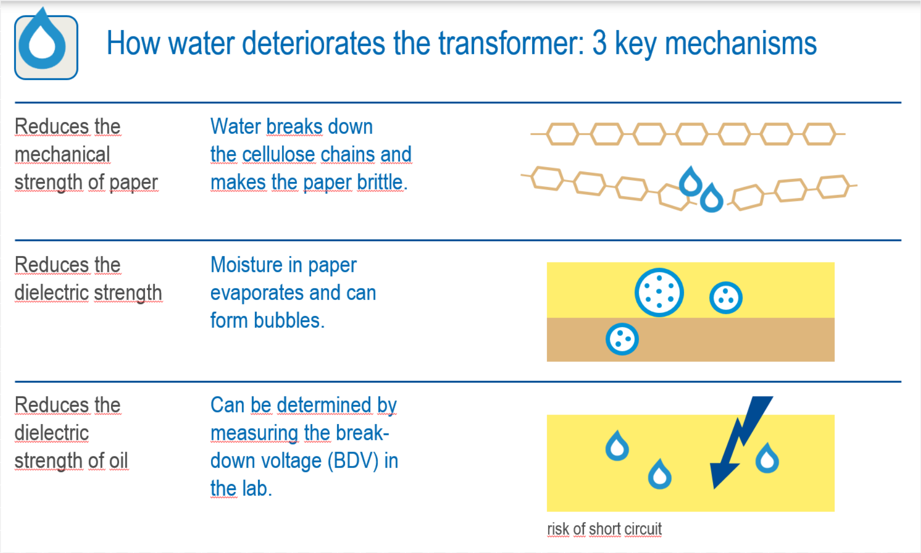
Figure 3:
Second Example of a DGA interpretation of a vacuum tap changer based on a statistical approach.

The example shown in Fig. 3 illustrates how, at the same gas concentrations as in Fig. 2, the reliability of the statement decreases when only very little information is available on the tap changer. The proportions of the gray areas (uncertainty ranges) are very large. This also indicates that a diagnosis based on too little data is not meaningful.

As part of the condition monitoring of on-load tap-changers, the online DGA is a valuable tool for detecting deviations from normal operation at an early stage and thus avoiding damage or failures. It contributes to a cost-optimized condition-based maintenance strategy. For continuous trend monitoring, the analysis of a few key gases using cost-effective and robust online DGA systems is sufficient. Caution should be exercised when interpreting DGA data for fault diagnosis, as the most accurate knowledge of the operation and function of the on-load tap-changer under consideration is additionally required and should be taken into account in the interpretation.

Oil moisture and breakdown voltage

In insulating systems for electrical equipment moisture is undesirable. Excessive moisture in insulating oil or insulating paper impairs their insulating strength. Water promotes degradation reactions of the insulating oil and the insulating paper and reduces the service life of a transformer or on-load tap-changer.



How water deteriorates the transformer: 3 key mechanisms

Reduces the mechanical strength of paper	Water breaks down the cellulose chains and makes the paper brittle.
Reduces the dielectric strength	Moisture in paper evaporates and can form bubbles.
Reduces the dielectric strength of oil	Can be determined by measuring the breakdown voltage (BDV) in the lab.

Figure 4:
Deterioration of insulating materials because of water

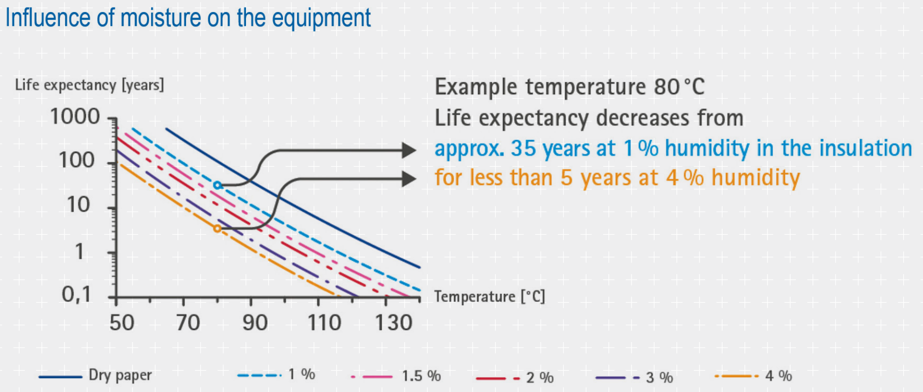


Figure 5:
Loss of lifetime because of increase water content

This results in two aspects regarding to moisture: a) The penetration of moisture into the transformer or tap changer should be avoided. This is done by appropriate handling of the insulating materials and by using dehumidifiers to dry the air breathed in by the transformer or tap changer. b) The moisture content of the insulating oil should be continuously monitored. Since it is not possible to monitor the moisture content of the insulating paper directly while a transformer is in operation, this is also done indirectly via the moisture content of the insulating oil. The insulating strength of the liquid insulating medium is determined by means of the breakdown voltage in accordance with appropriate test standards such as IEC 60156 or ASTM D 1816. For this purpose, a defined quantity of the insulating oil is filled into a test chamber, where there are two electrodes at a defined distance - in the case of IEC 60156 this is 2.5 mm. The test voltage between the two electrodes is continuously increased until breakdown occurs. Several test runs are carried out from which individual values of the breakdown voltage are determined by averaging in kV. According to the requirements for a fresh insulating oil in IEC 60296, the breakdown voltage must be at least 30 kV. Fresh insulating oils usually have breakdown voltages between 60 and 80 kV. A major influencing factor on the breakdown voltage, as a characteristic parameter for the insulating strength, is the moisture content of the insulating oil. The breakdown voltage of an insulating oil is thus another important parameter for assessing the condition of the liquid insulating medium and thus of the transformer or tap changer. Continuous monitoring of the breakdown voltage is therefore recommended.

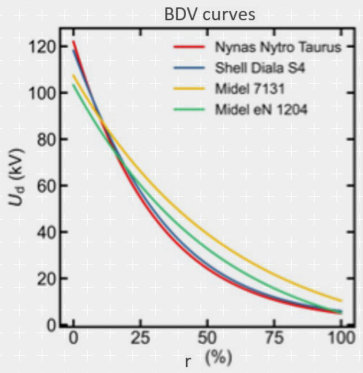


Figure 6:
Resulting BDV models for different oil types

The methods described in the relevant test standards for determining the breakdown voltage are not suitable for online monitoring. The construction of a device that can be used in the field is complex and expensive, and breakdowns in the oil would be provoked, which would damage the insulating oil with time. A relatively simple way of implementing online monitoring of the breakdown voltage makes use of the influence of the 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 data for the breakdown voltage at different oil temperatures and humidities are determined experimentally using a reference method, IEC 60156. A mathematical model is trained with these data. The model is validated and optimized using test data that are independent of the training data.

Since the test standard used to determine a breakdown voltage in the laboratory already has a large measurement uncertainty, it is advisable to divide the results of the BDV calculation into classes based on the IEC 60422 standard, and display the information in the form of a traffic light. This is considered sufficient for long-term trend monitoring. Integrated into a higher-level monitoring system, a condition assessment of the equipment is thus obtained, taking into account other characteristics of the equipment.

Bushing monitoring

Based on the CIGRE study working group A2.37 and A2.43, "Transformer Reliability Survey" and "Transformer bushing reliability", almost 18% of all failures documented for substation transformers can be tracked down to malfunctions related to transformer bushings. Those numbers show how critical and important monitoring of transformer bushings can be.

The most efficient way to estimate bushing condition based on on-line monitoring is to control the change of the main capacitance C1 and the associated dielectric dissipation factor tanδ. It is proven that humidity and aging are impacting capacitance only at higher temperatures. A short circuit between elementary condensers will increase the capacitance independent of temperature. Change of the tanδ and PF is temperature dependent. Increase of tanδ indicates a higher loss in the bushing's insulation system and is often caused by introduction of moisture or ageing.

Limits for the change of C1 and tanδ depend on the system voltage and technology used for bushings construction.

The tanδ measurement is much more sensitive to external factors (temperature, weather condition) than capacitance due to the very small value of angle δ. Bushing condition evaluation based on tanδ measurement depends on the bushing insulation type and construction. Two evaluation methods can be applied: based on the specified tanδ value or a relative tanδ change.

Sum of current method: The amplitude and phase angle of the current at all of three bushing taps are measured and compared to each other. Simple current amplitude changes with change of the capacitance and the phase shift with the dielectric loss factor of the bushing assuming that the summation of the currents of the three bushing of the different phases under consideration of its phase angles is zero. In that method the measurement is very strongly affected by the fluctuation of the system voltages and phase. Monitoring system utilizing that method can be easily installed on the transformer. Less technical effort and simplicity are the main advantages; however, the results are impacted by the imbalance and external factors.

Comparison method: to avoid problems recognized in the sum of currents method, the comparison method was introduced. This method uses a signal from voltage transformers installed on the same phase as a reference. The voltage transformer is not affected by the defects and aging that typically affects bushings. Monitoring systems utilizing this method need additional technical effort to connect the reference signal. In most cases the VT are placed far away from the transformer, however the results are not affected by network imbalance and external factors.

Measured voltage signal can be additionally compared with other phases of the same transformer, improving immunity to external factors like temperature or weather condition.

The double-reference method improves the voltage comparison method and capacitance measurement if the reference voltage is not accessible (voltage change during tap changer switching).

Bushing monitoring system in most cases can utilize the same decoupling devices for electrical Partial Discharge (PD) measurement. Signals in different frequency ranges can be used for PD activity recognition and early warning. The electrical measurement on bushing is strongly affected by external noise, which can be compensated by combining it with the UHF method (antennas installed on the transformer tank) for better PD recognition.

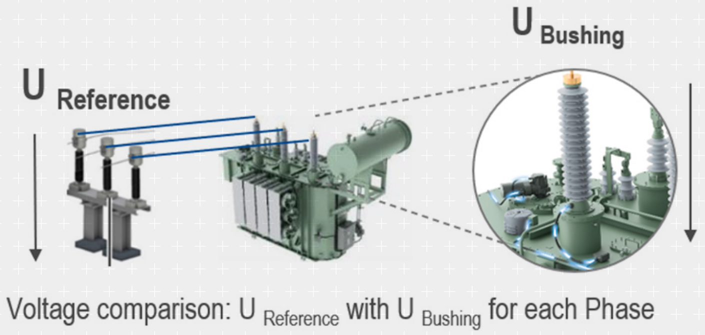


Figure 7:
Voltage comparison method can be easy and cost effective integrated with ETOS® or work as a stand-alone (MSENSE®BM) providing best solution for bushing monitoring.

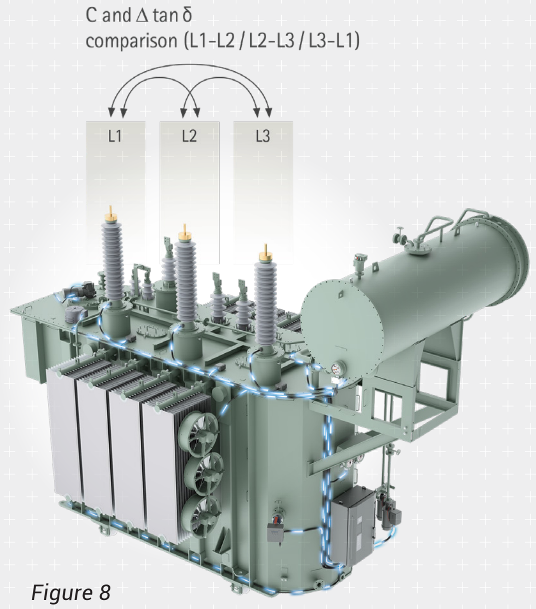


Figure 8

Vibro acoustic monitoring of OLTCs

Since on-load tap-changers are among the most important components of power transformers, it is crucial for network operators to know their conditions at all times. Thanks to more than 20 years of experience in on-load tap-changer monitoring, Reinhausen has developed a unique online diagnostic tool: MSENSE® VAM. "VAM" stands for vibroacoustic measurement and can be used universally for all types and brands of OLTCs. The basis of MSENSE® VAM is a high-resolution vibroacoustic measurement system for detecting vibrations that occur during the switching sequence of an OLTC. Envelope curves are generated from the time-frequency spectra emitted during the switching sequence. The evaluation of these envelope curves is performed with the aid of a dynamic limit value curve which increasingly approximates the envelope curve during each switching sequence by means of a self-learning algorithm.

Assuming a Gaussian probability distribution, the significant peaks of the recorded curve are then expanded. As a result, a limit curve is generated over the sound signal peaks characterizing the tap changer switching process.

Reverse tap-change op. 10 -> 9, 16.08...
θ_OLTC 51.4 °C
Operations counter 91083
Status
Next tap-change operation: All
142 / 319
14.11.2019 21:58

Reverse tap-change op. 10 -> 9, 19.08...
θ_OLTC 53.5 °C
Operations counter 91095
Status
Next tap-change operation: All
136 / 319
14.11.2019 21:59

Reverse tap-change op. 10 -> 9, 24.09...
θ_OLTC 51.4 °C
Operations counter 91191
Status
Next tap-change operation: All
89 / 319
14.11.2019 22:00

Figure 9:
Self- learning limit value curve for an easy installation

An upper limit value curve is generated from the statistics, which represents an absolute limit value for the acoustic signal. The limit value curves are determined independently by the system using statistical methods on the basis of the stored historical data.

The resulting limit value curve serves as an alarm limit value and is at the same time used for flexible adjustment of the amplitude range that is still permissible. The limit values are thus updated. Through this tracking procedure, the system iteratively learns during the switching operations what the acoustic signature of a correctly operating on-load tap-changer looks like, in order to check the correct course of all subsequent on-load tap-changer switching operations on the basis of the self-generated envelope curve. Whereas in the past it was necessary to determine individual limit value curves via the temperature curve in a test pro-cedure that took months, the system now learns the correct limit value curves for the specific on-load tap-changer.

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Jürgen Schübel completed a PhD in physical chemistry in 1991 and worked for 20 years in a major European mineral oil company. He is senior expert for insulating materials and analytics at MR, Product Owner of DGA-, Fiber Optic- and Moisture sensors and is an active member of CIGRÉ D1.

Photo: MR

To be continued in our MAY Issue.
In the next article, we will describe the use and integration of typical sensors with more analysis and inside-view and will expand the collection and further analysis by edge devices and central solutions.