Measure. Regulate. Across all grids.

TrafoStick™

Condition-based maintenance today!

One Sensor for ONLINE BDV- and DGA-measurement

To ensure the longevity and reliability of critical components such as power transformers with On-Load Tap Changers (OLTCs), comprehensive diagnostics of the insulation system have become paramount. These diagnostics assess the breakdown voltage of the oil (BDV) and the water content (W_C). Additionally, determining the levels of two crucial gases, hydrogen (H_2) and carbon monoxide (CO), provides significant insights into the transformer's condition. This has led to the development of advanced diagnostic tools like the TrafoStick™, which provides precise and efficient assessments of transformer health.

Special Publication

» In the original definition, diagnostics means the ability to recognize diseases. «

In the technical field, diagnostics is associated with the term examination procedure, meaning the condition of a device or its components is determined, with additional suggestions for measures that may be necessary to secure the actual operation process and to extend it as best as possible. In the field of electrical power engineering, diagnostics has gained considerable importance today. The change from previous time-based maintenance of the system to condition-based maintenance of the system requires better knowledge of the most important parameters in order to be able to take appropriate measures just in time.

Transformers and On-Load Tap Changers (OLTCs) are used mostly in substations of transmission and distribution, in big industries either, to transform under load from the primary voltage level to the secondary one. Regardless of whether they are used for the operation of railway networks, for the general energy supply of industry and private households, or other tasks, flawless functioning is a necessity. However, operating conditions for these key elements in our energy network are becoming more and more challenging, which consequently results in higher demands on the working components, like the insulating fluids. Regular checking of these special liquids (mineral or ester-based oils) is becoming more important than ever before, as only these can provide information about the condition and allow conclusions to be drawn about the entire transformer or OLTC with a preview.

A possible early detection of incipient errors in such systems and components is extremely advantageous and in the longterm view very cost-effective, since unplanned shutdowns can be significantly reduced. A stable, future-oriented, and future-proofed supply of the electrical energy system can only be guaranteed if the operating conditions of the transformers with OLTCs, in particular their electrical insulation, are monitored continuously and online.

According to the existing IEC regulations, the "Basic Monitoring" consists of recording the dielectric-chemical parameters. These are the breakdown voltage (BDV; IEC 60156) and the dielectric loss factor tan δ (IEC 60247). Determining the breakdown voltage (BDV) and the dielectric loss factor tan δ offers the possibility of assessing the current insulation condition of the transformer- and OLTC-oil, too. An increased water content (W_C; IEC 60814) drastically worsens the insulating properties of the oil. Other oil properties, such as the neutralization number (IEC 62021-1), are used to make a prognosis about the further operation of the transformer. The neutralization number or Total Acid Number (TAN) indicates the oxidation state of the insulating oil. If the neutralization number is too high, the formation of organic acids is advanced too, meaning there is a risk of sludge precipitation, which can result in total damage of the most expensive asset of the power utility. To understand the "Breakdown Voltage" (BDV) of transformer- and OLTC-oil, the dielectric strength needs to be taken into consideration.

There are several types of insulating oil:

- Mineral Oil (Petroleum product)
- Naphthenic Oil
- Paraffinic Oil
- Synthetic Oil (Chemical product)
- Silicon Oil
- Bio-based Oil (Vegetable Oil)

which are in use worldwide nowadays. Dielectric strength is defined as the ability of the oil to withstand electrical stress without breaking down. Here, breaking down refers to the failure of insulating properties. The breakdown voltage test of transformer oil is crucial for the smooth operation of the transformer. A periodical BDV testing of the transformer oil ensures the quality and healthiness of the transformer oil. A low BDV value indicates that the oil contains moisture and conducting substances. As per the International Electrotechnical Commission (IEC), the minimum BDV value of transformer oil should be at least 30kV.

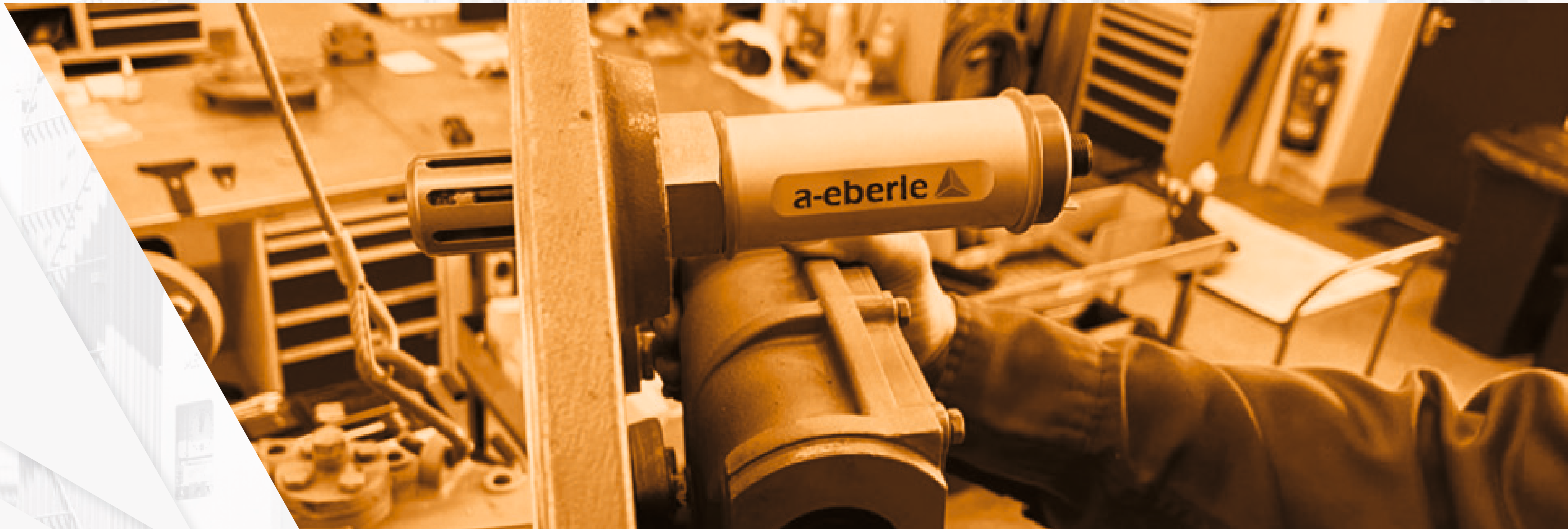


Figure 1: TrafoStick™ Factory Acceptance Test (FAT)

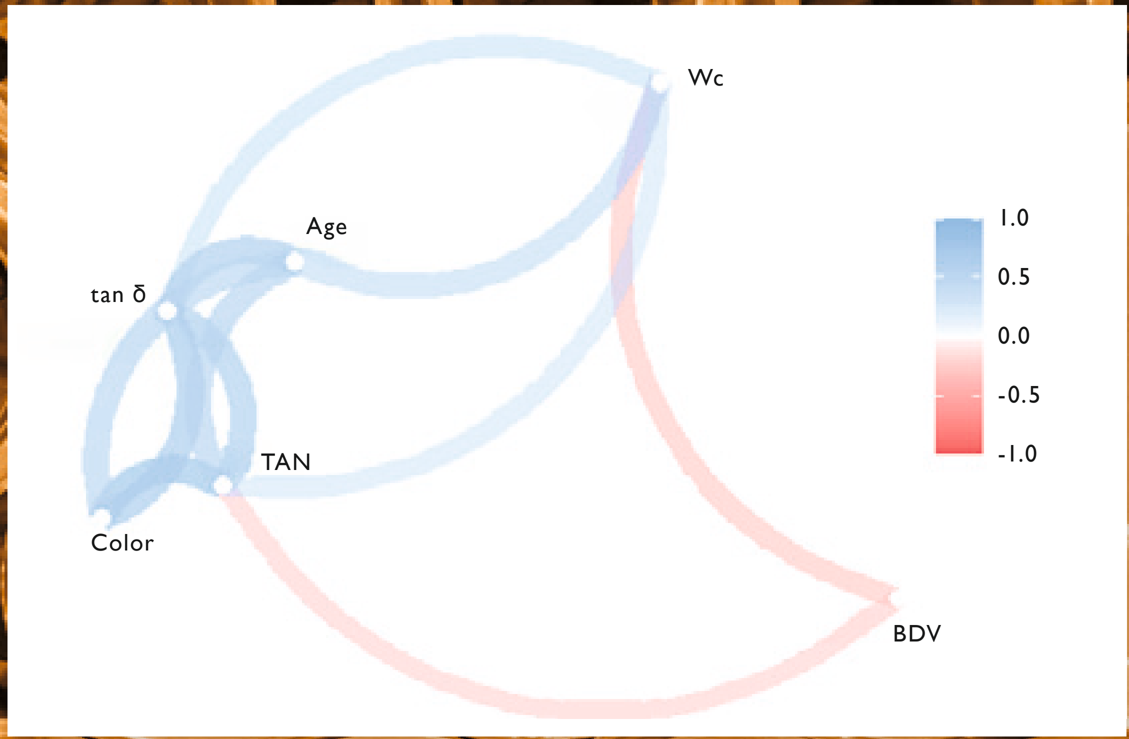


Figure 2: Function chart graph of the relationship between many of the oil's variables. The color bar shows the correlation coefficient between all the oil parameters.

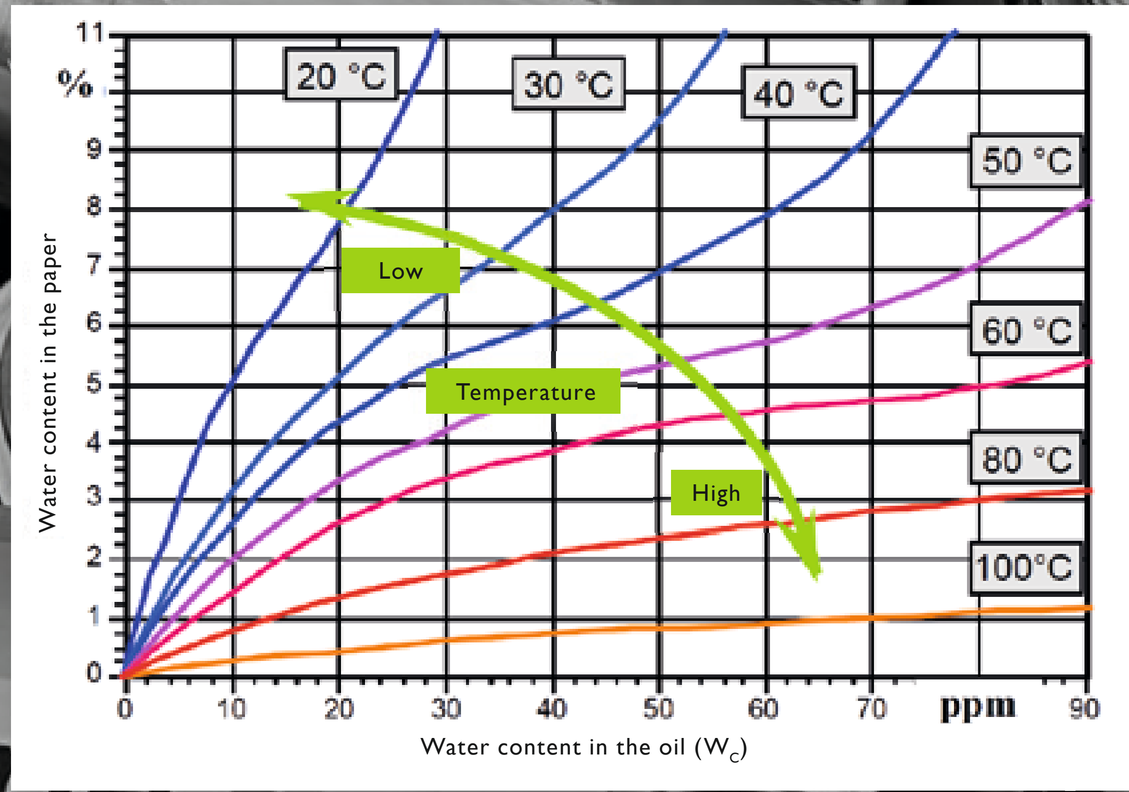


Figure 3: Moisture distribution in a paper / liquid insulation as a function of the oil temperature

Importance of insulation oil testing and condition-based maintenance in high voltage systems

Since there is a strong correlation between W_C, TAN, and BDV for mineral oil-based insulating liquids as shown in Figure 2, acid and moisture are the "driving forces" of BDV. It is also well known that the water content very strongly influences the properties of solid insulation materials, but water content usually cannot be measured directly during operation, since water content measurement needs, e.g., KF-titration. The moisture in the solid insulating material can only be determined from the moisture measurements of the liquid under known conditions, so that information about the development of the moisture in the solid insulating material can be obtained due to the established model by continuously determining the moisture in the liquid (see Figure 3).

Furthermore, insulating oil in high voltage systems is subjected to electrical, mechanical, and thermal stress during its operation. This results in the contamination of the oil by the formation of carbon deposits, sulfur, acids, various types of gases, and sludge, which is mainly an oxidation product, whose formation is increased by temperature and contact with air. If the moisture and conducting impurities are higher, then the breakdown voltage will be lower in the transformer oil. All of this needs to be taken into consideration and addressed through condition-based maintenance.

Periodical insulation oil testing is an important preventive measure that will help keep high voltage devices up and running. This procedure is cost-intensive and up to now it "only" provides a snapshot under laboratory conditions. The laboratory measurement of the oil parameters under IEC guidelines is usually done at 20°C and cannot provide any information on the behavior of the oil at operating temperatures that are deviating from 20°C; also keeping in mind that an error due to falsifying oil samples by incorrect human handling is omnipresent.

These topics are the main issues in case of deciding for online monitoring. It is very important to periodically monitor the dielectric strength of insulating oil, especially before it leads to internal arcing or total failure. Unplanned breakdowns of electrical equipment lead to commercial losses and reduce power system reliability (blackout scenarios).

With the knowledge of the relationship between Wc and TAN (see Figure 2), as well as information on water migration between oil and paper insulation (see Figure 3), the processes of increasing TAN in the presence of moisture, where the water is washing out the acid from paper, observed in the older transformer population, becomes perfectly clear and understandable.

Unfortunately, the aging factor accelerates significantly with increasing temperature. At very high core temperatures, meaning over 90°C (190°F), the aging factor (IEC 60354, IEC 60076) doubles with each additional 6°C (10°F). For the aging diagnostics of the paper, this statement also means that it is important to precisely know the temperature in the insulating material, especially at the points of highest temperature (core), since the aging processes experience a very strong acceleration there and lead to local destruction of the insulation and can lead to the device's failure.

BDV values for new oil

Equipment Voltage	Breakdown Voltage
≤72.5 kV	>55 kV
≥72.5 kV	>60 kV

BDV values for oil in service

System Voltage	Good	Fair	Poor
≤72.5 kV	>50 kV	40-45 kV	<30 kV
>72.5 kV ≤170 kV	>55 kV	45-55 kV	<35 kV
>270 kV	>65 kV	50-65 kV	<40 kV

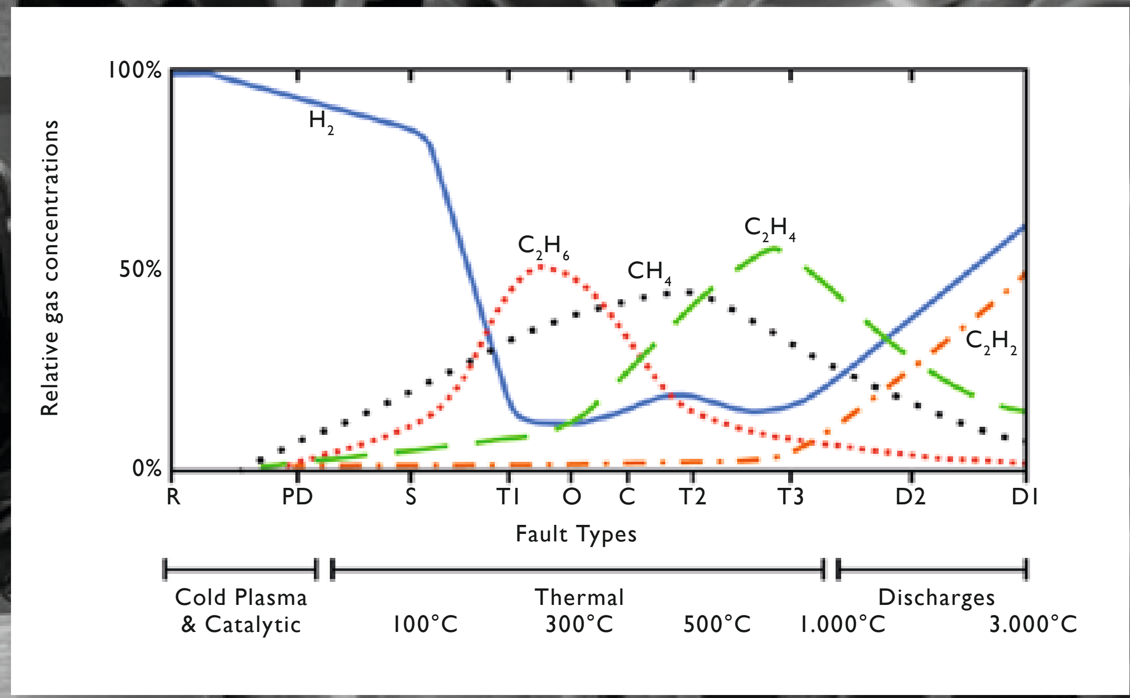


Figure 4: Relative percentage of dissolved gas concentrations in mineral oil as a function of temperature and fault type (Image courtesy of IEEE)

Determining the decomposition of gases dissolved in the oil (IEC 60567 and IEC 60599)

Due to a high electrical field strength, the occurrence of partial discharges is usually a very early warning sign for local defects and leads to an increased formation of decomposition gases. With abnormal thermal aging of solid insulation (cellulose), various furan derivatives are formed, which greatly accelerate the aging of the solid insulation. The DGA (Dissolved Gas Analysis) enables a diagnosis of the processes that have occurred in the insulation system, for example, partial discharges, thermal overload, or low-energy or high-energy breakdowns.

Figure 4 shows that mineral oils for transformers are mixtures of many different hydrocarbon molecules and the decomposition processes for these hydrocarbons during thermal or electrical faults are extremely complex. The basic steps in gas production are the breaking of carbon-hydrogen and carbon-carbon bonds. Active hydrogen atoms and hydrocarbon fragments are formed. These free radicals can combine into gases, molecular hydrogen, methane, ethane, etc., or recombine into new, condensable molecules. The acronyms and abbreviations used in Figure 4 mean:

- R – catalytic reactions
- PD – partial discharges
- S – stray gas formation
- T1, T2, T3 – thermal
- O – superheating of paper or mineral oil
- C – possible carbonization of paper
- D2 – high-energy discharges
- D1 – low-energy discharges

The amount of hydrogen produced can be relatively high and temperature-insensitive for some failure types such as stray gas formation, partial discharge (PD), and catalytic failure. The formation of acetylene only becomes noticeable at temperatures close to 1,000°C. Also, the formation of methane, ethane, and ethylene has a unique dependence on temperature each. In addition to the number of gases produced by the processes, the ratio between the gas types is also important. The IEEE-guide for the interpretation of gases generated in mineral oil-immersed transformers provides a very comprehensive overview of this topic.

BDV values for oil in service

Gas	Normal	Abnormal	Interpretation
Hydrogen H_2	<150 ppm	>1.000 ppm	Arcing corona
Carbon Monoxide CO	<500 ppm	>1.000 ppm	Severe overloading

Recommended safe fault gas levels in oil-immersed equipment (max., ppm)

Gas	Dorneburg /Stritt.	IEEE	Bureau of Reclam.	Age Compensated
Hydrogen H_2	200 ppm	100 ppm	500 ppm	20n* +50
Carbon Monoxide CO	500 ppm	350-720 ppm	750 ppm	25n* +500

**) n = years in service*

Based on the Westinghouse Guidelines of Total Combustible Gases (tcg), the increase in gas quantity over a certain period of time (the gradient) should be taken into account.

Total combustible gasses	Recommended action
≤500 ppm	Normal Aging Analyze again in 6-12 months
501 - 1.200 ppm	Decomposition maybe in excess of normal aging Analyze again in 3 months
1.201 - 2.500 ppm	More than normal decomposition Analyze in 1 month
>2.500 ppm	Make weekly analysis to determine gas production rates Contact manufacturer

Combustible gas generation in service also has to be determined. A generation of above 100 ppm combustible gases in a period of 24h merits attention. Weekly or monthly samples may be necessary.

Total gas level	ppm / day	Operating procedure
≤720 ppm	<10	Continue a normal operation
	10 - 30	Exercise extreme caution, determine load dependence
	>30	Exercise extreme caution, determine load dependence
721 - 1.920 ppm	<10	Advise manufacturer
	10 - 30	Analyze for individual gases
	>30	Exercise extreme caution, plan outage
1.921 - 4.630 ppm	<10	Advise manufacturer
	10 - 30	Analyze for individual gases
	>30	Plan outage
>4.630 ppm	<10	Advise manufacturer - Plan outage
	10 - 30	Consider removal of service
	>30	Removal of service

Conclusion

A continuous measurement of the oil parameters not only offers exact instantaneous values but also shows chronological trends. With this knowledge, the assets transformer and OLTC can be used in a more guided manner, thereby optimizing the economic efficiency of the equipment.

In such a case, two major questions appear:

- What skills do we need to be able to develop and use such an online monitoring system?
- What knowledge about the oil behavior do we have, and which one do we need?

Exactly with these questions in mind, the TrafoStick™ sensor (TS Generation 5 (TS G5)), an extended version of TS G4, for measuring the oil temperature, water content (W_C), breakdown voltage (BDV), as well as hydrogen (H_2) and carbon monoxide (CO), has been developed. It can be recommended as the best and most sufficient "first line of diagnostic defense."The main measuring module of this sensor is located in a robust metal housing made of anodized aluminum. The connection zone consists of stainless steel (1.4571). The holes in the measuring zone made of hard anodized aluminum allow the internal sensors to be filled with mineral transformer oil. TrafoStick™ TSG5 is fitted with a Parker R11EDX3/471-like connector for general use. This connection allows the device to be mounted at the target connection, means the device is screwed directly onto the threaded flange on the transformer or on-load tap-changer. The installation location of the sensor is almost arbitrary, but a free flow of oil in the measuring zone must be guaranteed. The cable socket is located on the top of the device. The connection between the device and the host is made using the supplied cable with the WEiPU ST1210/S9 connector. The user should connect the device to a computer, router, modem, or similar device using the supplied TCP/IP cable.

The construction of TrafoStick™ had a strong regard for "on-the-line usage" in mind. Crucial and fragile components are covered and protected by a robust and sophisticated interplay of placement and housing materials. The resonance chamber, where the acoustic converter is located, on the lower left ends, holds not only the state-of-the-art acoustic resonator but also the humidity sensors and cutting-edge gas sensors. The electronics, which can easily handle the necessary data stream, are managed by a 32-bit embedded processor with a floating point unit (FPU) and matrix-vector co-processor. This allows TrafoStick™ to perform over 10 measurements per second and to present a new set of data each second on MODBUS TCP/IP.

Diagnostics is a decision-making factor in maintenance and asset management and can provide significantly better information about the condition of oil-insulated electrical systems with the online and real-time monitoring devices and methods available today.

Figure 5: TrafoStick™ TS G5 scale 1:1

Technical information TrafoStick™

Performance	
Breakdown voltage (BDV)	10kV – 120kV (± 2.5%)
Water Content (WC)	2ppm – 80ppm (± 2%)
Temperature (Temp)	-40°C – 120°C (± 0.2°C typical)
Oil Pressure (P)	20kPa – 550kPa (± 5.3kPa) 0.2bar – 5.5bar (± 0.05bar) 2.9PSI – 80PSI (± 0.7PSI)
Internal measurement interval	0.1s
External data output interval	1.0s
Hydrogen (H_2)	0ppm – 5.000ppm (± 10%)**
Carbon Monoxide (CO)	0ppm – 5.000ppm (± 10%)**
Operating environment	
Ambient temperature range	-20°C to 70°C
Oil temperature range	-20°C to 85°C
Operating pressure	Up to 700kPa (7bar; 100PSI)
Inputs and outputs	
Power supply	4.5-7.5V (nominal 5V DC) 24V/DC with 900A Kxx - Cable
Digital output	Digital protocol
PC interface	MODBUS TCP, MODBUS UDP
Internal data logging capacity	Dynamic latch buffer cache chains (64-512-8192)
General	
MODBUS	Cable available separately
Housing material	EN-AW-6063 (anodized)
Mechanical connection	Parker R11EDX3/471 - like connector
Measuring zone material	EN-AW-6066 (hard anodized)
Housing classification when assembled	IP68
Control software (Windows 8 or later)	Ver. 2.0
Absolute maximum ratings	
Maximum operating voltage	9.0V/DC
Operating temperature	-40°C to 100°C
Maximum pressure (never exceed)	900 kPa (9 bar; 130 PSI)
Storage temperature (without MODBUS cable)	-65°C to 150°C (excluding external cable)

*) *Corresponds to a measurement according to IEC60156:2018 - Determination of breakdown voltage at mains frequency - Test method*
**) *On the measured value)*

References

[1] IEC 60156 – Insulating liquids – Determination of the breakdown voltage at power frequency – Test method

[2] IEC 60247 – Insulating liquids – Measurement of relative permittivity, dielectric dissipation factor (tan d) and d.c. resistivity

[3] IEC 60814 – Insulating liquids – Oil-impregnated paper and pressboard – Determination of water by automatic coulometric Karl Fischer titration

[4] IEC 62021-1 – Insulating liquids – Determination of acidity – Part 1: Automatic potentiometric titration

[5] ISO 6295 – Petroleum products — Mineral oils — Determination of interfacial tension of oil against water — Ring method

[6] IEC 60666 – Detection and determination of specified additives in mineral insulating oils

[7] IEC 60567 – Oil-filled electrical equipment – Sampling of gases and analysis of free and dissolved gases – Guidance

[8] IEC 60599 – Mineral oil-filled electrical equipment in service – Guidance on the interpretation of dissolved and free gases analysis

[9] IEC 61198 – Mineral insulating oils – Methods for the determination of 2-furfural and related compounds

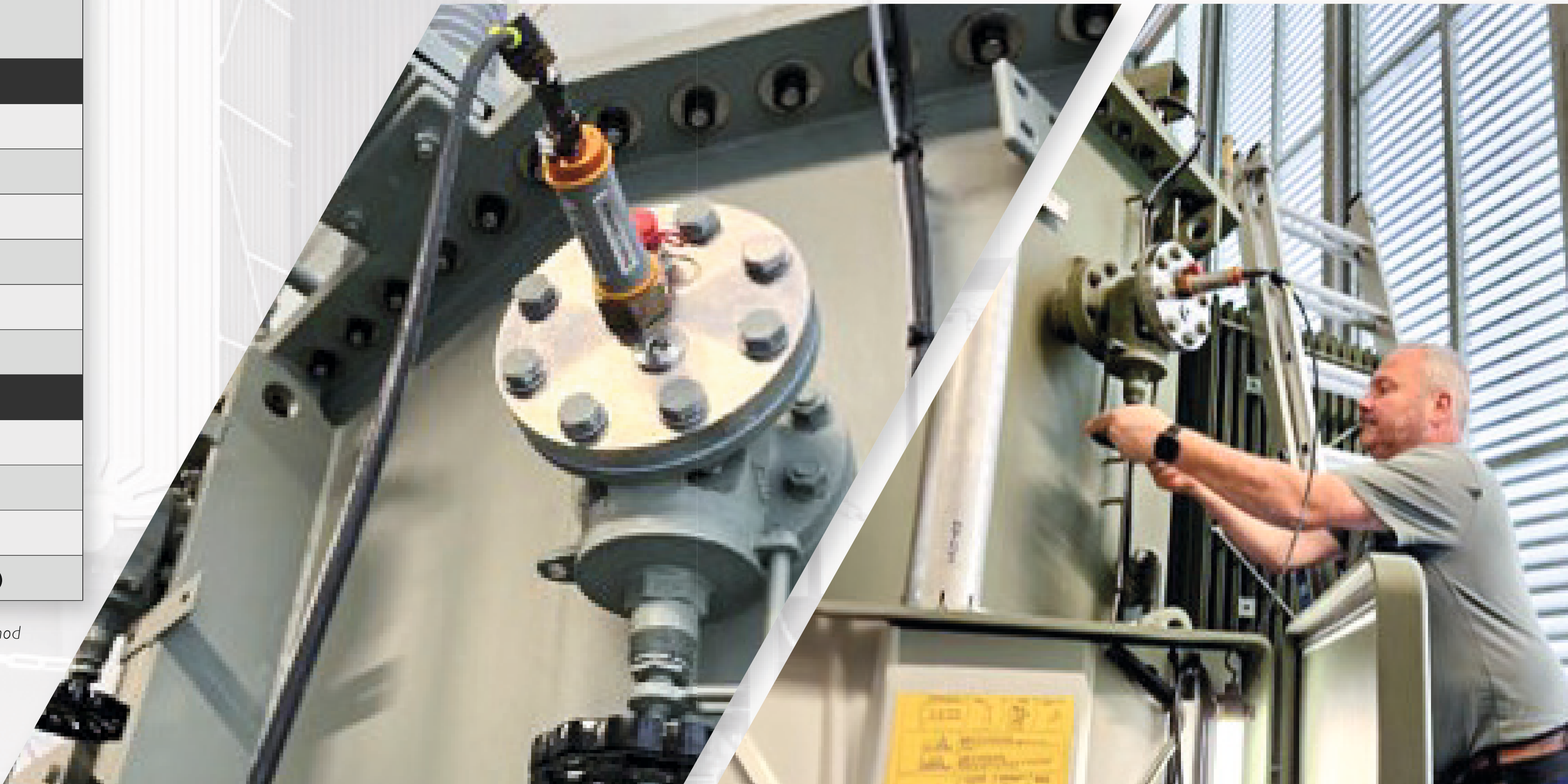
[10] IEC 60475 – Method of sampling insulating liquids

[11] Y.Du et. all, "Moisture Equilibrium in Transformer Paper-Oil System", IEEE electrical Insolation Magazine Vol. 15, No. 1

[12] E.T. Norris, "High Voltage Insulation", Proceedings IEEE Vol. 110, No.2

[13] IEEE Std C57.104TM-2019, "IEEE Guide for the Interpretation of Gases Generated in Mineral Oil- Immersed Transformers"

Figure 6: Installation of TrafoStick™ integrated mount version



A. Eberle in Africa for Africa

A. Eberle Africa (Pty) Ltd.

Unit 5, Edstan Business Park
2 Ibhubesi Road
Riverhorse Valley, Durban
South Africa, 4017

www.a-eberle.co.za

08/2024