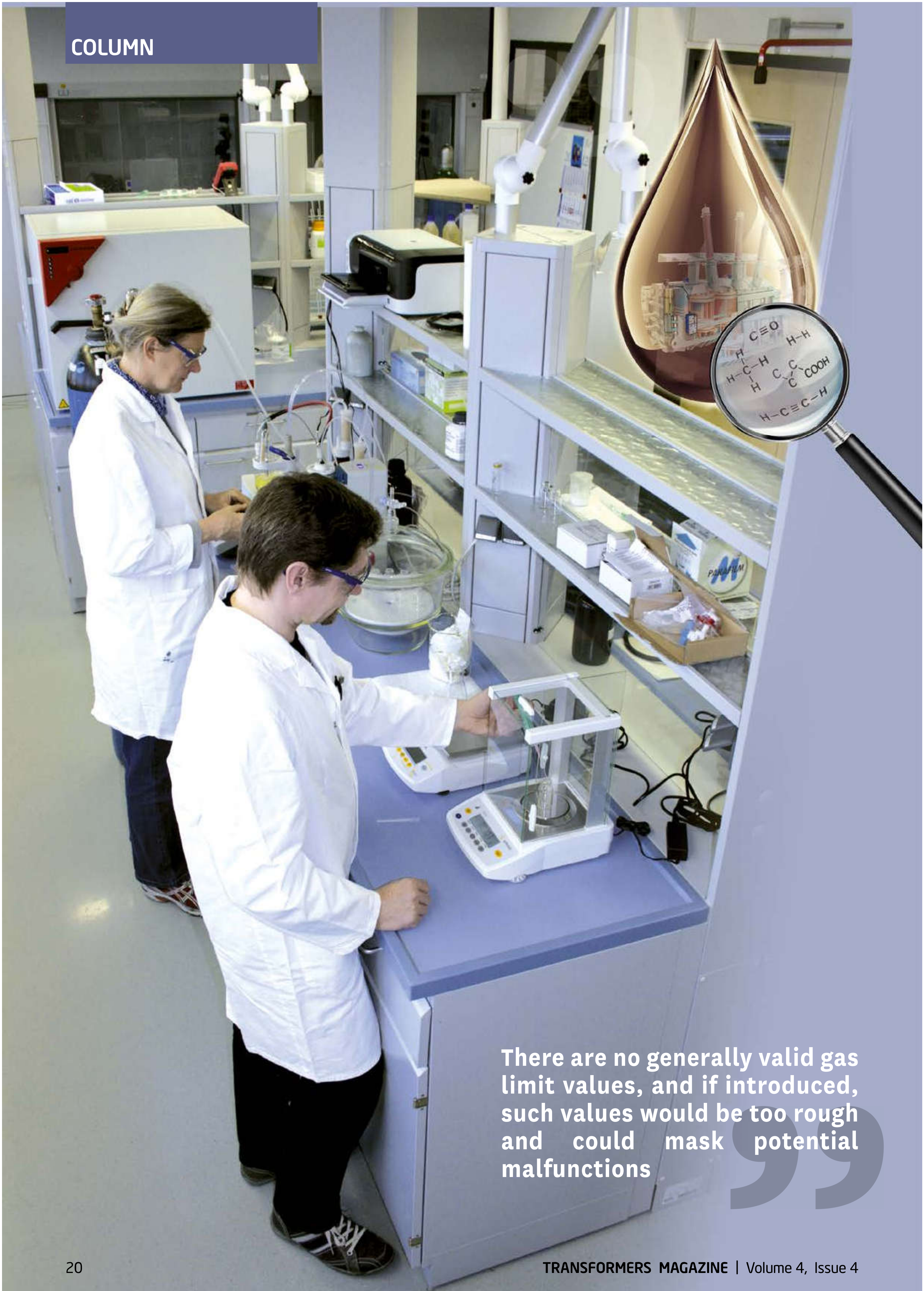


There are no generally valid gas limit values, and if introduced, such values would be too rough and could mask potential malfunctions

Rainer FROTSCHER

Tap-changer DGA: Uncovering an enigma

Part 2: Basic procedures

In Part 1 of this article [9], the general field of tap-changer DGA has been outlined. In Part 2, I will dig somewhat deeper and show some basic procedures which enable the user to define limit values for gas concentrations and gas increasing rates, or which allow a distinction between "good" and "bad", based on the qualitative evaluation of gas patterns which have been recorded in service. Limit values cannot be obtained from the tap-changer manufacturer, but they can be generated from field data. Only the end user knows about the characteristic operating conditions of his specific tap-changer population and only he has the DGA data available for evaluation. Usually, the tap-changer manufacturer has no access to these data. He has to rely on own tests which only reveal the typical gassing behaviour of a specific tap-changer model under laboratory conditions. But these figures do not necessarily represent the gas formation in "real life" – big differences between laboratory data and field data are observed. Depending on the OLTC type and specific operating conditions, the typical values for dissolved gases span over several decades. With this, it is not helpful to define limit values which can be regarded as generally valid, because they are too rough and will mask potential malfunctions. DGA values which are regarded as normal for one OLTC type may represent a malfunction for another type.

There are basically two pathways how to perform tap-changer DGA: the numerical and the phenomenological approach. While the numerical approach is based on a (more or less) "dull number crunching", the phenomenological approach "tries to understand" and uses well-defined gas patterns for comparison with patterns observed in the field.

4. The numerical approach

The numerical approach needs a sufficient amount of field data, collected from fault-free and faulty equipment. The more data available, the better. The data are usually stored in databases which should show an appropriate structure to enable a proper selection and evaluation of data.

4.1.Classification of OLTCs

We have seen in Part 1 of my DGA column that there are many different OLTC models in the field which all produce different gas patterns. So they should be clustered in groups with comparable gassing behaviour. Appropriate classification schemes according to the electrical components used and the type of design have been developed by CIGRE [10] and IEEE [11]. Figure 5 shows the CIGRE scheme, Figure 6 the IEEE scheme. Both basically give the same results. The major difference in gassing appears between non-vacuum and vacuum type models, so the most important classification is "A" (for arcing type) or "V" (for vacuum type). The second grade attribute is the type of transition impedance. "R" stands for transition resistors and "X" for transition reactances.

The third grade attribute considers the type of mechanical design. If diverter switch and tap selector are located inside the same oil compartment ("C" (CIGRE) or "A" (IEEE)), the change-over selector may add some sparking gases and overheated selector contacts may contribute heating gases to the tap-changer oil. IEEE additionally allows the definition of a separate tap selector compartment ("N") and the distinction between sealed ("S") and free-breathing ("B") OLTC compartments. In free-breathing equipment, the ppm level of dissolved gases is expected to be lower than in sealed equipment, because a certain amount of gases is lost via the breather. CIGRE doesn't regard this additional tag as relevant, because the differences in ppm values which are observed between individual OLTCs of the same class usually cover the differences between sealed and non-sealed units. The sealed/breathing tag may be helpful for arcing compartment types (CIGRE: "AXC", IEEE: "AXAS/B"), as they are common in the U.S.

Tap-changers of the same class show similar gas patterns during normal service, which means that DGAs of these individuals can be clustered in one data set. It is important that DGA databases allow to set these tags or contain other appropriate means which allow a comparable classification.

Limit values can be generated from field data for a specific tap-changer model, while gas ratios are more helpful in detecting behaviour which may lead to a failure

Appropriate classification schemes have been developed by CIGRE and IEEE, and basically both give the same results

A	Arc-breaking in oil for breaking/making load current			
V	Vacuum interrupters for breaking/making load current			
	R	Bridging current through resistors (resistor type)		
	X	Bridging current through reactances (reactor type)		
		S	Diverter switch and tap selector in different oil compartments (separate)	
		C	Diverter switch and tap selector in the same oil compartment (combined)	

Figure 5. Classification scheme for OLTCs according to CIGRE TB443

A	With arcing contacts (switching arcs in oil during a normal tap change operation)			
V	With vacuum interrupters (switching arcs encapsulated inside vacuum interrupters)			
	R	Resistor type (bridging through resistors)		
	X	Reactor type (bridging through a reactance)		
		S	Diverter switch and tap selector in separate compartments	
		A	All arcing switches in one compartment (selector switch)	
		N	All non-arcing switches in one compartment (tap selector compartment)	
			S	Sealed LTC tank
			B	Non-sealed LTC tank (breathing)

Figure 6. Classification scheme for OLTCs according to IEEE C57.139

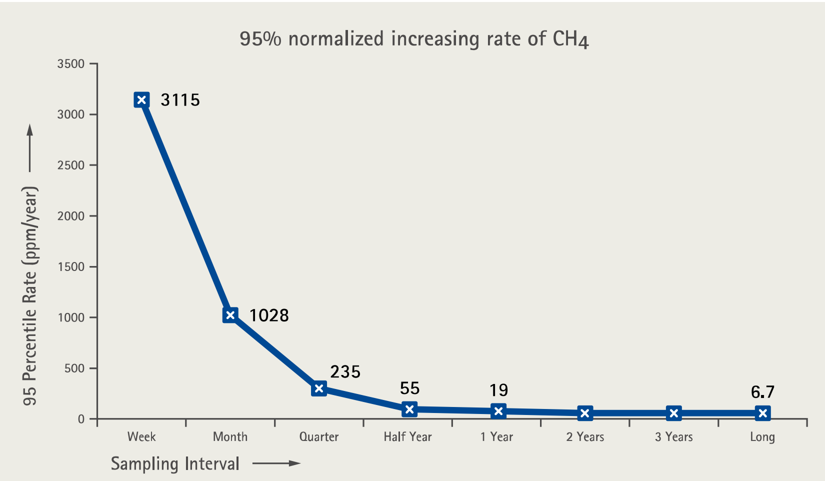


Figure 7a. Gas increasing rate [ppm/year] strongly depending on sampling interval

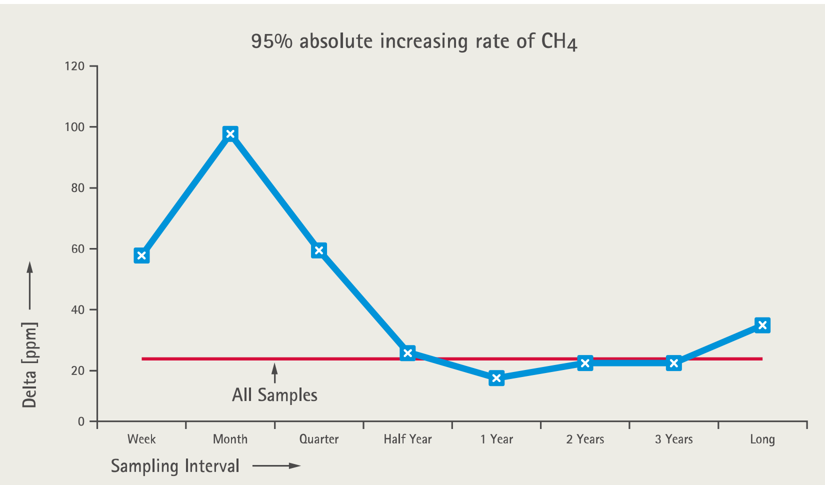


Figure 7b. Gas increasing rate [ppm] with weak correlation to sampling interval

4.2. Typical values

By using above classification, typical concentration values and gas increasing rates can be calculated for a data set by following the guidelines given in IEC 60599 [12]. These values represent the acceptable gas quantities that are exceeded by only an arbitrarily low percentage of higher contents, for example 10 %. Units showing these high values represent a higher risk of failure and so should be set in focus for early maintenance. It does *not* mean that these units are faulty. In this example, the typical gas concentration values or gas increasing rates are defined as the 90 % typical values. Other percentages may also be appropriate. If DGAs of faulty equipment (or with other incident in service, such as tripping of protective device or repair) are identified, the values observed there can be compared to the typical values to confirm or adjust the percentage. As for transformers, typical gas concentration values or gas increasing rates can be calculated for each characteristic gas considered and also for TDCG (Total Dissolved Combustible Gases). It may happen that, due to poor data quality or too less data, the calculated typical values are biased. Expertise is needed to adjust the typical values manually for reasonable values.

Gas increasing rates can be defined if there is more than one DGA for each tap-changer available. The Delta ppm value between two consecutive samples is the basis for calculating increasing rates. The interval between these samples may not include an oil change (OLTC maintenance), because by that gas values are reset to (almost) zero.

The definition of a suitable time interval hides some pitfalls. During the revision of IEEE Guide C57.104 [13], hundreds of thousand DGA data from transformers of all sizes were evaluated to derive the 95 % gas increasing rates of all relevant gases. It has been found that a "ppm-per-time" rate strongly depends on the sampling interval [14]. Figure 7a, as an example, shows an increasing rate of CH_4 in ppm/year over the actual sampling intervals. The factor between weekly and long-term sampling is 463! For other hydrocarbon gases, similar values were found. Such increasing rates are useless.

In case the gas increasing rate is expressed as absolute value instead, the influence of the sampling interval is much smaller (≈ factor 5), Fig. 7b. Because sampling intervals shorter than a half year are quite unusual, the average Delta ppm value over all samples gives a quite good representation of the true gas increasing rate. With this, the Delta ppm values between two consecutive samples should be used and compared with the typical gas increasing rate, without normalization by the sampling interval.

The major difference in gassing appears between non-vacuum and vacuum type models, while the differences between sealed and non-sealed units are not that significant

4.3. Caution limits

IEEE Guide C57.139 [11] depicts a method for the calculation of statistical outlier limits to identify gas concentrations which are so extreme that they can be suspected to represent faults or unusual stress. Again, this method shall only be applied on data sets after running through OLTC classification. The data sets should favourably contain at least 100 records; limits based on fewer than 50 records must be used with caution or have to be adjusted according to experience. After sorting the data for a specific gas from smallest to highest, the data set is divided into quarters (quartiles: Q1=25th, Q2=50th, Q3=75th percentile). An interquartile range is calculated: IQR=Q3-Q1. Now, an upper outlier limit is calculated: U1=Q3+1.5·IQR. This limit represents the border between normal and abnormal values and is usually close to the 95 % typical value (depending on the data distribution). A second outlier limit U2=Q3+3·IQR is recommended as caution limit for the detection of faulty equipment. In contrast to the 90 % or 95 % typical value, the outlier limit U2 is a statistical standard criterion for identifying values which seem to be too extreme to be part of the same population than the majority of data points.

4.4. Ratios

Besides limit values for absolute gas concentrations, gas ratios are helpful to detect suspicious behaviour which may lead to a malfunction of the OLTC. For non-vacuum OLTC types, the C_2H_4/C_2H_2 ratio tells when heating gases (mainly C_2H_4) are being formed at an unusually high rate compared to the arcing gases (mainly C_2H_2). Usually this behaviour is caused by degradation of the arcing contacts or by contact coking. The absolute gas concentrations play a minor role here, but there are cases where mechanical or other failures cause abnormal gas production without showing abnormal gas ratios. So, both values have to be regarded. A distribution of the C_2H_4/C_2H_2 ratio for a big population of arc-switching compartment type LTCs in the U.S. (CIGRE classification: "AXC" or "ARC") is shown in Figure 8. The typical range (upper/ lower limit) has been determined graphically to values between 0.1 and 0.7. Figure 9 shows this range in Duval Triangle #2. It covers most of the "N" zone and is applicable to all non-vacuum OLTC types when new (CIGRE classification „ARS", „ARC", „AXS", „AXC"). The range can be used as initial value and may be adjusted according to specific needs. Ratios derived from faulty equipment may narrow the admissible range. James Dukarm adds: *"The triangle can show us what is unexceptional, and gas ratio limits, plotted on the triangle as straight lines, can show us what is (relative to a specific population) exceptional, i.e. suggest when something that is not entirely 'normal' may be a candidate for maintenance."* It does **not** mean that all data outside the typical range represent faulty equipment.

For vacuum type OLTCs, the C_2H_4/C_2H_2 ratio will give much larger values, as C_2H_2 values are extremely low. They usually show up in the 1-digit ppm range and are often below 1 ppm. Because ratios may vary extremely when calculated with low values, they may not be applicable. This is also true for the Duval Triangle, which is regarded as ratio method.

Some OLTC types (like "ARC", "ARS", "VRC", "VRS", according to CIGRE

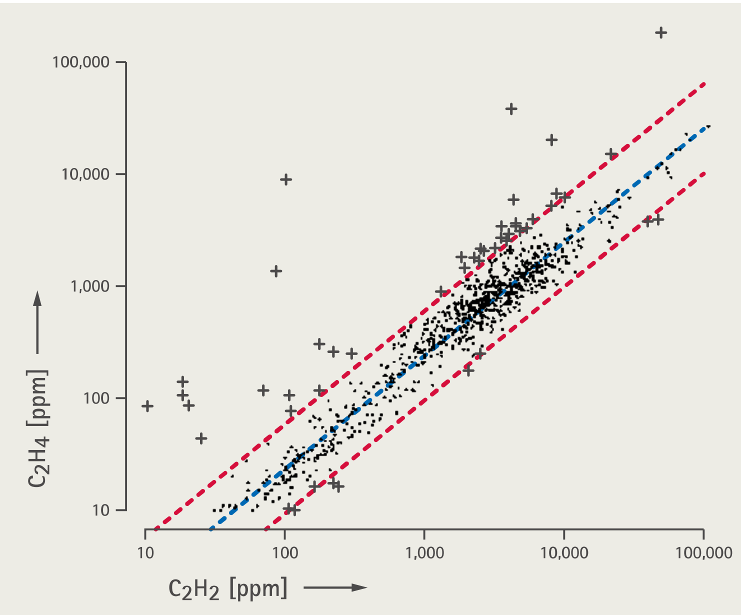


Figure 8. C_2H_4/C_2H_2 gas ratio of CIGRE classification „AXC" / „ARC" OLTCs

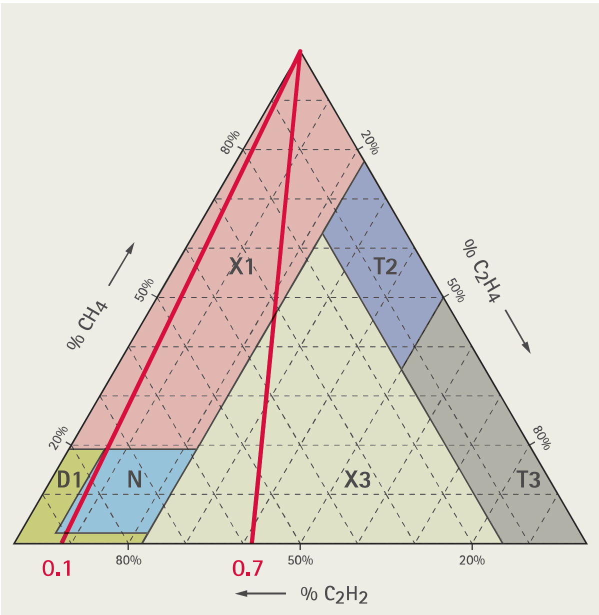


Figure 9. Typical range for C_2H_4/C_2H_2 gas ratio in Duval OLTC Triangle

We have identified three basic gas patterns which can be assigned to normal service: arcing, sparking and heating <300 °C, plus the exceptional arcing pattern for carbonized oil

classification) deliver their typical gas fingerprints for normal operation in different parts of the Triangle #2. To cover that, additional N zones have been defined, which can be used as an overlay on the Triangle #2, Fig. 10. The boundaries of these additional N zones as given should be used only as initial idea and may be adjusted according to the individual behaviour of the tap-changer population in focus. Even if the additional N zones are located in fault zones, they will represent the normal behaviour of the specific OLTC model, as long as the data points don't move significantly. If a trend is detected with subsequent data points steadily moving out of the defined N zone(s), then the fault zone aimed for likely defines the nature of an incipient failure. See IEEE C57.139 Annex D for additional information [11].

4.5 .Elaborated statistics / Data mining methods

There are several approaches how to use data mining methods, fuzzy logic, artificial neuronal networks or elaborated statistics like cluster analysis etc. to improve the common DGA interpretation methods for transformers. Up to now, there was no real "break-through", say: the hit rate for detecting faulty equipment didn't improve significantly. Still, the set of Duval Triangles 1, 2, 4, 5 is acknowledged to give the best results (Triangle 3 is for non-mineral liquids). Up to now, the said sophisticated methods (and combinations thereof) have not been applied to tap-changer DGA.

5. Phenomenological approach

As explained in Part 1 of this article [9], the generation of gases from mineral oil can be assigned to specific temperature ranges, which represent a certain amount of energy. The normal OLTC operation (and malfunction, of course) introduces energy into the oil and so causes specific gas mixtures. The absolute gas concentrations or gas generation rates are a measure for the stress of the OLTC or the severeness of a failure. All fault types (D1, D2, T1, T2, T3) can be represented by key gases and significant gas ratios. Key gases and ratios have been originally defined for transformers, but they are basically applicable also to OLTCs, depending on the specific model. It would go far beyond the range of this column going into details on key gases and ratios, so I may just refer to the path-breaking publications of Müller/Schliesing/Dörnenburg, Rogers and Duval [15, 16, 17].

In OLTCs, the gas concentrations of all significant gases vary over several magnitudes, as they depend on numerous parameters. After classifying the OLTC(s), it helps to identify the gas generating components present and know about the determining parameters. Each component produces a typical gas pattern with varying absolute values and varying ratios. Depending on the OLTC type, different components are present. Their patterns superimpose and give a mix gas pattern, also with varying values and ratios. By evaluating the operational parameters, the expected mix gas pattern can be improved and then compared to the measured DGA pattern. The result is a qualitative evaluation, such as "good", "suspicious", "incipient fault" or "faulty".

5.1. Gas generating components in OLTCs

a) Arc-switching contacts

Non-vacuum OLTCs use arc-switching contacts to perform the load-switching operation. The switching arcs usually produce huge amounts of C_2H_2, plus a "tail" of heating gases in lower amounts. The amount of gases strongly varies with the transformer load and number of operations per day and is further influenced by the step voltage, the electrical design of the transition impedance and the breathing conditions. As already mentioned in Part 1 of this article [9], the switching arcs may also produce a completely different pattern in carbonized (aged) oil, with C_2H_4 as the major gas and less C_2H_2.

b) Vacuum interrupters

In vacuum type OLTCs, the arc-switching contacts are substituted by vacuum interrupters. Vacuum interrupters are sealed systems, which do not release or produce any gases in the surrounding oil. In case of an unlikely leakage, the vacuum inside the interrupter tube is lost, oil may intrude and the switching contacts act under oil with highly reduced switching capability. It may

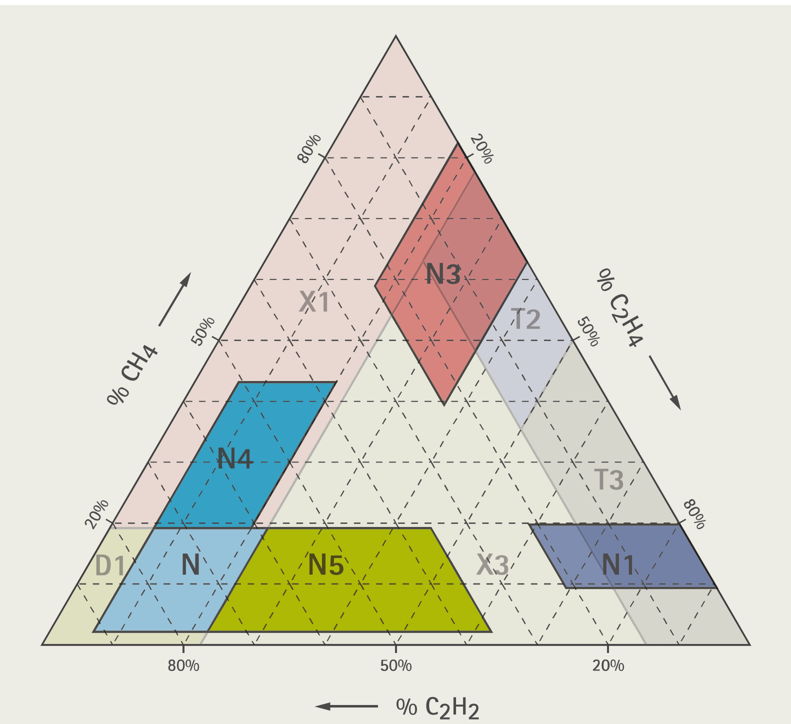


Figure 10. Additional N zones for specific OLTC types

happen then that the tube breaks, due to enormous overpressure. In this case, huge amounts of arcing gases will be produced which can easily be detected as a failure.

c) Main contacts / By-pass contacts

In some OLTC types, a main contact respectively by-pass contact commutates the load current from the continuous current path onto the main switching path, causing it to flow through the vacuum interrupter or switching contact. Because inductance and resistance of the main switching path are higher than in the continuous current path, some sparks or low-energy arcs are generated at the main or by-pass contact.

d) Transition resistors

Transition resistors are heated by the load current and by the circulating current during bridging position flowing through the transition path. For nominal load operation, the maximum temperature at the transition resistor surface will be usually below 300 °C, causing a T1 heat

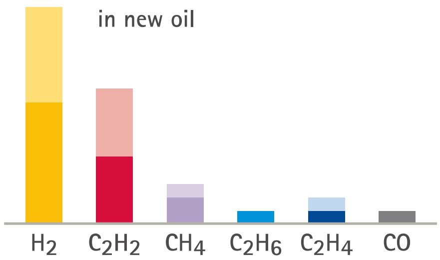
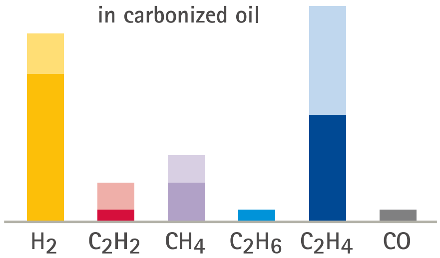
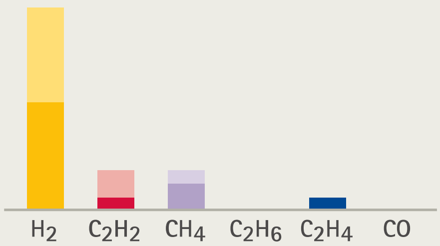
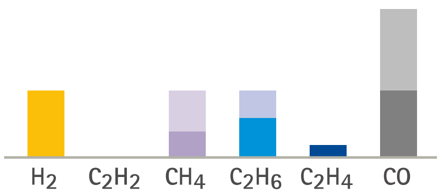
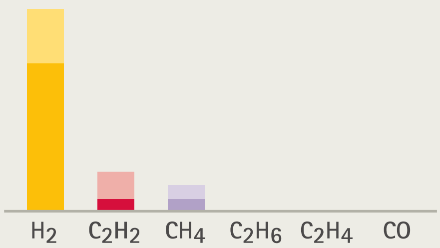
Gassing Source	Typical Pattern of Dissolved Gases		Determining Factors
arc-switching contacts	arcing	in new oil  in carbonized oil 	number of operations per day transformer load *(I_u)* step voltage *(U_i)* transition impedance grade of oil carbonization breathing conditions
main contacts, by-pass contacts	sparking / low-energy arcing		inductance and resistance of main current path load current
transition resistors	heating < 300°C		design values for step voltage and through-current (application-specific) actual load load profile oil temperature
change-over selector	low-energy arcing / sparking		capacitances of regulating winding to neighboured windings or core / tank voltage of regulating winding design (type-specific) contact opening speed

Figure 11. Typical gas patterns of OLTC components

Units showing higher gas values represent a higher risk of failure and so should be set in focus for early maintenance, but it still does not mean that these units are faulty

gas pattern. Operations under overload, or multiple consecutive operations as they may occur in service, will cause higher temperatures, but because they are rare, they will not change the typical gas pattern significantly. On the other hand, when switching operations under no load or partial load are performed, the resistors heat up very moderately and so will produce none or only negligible amounts of hydrocarbon gases. At surface temperatures of less than 100 °C, mainly CO and CO_2 are produced due to incipient oil ageing which can be used as indicator for moderate thermal stress of the oil [18]. The use of CO and CO_2 as thermal indicators is possible here because tap-changers only contain negligible amounts of cellulose, whose degradation usually causes CO and CO_2.

e) **Transition reactances**

Transition reactances show very low losses. They don't heat up significantly and so produce only negligible amounts of gases. As they are always located in the transformer tank, they cannot influence the DGA of the tap-changer oil compartment. Malfunctions can be likely detected in the transformer DGA.

f) **Change-over selector**

The tap selector inside the transformer tank or selector tank can be equipped with a change-over selector which may produce switching sparks or low-energy arcs (D1) when operated. The determining parameters have been depicted in Part 1 of this article [9].

g) For the sake of completeness, the fine tap selector contacts and DETC contacts are listed. They cannot switch the load current and may only heat up very moderately (max. 20 K (for OLTCs) resp. 15 K (for DETCs) at $1.2{\cdot}I_u$), so they won't produce any gases.

In general, if contacts are operated very infrequently or are of poor design, they may fail due to overheating (T2 or T3 fault). This is true for fine tap selector contacts as well as for the change-over selector. If mounted in the transformer tank, they will show their behaviour in the transformer DGA.

With this, we have identified three basic gas patterns which can be assigned to normal service: arcing, sparking and heating <300 °C, plus the exceptional arcing pattern for carbonized oil looking like a T2 fault. Figure 11 summarizes the above said.

How these patterns superimpose in the different OLTC types and how the resulting mix gas patterns should be interpreted, will be the content of my next column. Stay tuned!

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