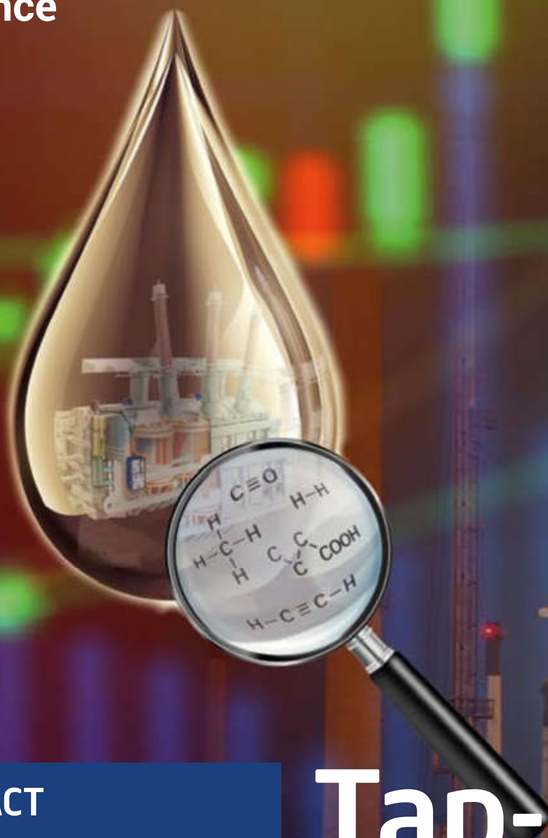
In many cases, DGA will help us reveal suspicious behaviour – by looking at gas patterns, evaluating gas concentrations and increasing gas rates, and – by using experience



Tap-changer DGA: Uncovering an enigma

Part 3: Interpretation

ABSTRACT

Gas generation in OLTCs is influenced by operational and design parameters. There are multiple gas generating components present depending on the specific OLTC model or class resulting in a superimposed gas pattern thus making its interpretation for the purpose of fault detection more difficult. In many cases, suspicious behaviour can be revealed, and in some. the normal bandwidth of observed gas pattern can fully mask a thermal or electrical fault. The DGA results can be misleading or fail to identify an actual fault, so they should be confirmed by additional testing and never be used as a single criterion for shutdown or repair decisions.

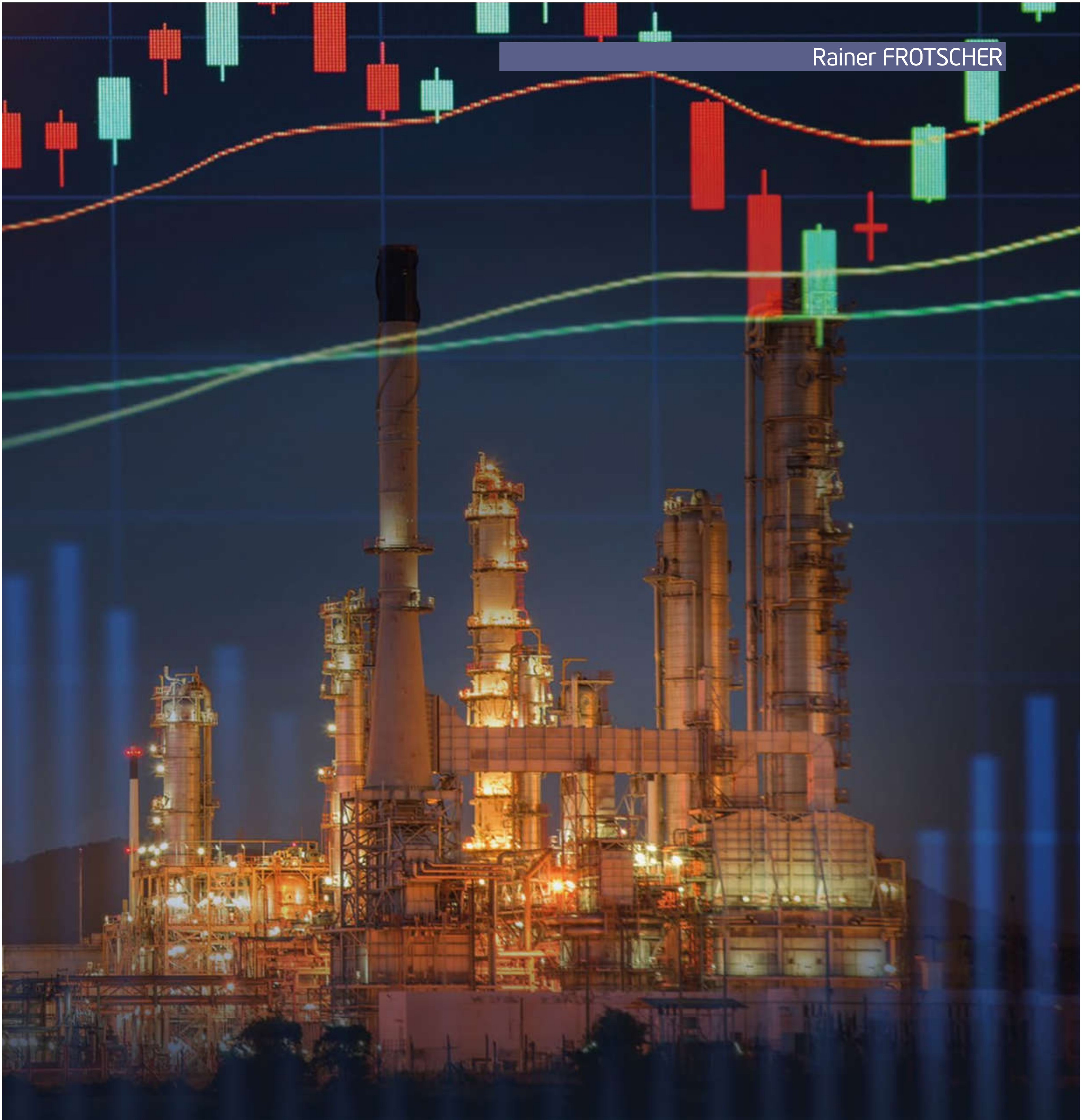
KEYWORDS

on load tap changers (OLTC), dissolved gas analysis (DGA), gas pattern, fault detection

Part 2 of this article [19] showed different pathways how to evaluate the DGA patterns observed in OLTCs. The numerical approach is based on a statistical evaluation of as much as possible DGA data of a selection (class) of OLTCs, while the phenomenological approach starts by identifying the gas generating components inside an OLTC and assigns typical gassing patterns to each component. The ppm values for each gas generating component vary with the actual operating conditions. Depending on the specific OLTC model or class, there may be more than one gas generating component present, so the respective gas patterns superimpose and give a resulting mix gas pattern which may be clearly interpretable – or not. But before we discuss these mix gas patterns, we should first identify the parameters which influence the gas generation and assign possible tap-changer faults to fault gas patterns.

5.2. Parameters influencing gas generation

The factors which determine the amount



of gases generated by the respective component have been listed in Fig. 11 of Part 2 of this article [19]. A few more words are advisable.

- OLTC type

The main difference in gassing appears between non-vacuum and vacuum type OLTC models. While non-vacuum type models can generate more than 100,000 ppm of combustible gases, vacuum type models only generate very low amounts of gases, usually in the same range as in the transformer. See also of Part 1 of this series, section 2.2, for more details [9]. Also the influence of the oil volume is very evident: gases generated by the same energy amount cause only the half ppm amount if the oil volume is doubled.

- Switching principle

Several different switching mechanisms are available to perform the load switching operation. In case of arc-switching models for example, the switching contacts can break the current by one to four switching arcs connected in series, and two or four transition contacts can be used to smooth the load switching operation. Vacuum type models show an impressive variety of possible switching principles, using one to four vacuum interrupters per phase. Depending on that, auxiliary and commutation contacts may be necessary to allow a reliable load switching operation without interruption of the load current. For details see [20]. The sparking intensity on the commutation contacts is mainly determined by the internal impedances of the tap-changer.

Non-vacuum type OLTCs can generate more than 100,000 ppm of combustible gases, while vacuum type models only generate very low amounts of gases

- Design of transition impedance

In combination with the step voltage, the ohmic value of the transition resistors or the impedance of the transition reactance determines the circulating current, which has to be broken by the transition contacts. The transition impedance values are usually set in a way that the transition contacts see a similar load like the main switching contacts. The cross section of the transition resistors is optimized to the individual application so that surface temperatures <300 °C are achieved for normal operation. Temperatures beyond 450 °C are only exceeded in very severe overload cases which are rare.

- Transformer load conditions and number of operations per day

These figures vary in daily and yearly cycles. It is obvious that, especially for non-vacuum OLTC models, a partly loaded transformer leads to lower gas production inside the tap-changer oil compartment than a transformer under full load or overload conditions. Depending on the application and system voltage control strategy, the number of operations per day may vary from one or two (network service) to more than hundred switching operations (industrial). There is also some evidence that the shape of the load current (non-sinusoidal, harmonics) as well as the power factor (phase angle between system voltage and load current) influences the gas generation behaviour in unexplored manner.

- Breathing conditions

As a result of transformer load changes, the average transformer oil temperature also varies – and likewise the OLTC oil temperature (very true for in-tank types, less significant for compartment types). For free-breathing applications, the thermal oil expansion determines the air exchange in the oil conservator, causing a more or less quick escape of dissolved gases to ambient air. Vacuum type OLTCs can be operated also in sealed environment, which leads to a greater accumulation of dissolved gases than in free-breathing environment. Nevertheless, a non-definable amount of gases will volatilize through membranes or gaskets, leading to steady-state conditions of the ppm values long-term.

- Grade of oil carbonization

As already discussed in [9], non-vacuum OLTCs models can fundamentally change their typical gassing behaviour, depending on the grade of oil carbonization. The "high-ethylene-phenomenon" (as I call it) shows an exceptional gas pattern with predominantly C_2H_4 instead of C_2H_2, which cannot be explained by the phenomenological approach.

All these factors are responsible for the wide range of OLTC DGA values which are observed in the field. Basically, each OLTC shows an individual fingerprint. One could now assume that OLTC DGA is a hopeless attempt. Well, if one tries to simply apply the valid methods and statements for transformers (e.g. "arcing or sparking is always a fault", and "high amounts of C_2H_4 indicate non-tolerable overheating"), then OLTC DGA will be a fail, yes. But, if one approaches this topic cautiously and tries to understand where the gases come from and how gas generation is influenced by operational and design parameters, then, in many cases, suspicious behaviour can be revealed – just by looking on the pattern and evaluating ppm values and gas increasing rates. Experience is the best teacher.

5.3. OLTC faults detectable by DGA

For non-vacuum OLTC types, arcing is normal, and arcing in carbonized oil can cause huge amounts of C_2H_4 without representing a fault (class ARS, ARC; classification acc. to CIGRE TB443; see [10] and section 4.1. in [19]). For these

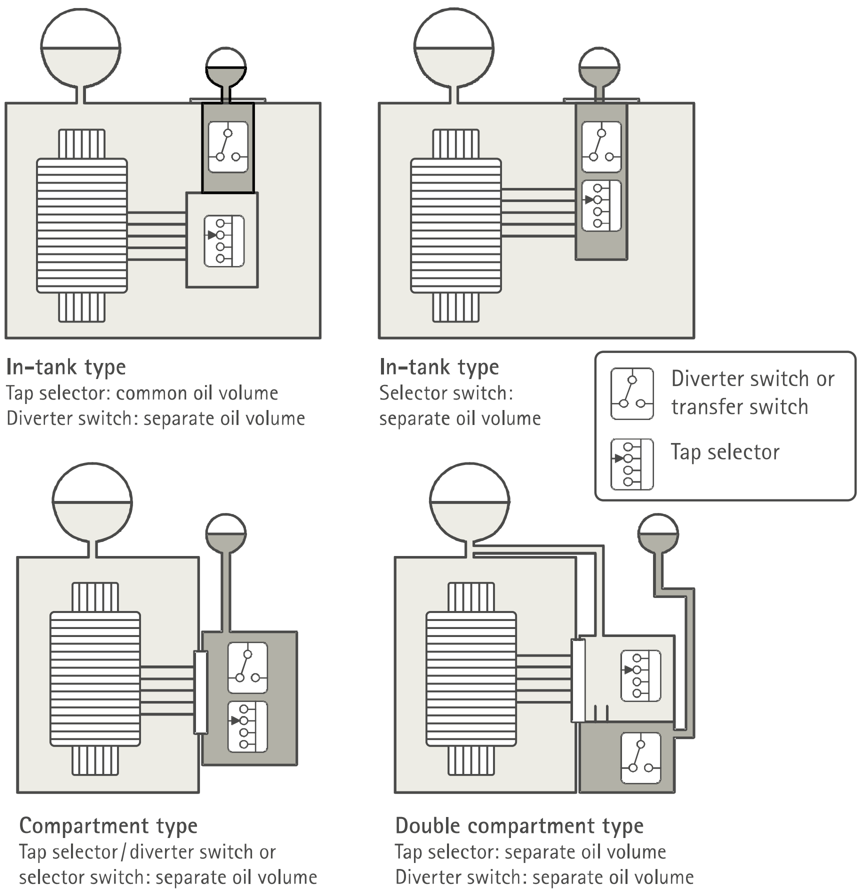


Figure 12. Oil compartments of different OLTC designs [20]

types, interpretation is a challenge, because the normal bandwidth of the observed gas pattern can fully mask a thermal or electrical fault. In general, these typical tap-changer faults can be detected by DGA, following the fault categories defined by M. Duval [17]:

X1: Overheating of current-carrying parts (contacts, leads; T<300 °C), metallic parts on floating potential (causing unwanted low-energy arcs or sparks)

T2: Coking of contacts, overheated transition resistors, partially broken braids (300<T<700 °C)

T3: Heavy coking of contacts (T>700 °C)

D1/D2: Worn or broken contacts, broken braids or leads (abnormal arcing)

X3: Overheating in progress, increased contact resistance, unwanted arcing (combined faults)

5.4. OLTC compartments

It is essentially important to identify the oil compartment for which DGA shall be performed. The DGAs from each compartment must be treated separately. During the sampling process, the type of oil compartment must be noted in the accompanying document (sample sheet). Figure 12 illustrates the available OLTC designs [20].

- The diverter switch compartment accommodates the arc-switching contacts or vacuum interrupters, commutation contacts, main contacts and the transition resistors. The oil volume depends on the OLTC size (kVA step capacity) and voltage class and varies between 125 and 970 litres.

- For some in-tank OLTC models (class ARS, VRS), the tap selector with or without change-over selector is located in the main transformer tank. DETCs are usually also located in the transformer tank. It is obvious that, due to the huge oil volume, the normal switching activity of the change-over selector causes only negligible amounts of gases, which will be hardly detectable in the transformer DGA [21].

All vacuum type models show very low gas values during normal service, and unexpected high values of hydrocarbon gases indicate a fault

- A separate selector tank shall prevent from any influence of the change-over selector on transformer DGA. Nevertheless, this selector tank usually uses the same oil conservator as the main tank. So it still may happen that gases from the tap selector are introduced in (very) low amounts into the transformer oil via the air/gas space in the conservator. All leads from the regulating winding must be routed through a panel board. The oil volume of such a selector tank can reach 3000 litres for in-tank OLTC models, for double compartment type OLTCs it is typically 600-800 litres.

- Many OLTC models use a common or combined oil compartment for the diverter switch and the tap selector/change-over selector (class ARC, AXC, VRC, VXC). These models often operate as selector switch which combines the tap selection with the load-switching operation in one movement. As a derivate, only the fine tap selector may be located in the OLTC compartment, leaving the change-over selector in the transformer main tank. The range of the oil volume goes from 125 litres (in-tank single phase selector switch, U_m 76 kV) to ca. 1200 litres (compartment type models, U_m 76 kV).

5.5. Resulting mix gas patterns

The classification acc. to CIGRE TB443 or IEEE C57.139 (both illustrated in [19]) should be sensibly used to distinguish between the different OLTC designs. All available designs can be represented by this classification. Each class produces a typical mix gas pattern, which is the result of superposition of patterns from the respective gas generating components. Fig. 13 shows the resulting mix gas patterns for all OLTC classes for normal service qualitatively. While the non-vacuum types (class begins with "A") can show values of more than 30,000 ppm per single hydrocarbon gas (especially true for H_2, C_2H_2, C_2H_4), the vacuum types (class begins with "V") typically generate hydrocarbon gas values of less than 30 ppm.

An extra factor of 5 to 10 applies between the values of class VRC / VRS (in-tank) and VXC (compartment) types, due to the higher oil volume of compartment type OLTCs. Fig. 13 cannot display these huge differences by using a linear scaling, and a logarithmic scaling would mask relations between the single gases. This is why a ppm scale is not displayed. The bar charts shall only give a visual impression of the resulting mix gas pattern. It can be seen that the huge amounts of gases which are caused by arc-switching contacts clearly dominate the mix gas pattern and almost completely mask the gases from transition resistors, change-over selectors, by-pass contacts etc. For vacuum type models on the other hand, only these gases are present, which allows a clear detection of faults. The pale sections of the bars coarsely indicate the usual variation of values, caused by the influencing parameters outlined in section 5.2.

Please note that only the gases inside the OLTC oil compartment (diverter switch or combined oil compartment) are discussed here. Gases from the change-over selector mounted inside a separate selector compartment or inside the transformer tank have to be treated separately.

Class VXS types are not existing.

For non-vacuum OLTC types, interpretation is a challenge, because the normal bandwidth of the observed gas pattern can fully mask a thermal or electrical fault

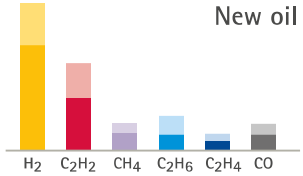
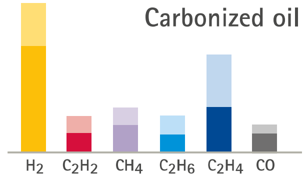
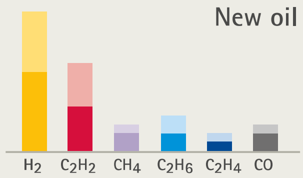
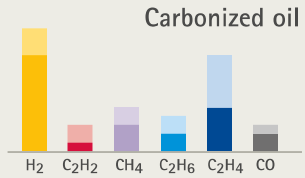
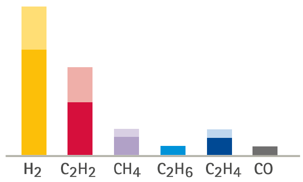
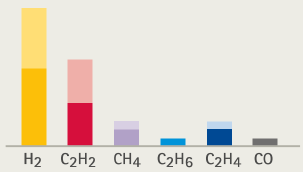
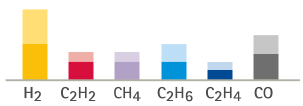
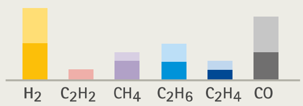
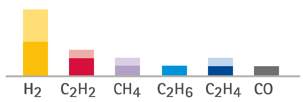
Class	Gas generating components	Typical mix gas pattern	Interpretation
ARC	Arc-switching contacts Arcing		Duval triangle #2 with additional N zones (as far as possible)
	Transition resistors Heating < 300°C		
	Change-over selector Low-energy arcing		
ARS	Arc-switching contacts Arcing		Duval triangle #2 with additional N zones (as far as possible)
	Transition resistors Heating < 300°C		
AXC	Arc-switching contacts Arcing		Duval triangle #2
	Change-over selector Low-energy arcing		
AXS	Arc-switching contacts Arcing		Duval triangle #2
VRC	Sliding selector contacts Sparking		High ppm values indicate fault Duval triangle #2 with additional N zones (if ppm values are sufficiently high) Trend analysis
	Change-over selector Low-energy arcing		
	Transition resistors Heating < 300°C		
VRS	Main (by-pass) contacts Sparking		High ppm values indicate fault Duval triangle #2 with additional N zones (if ppm values are sufficiently high) Trend analysis
	Transition resistors Heating < 300°C		
VXC	Main (by-pass) contacts Sparking		High ppm values indicate fault Duval triangle #2 Trend analysis
	Change-over selector Low-energy arcing		

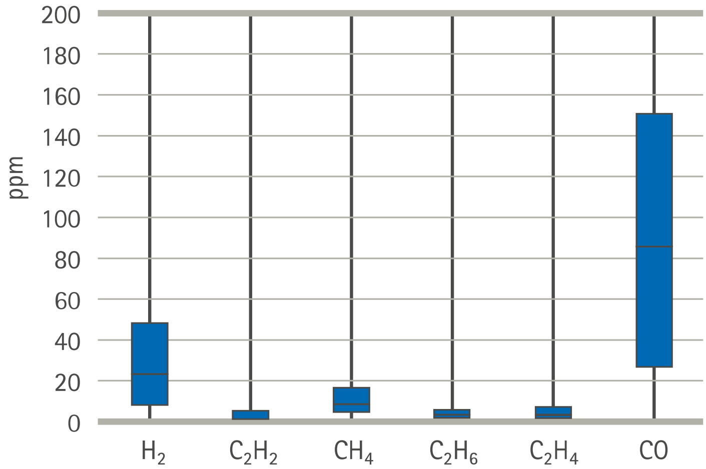
Figure 13. Mix gas patterns for OLTC oil compartment (classification acc. to CIGRE TB443 [10])

6. Interpretation

6.1. Limit values

As discussed in section 5.2., the absolute values vary significantly due to the influencing parameters. Limit values can be derived for generic OLTC classes, using the method described in IEEE C57.139 [3]. To minimize spread, only tap-changers of the same class in comparable applications should be grouped. As an example, field values from the manufacturer's database for class VRS types in network service are given in Figure 14, including the respective box plot. The database contains 315 data sets from laboratory analyses as well as from online DGA systems (which have been thinned out to avoid overweight), and includes also several fault cases. The upper outlier limit U1 flags the border between normal and abnormal values. U2 is the caution limit (see section 4.3. in [19] for additional information on this method). The fault cases show values far beyond the U2 limit and so are clearly detectable. In comparison with the expected mix gas pattern from Fig. 13, it can be seen that C_2H_6 and C_2H_4 are much smaller than expected, and CO turns out to be significantly higher. This can be explained by the low temperatures of the transition resistors which are typical for network service, favourably producing CO (see [8], [9]).

The DGA fingerprint of ARS OLTCs changes from "classic arcing pattern" to "high-ethylene behaviour" six to seven years after commissioning



	H_2	C_2H_2	CH_4	C_2H_6	C_2H_4	CO
Minimum value	0	0.0	0	0	0	0
1st Quartile Q1	7	0.0	3	0	1	27
Median value	21	0.5	7	1	2	84
3rd Quartile Q3	48	2.4	15	3	4	152
Maximum value	2,765	663.0	356	215	562	1,048
IQR = Q3 – Q1	41	2.4	12	3	4	125
U1 = Q3 + 1.5 x IQR	110	6.0	33	7	10	340
U2 = Q3 + 3 x IQR	171	9.6	51	11	16	528

Figure 14. Data Distribution for class VRS OLTCs (network service)

Much more difficult is the fault detection for class ARC and ARS types. A preliminary statistical evaluation of ≈460 samples from class ARS OLTCs of all ages shows U1 limit values which could – or could not – indicate a malfunction. To use the IEEE method on such OLTCs, it must be distinguished between new oil and carbonized oil. It must be known how long the unit has been in service since the last inspection / oil change, and if an oil filter unit is used or not. This information is often not available. As a rule of thumb, one can say that, for network service, the DGA fingerprint changes from "classic arcing pattern" to "high-ethylene behaviour" six to seven years after commissioning. After the first inspection, the interval tends to shorten to four to five years. At present, generally valid limit values are not available for these types. Field data from ARC types are rare, because these tap-changers are used in smaller power transformers, where DGA often is not applied. ARC and ARS models may be pooled, because their typical gas patterns are very similar.

However, the world looks much friendlier for class AXC or AXS models, which are all compartment types. Huge DGA databases are available at the utilities which allow the calculation of individual limit values for the particular OLTC population under investigation. For these models, excessive heating gas values clearly indicate an overheating fault, and arcing gases beyond the set limit values may flag worn or broken contacts or braids (see section 5.3.).

As all vacuum type models (class VRC, VRS, VXC) show very low ppm values during normal service, unexpected high ppm values of hydrocarbon gases indicate a fault. Limit values for H_2 are unreliable, as H_2 may also originate from stray-gassing issues. For all other gases, limit va-

Table 1. TDCG gas increasing rates for generic OLTC types (CIGRE TB443 [10])

OLTC class	≈ ppm / 1,000 op's
ARC, AXC, AXS	500
ARS	6,000
VRC, VRS	10–30
VXC	0–10

Table 2. Maximum gas increasing rates for C_2H_2 for network service [22]

OLTC type	OLTC class (CIGRE TB443)	ppm C_2H_2/1,000 op's
VACUTAP® VV	VRC	< 2
VACUTAP® VR	VRS	< 4
VACUTAP® VM	VRS	0
VACUTAP® RMV-II	VXC	< 3

lues can be calculated and optimized for a given OLTC population. Class VRC and VRS models may be pooled, as their gas patterns are very similar. Generally, a limit value of 50 ppm can be set for C_2H_2 to mark abnormality and to initiate further investigation [22].

Gases from change-over selectors mounted in a separate selector tank can reach more than 200 ppm of H_2 and more than 20 ppm of C_2H_2 without showing a fault, when operated frequently.

6.2. Gas increasing rates

Gas increasing rates in "ppm-per-time" strongly depend on the sampling interval (explained in [19], section 4.2), so the Delta ppm value between two samples should be used instead. This value can be divided by the number of operations performed in that interval to gain a "ppm-per-1000-operations" value. In CIGRE Brochure TB443 [10], typical values for such gas increasing rates have been derived for TDCG from field data for the generic OLTC classes, see Table 1. It can be seen that all compartment type OLTCs (class AXC, AXS, VXC) generate lower ppm amounts than in-tank types (class ARS, VRC, VRS), due to their higher oil volume in relation to the kVA step capacity. Please note that the given values are *typical values* and *do not* indicate limits. In case the "ppm-per-1000-operations" value of the actual interval is significantly higher than in previous intervals, and without changes of the average load conditions, then this should be valued as suspicious behaviour.

For designated vacuum type OLTC models in network service, a maximum generation rate for C_2H_2 has been defined [22]; see Table 2. As typical values are much lower, exceeding these limit values should cause action to contact the manufacturer.

6.3. Discussion

With the above said, it becomes visible that reactor type OLTCs (class AXC, AXS, VXC) can be evaluated much easier than resistor type OLTCs. Heat gases may only occur as accompanying gases to the normal arcing or sparking activity. Typical gas patterns for normal operation show up in the N zone of Duval Triangle #2. An additional evaluation method is the "Stenestam Ratio" (named after its inventor, Bengt-Olof Stenestam), which sets the sum of heating gases (CH_4+C_2H_4+C_2H_6) in relation to the main arcing gas (C_2H_2) [23]. In case the ratio is >5, overheating is assumed. Ratios between 0.5 and 5 should lead to shorter sampling intervals.

DGAs from vacuum type models (class VRC, VRS, VXC) are also easy to interpret, as unexpected high gas values or increasing rates in most cases indicate a malfunction. In case the ppm values are sufficiently high, the Duval Triangle #2 can be applied in combination with the additional N zones. While class VXC models often show their fingerprint in the "classic" N zone, VRC and VRS class models favourably appear in the N3 zone.

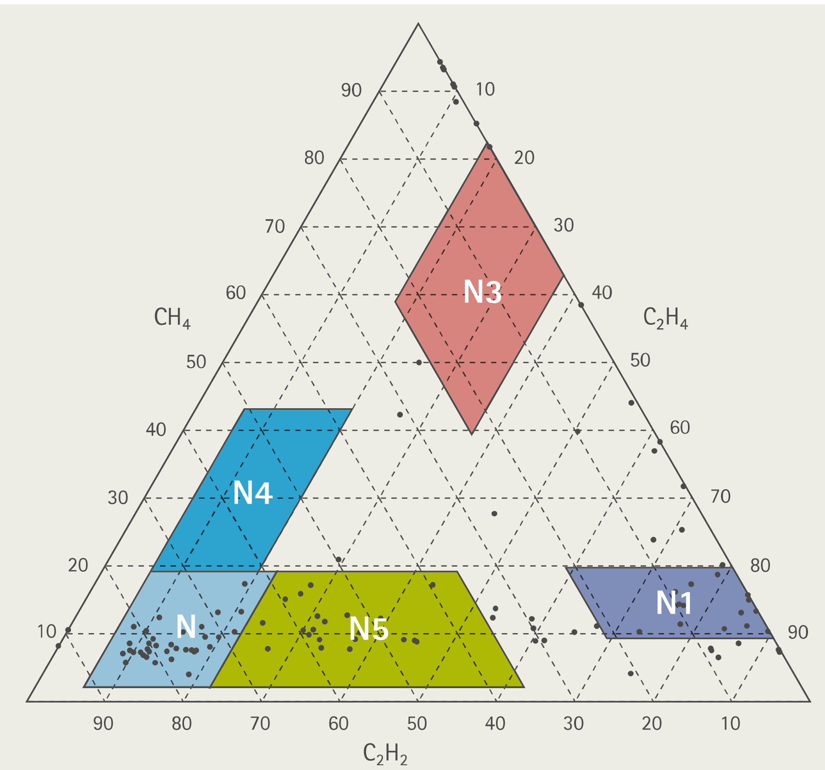


Figure 15. OLTC DGAs from class ARS types in Triangle #2

DGAs of the remaining arcing resistor type models (class ARC, ARS) are really difficult to interpret. Fig. 15 shows DGAs of ≈100 different OLTCs of the ARS class, mostly from Germany, in Duval Triangle #2. Besides the "classic" N zone, the additional zones N1 and N5 are used. The data originate from different OLTC brands and models of different age, and all OLTCs are fault-free. It can be seen that 20-30 % of them show the "high-ethylene behaviour". Because oil carbonization is a continuous process, one could think to adjust the N1 zone or expand it to merge with the N5 zone, to cover more cases. Using these additional N zones for Duval Triangle #2 are at present the only method which allows a coarse evaluation of single DGAs for such OLTC models. But there are some other (more or less exotic) approaches which deserve deeper investigation, so research goes on.

It has been proven, that sporadic DGAs (typically in a 0.5 – 1 year interval) cannot always prevent from outage caused by OLTC faults. Only incipient, low developing faults can be detected, such as overheating or excessive sparking, induced by loose bolts or partially broken braids. If the sampling interval is shortened, then, for in-tank types, the OLTC oil must be topped up from time to time, due to the comparatively low oil volume of these OLTCs. By doing so, DGA history will be likely influenced. To avoid this, and to detect faults which develop between subsequent laboratory DGAs, online-DGA can be applied. Online-DGA enables trend analysis – which is a mighty tool, if intelligent algorithms are applied. How to use online-DGA for OLTC monitoring, will be discussed in a future column here in Transformers Magazine. But even with online-DGA, fast developing faults like broken diverter springs, which cause severe malfunction of the OLTC, will not be detectable by DGA at all. Faults which develop within hours or a few days can either be detected by online-DGA (if the sampling interval is set accordingly) or by a gas relay (Buchholz relay), because such faults usually generate free gases also.

DGA results can be misleading or fail to identify an actual fault, so they should be repeated and confirmed by additional testing

Finally, it must be emphasized that DGA results can be misleading or fail to identify an actual fault. In case of suspicious DGA results, they should be confirmed by additional testing. DGA can be repeated or additional tools like Dynamic Resistance Measurement (DRM) or Vibro-Acoustic Measurement (VAM) can be applied to back up the diagnosis. If in doubt, it is also advisable to contact the OLTC manufacturer. DGA methods for OLTCs have not been perfected yet, so DGA should never be used as single criterion for shutdown or repair decisions.

Bibliography

[19] R. Frotscher, *Tap-changer DGA: Uncovering an enigma, Part 2: Basic procedures*, Transformers Magazine, Volume 4, Issue 4, pp. 20-26, October 2017

[20] A. Krämer, *On-Load Tap-Changers for Power Transformers*, Chapter 2, second edition, Kerschensteiner Verlag, Lappersdorf, Germany, 2014, ISBN 978-3-931954-47-5

[21] R. Frotscher, *Tap-changer know-how,* Transformers Magazine, Volume 3, Issue 4, pp. 18-24, October 2016

[22] R. Frotscher, D. Shen, T. Farell, *Dissolved Gas Analysis – Condition Monitoring of Vacuum Type Tap-Changers for Power Transformers*, CEPSI, Bangkok, 2016

[23] ABB Power Technologies, Dissolved gas analysis in on-load tap-changer oil, Info Sheet No. 1ZSC000498-AAAen, ABB, 2004

Acknowledgements

After eight columns, it is finally time to thank my lectors for their patient support: Dr. Dieter Dohnal, Dr. Axel Krämer, Dr. Uwe Kaltenborn, and Dr. Dazhong Shen (all Maschinenfabrik Reinhausen GmbH, Germany). I want to express that I am deeply grateful for all their comments and constructive reviews.

Correction

Referring to: Column *"Tap-Changer know-how – Insulating Liquids, Part 1"* (Transformers Magazine, Vol. 3, Issue 2)

In section 2.3., page 22, I wrote that GtL oil produces more and smaller carbon particles under arcing stress than conventional naphthenic mineral oil. A negative effect on the service life of an (optional) oil filter had been presumed.

Subsequent tests with other naphthenic oils of different brands have now revealed that this is not true.

It has been shown that some common naphthenic mineral oils (uninhibited or inhibited) produce a similar amount of carbon particles compared to GtL oil. An influence of the particle size on the service life of the filter cartridge could not be confirmed.

Rainer Frotscher

Author

Dipl.-Ing. (TU) Rainer Frotscher is working for Maschinenfabrik Reinhausen (MR) in Regensburg/Germany as senior expert for insulating liquids and -gases. His area of expertise is the applicability of alternative liquids and DGA for tap-changers. For many years, he has been working for the R&D department on manifold technology projects and conducted design calculations for special tap-changer applications. As core competence manager for insulating liquids and gases, he now develops the knowledge within the Reinhausen Group concerning the interaction of solid, liquid and gaseous insulating materials. As a member of CIGRE and DKE, he has done multiple publications and contributes to several working groups in CIGRE, IEEE and DKE. Dipl.-Ing. Frotscher was born in Bremen, Germany on March 4, 1960. He received his Master's Degree in Electrical Engineering from the Technical University of Munich where he wrote his thesis in high-voltage engineering.

Phone : +49 (0) 941/4090-4136
Fax : +49 (0) 941/4090-4005
Email : r.frotscher@reinhausen.com
Address : Maschinenfabrik Reinhausen GmbH
Falkensteinstraße 8, 93059 Regensburg, Germany