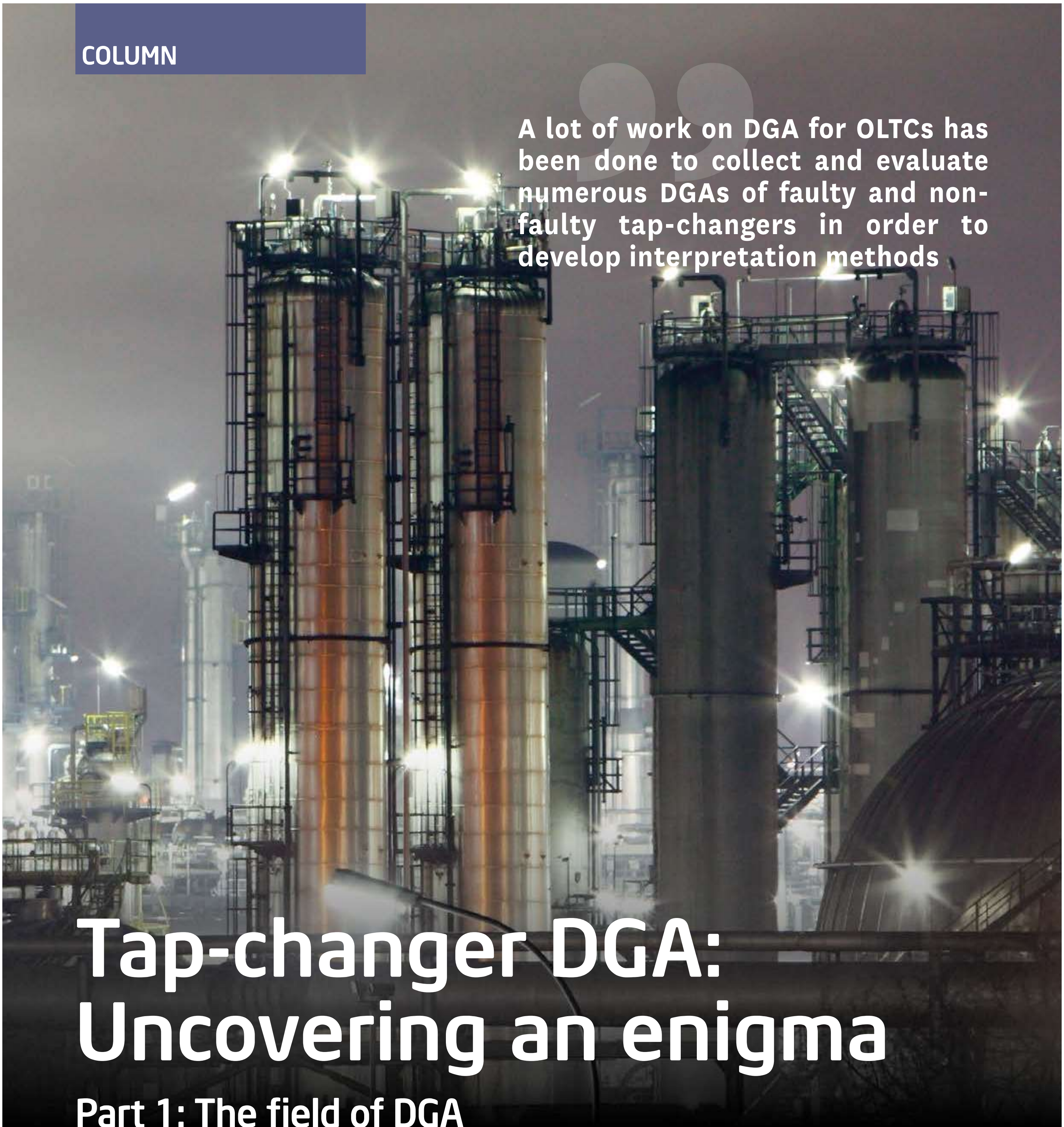


> A lot of work on DGA for OLTCs has been done to collect and evaluate numerous DGAs of faulty and non-faulty tap-changers in order to develop interpretation methods

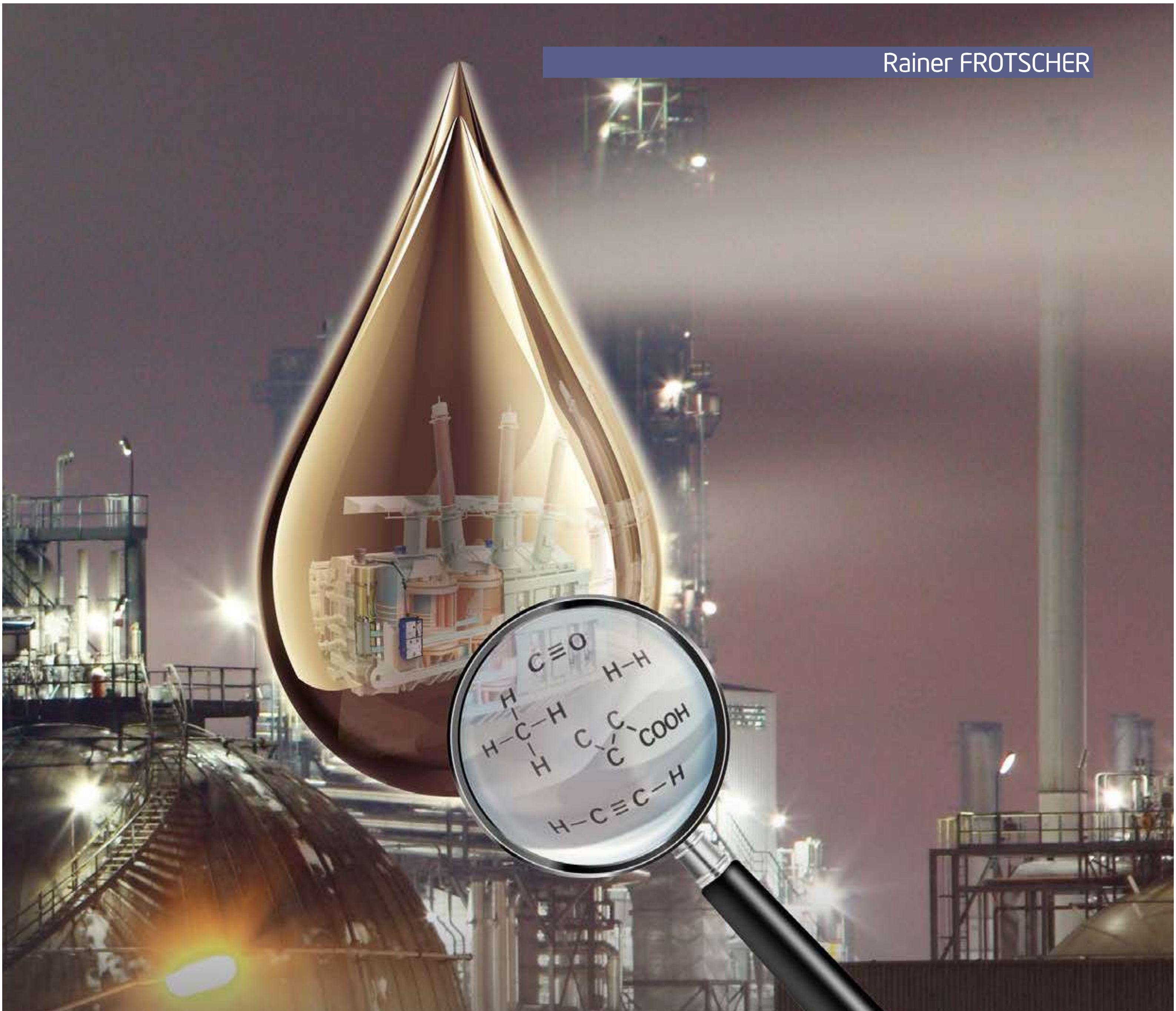
Tap-changer DGA: Uncovering an enigma

Part 1: The field of DGA

1. General

Gases dissolved in insulating liquids are generated by thermal deterioration of the insulating liquid or they are introduced by contact with a gaseous environment (air, for example). Gases can also be formed by normal ageing processes of the liquid or catalytic interactions with metals or paints. The analysis of these dissolved gases is called DGA. Electrical equipment suitable for DGA are power transformers, industrial and special transformers, instrument transformers, bushings, cables and switching equipment. DGA for transformers has been established more than 40 years ago and since then was continuously refined according to the proceeding technical development of liquid-filled transformers. IEC60599 [1] and IEEE C57.104 [2] give advice on how to apply DGA on transformers. While IEC60599 covers all electrical equipment listed above, IEEE provides separate documents for different equipment. For DGA on tap-changers, IEEE C57.139 [3] is applicable.

DGA for on-load tap-changers (OLTCs) is much more complex than DGA for transformers and still not comprehensively used. The reasons why tap-changer DGA didn't mature to a standard diagnostic



method so far are: a) there are many different OLTC types and models on the market which all perform differently; and b) the majority of OLTCs uses conventional arc-breaking-in-oil technology, which requires an exchange of the tap-changer oil in regular time intervals, precluding a long-term surveillance of the OLTC function. Nevertheless, tap-changer DGA has been successfully applied to certain tap-changer models mainly installed in the U.S.

The growing percentage of OLTCs with vacuum switching technology and deeper insights by further investigations let OLTC DGA slowly appear in a different, more promising light. A lot of work has been done by Michel Duval and others to collect and evaluate numerous DGAs of faulty and non-faulty tap-changers. I had long discussions with James ("Jim") Dukarm, Dave Hanson and Claude Beauchemin on the formation of gases in carbonized oil and how to interpret certain gas patterns and ratios. Even if the work on tap-changer DGA is still far from completion, there is now enough "food" to give some assistance and advice for users who aim to establish DGA as a diagnostic method for their tap-changers immersed in mineral oil. For DGA on the tap-changers working in alternative liquids like synthetic or natural esters, there is still insufficient operational experience to derive handy interpretation rules. In this column, the latest findings and most promising interpretation methods for DGA on tap-changers in mineral oil will be discussed. This will keep us busy for the next three or four issues of Transformers Magazine.

I always regard it as helpful to understand what is "behind" any technology or method, shedding some light on the origins. This gives valuable knowledge to gain expertise for interpreting DGA results correctly. No worries, I don't plan to roll up the whole DGA history, but some "basics" will give us the necessary background.

Experts often compare DGA to blood analysis. By analyzing the blood picture of a (human) being, conclusions can be drawn on current or incipient diseases. This method can be applied in the same way to the transformer insulating liquid by analyzing the dissolved gases. Insulating liquids generally suitable for DGA are liquids with (long) hydrocarbon chains, as they are found in mineral oils, natural and synthetic esters, and silicone oils. Under the influence of heat, these hydrocarbon chains break into small fragments of radical or ionic form. As these fragments are not stable, they recombine by more or less complex reactions to gas molecules, like hydrogen (H-H), methane (CH_4), ethane ($H_3C\text{-}CH_3 \Rightarrow C_2H_6$), ethene ($H_2C{=}CH_2$

⇨ C_2H_4, also called ethylene) or ethine ($HC{\equiv}CH$ ⇨ C_2H_2, also named acetylene). Other possible reactions lead to the formation of C_3- and C_4-hydrocarbon gases, as well as to solid carbon particles (soot) and hydrocarbon polymers (X-wax). C_3-hydrocarbon gases are used in some countries as supplementary gases to support the interpretation of thermal faults. C_4-gases are currently not used for DGA interpretation.

Carbon monoxide (CO) and carbon dioxide (CO_2) are additionally formed by oxidative ageing processes, or by degradation of cellulose (if present). A full DGA also contains values for dissolved oxygen (O_2) and nitrogen (N_2), as it gives valuable information on the saturation level with ambient air, and on the consumption of oxygen by oxidative oil ageing.

If the gases are formed slowly, they dissolve in the liquid until it is saturated with gas. How many gases can dissolve in the liquid depends on the individual solubility coefficients for each gas and the vapour pressure equilibrium and is difficult to calculate. If the gases are formed quickly, they will cause gas bubbles which can accumulate, dissolve slowly in the liquid or disappear through the oil conservator (in free-breathing systems) or through small leakages (in sealed systems). Gas bubbles are often harmful to the equipment, as they can cause flashovers.

The formation of hydrogen plays a special role, as it can be generated in manifold ways. Strongly hydro-treated mineral oils, for example, tend to deliver hydrogen at the beginning of the oxidative ageing process [4]. Steel (like used for the transformer core) acts as catalyst. With this, remarkable amounts of hydrogen can be observed in transformers, even if they have never been in service. Free water can react with coatings (varnishes, paints) of metal surfaces to produce hydrogen. And, of course, hydrogen is generated by thermal degradation of the oil, which starts at about 60 °C.

CH_4 and C_2H_6 are also known to be produced in low amounts under low thermal stress (<200 °C), especially when the oil is in contact with certain metals, for example a NiCr alloy, which is used for transition resistors, or certain grain-oriented core steels for transformers [5].

Gases are formed by normal ageing processes of the liquid, catalytic interactions with metals or paints, or by faults of the electrical equipment

These "stray-gassing" effects become important when interpreting low amounts of dissolved gases, as they may mask the gas patterns of incipient failures.

An overview on the evolution of gases from n-octane (a paraffinic hydrocarbon derived from petroleum; C_8H_{18}) assigned to certain temperature ranges is presented in Fig. 1.

2. Faults detectable by DGA

2.1. Transformers

Faults in high-voltage equipment become audible or visible by partial discharges (fault type: PD), sparks or flashovers. Under the stress of an electrical field, partial discharges are caused by impurities in the electric field, such as voids or inclusions in solid insulating material, (trapped) gas bubbles in the insulating liquid, or by conductive parts (e.g. bolts) with floating potential. They cause a cold plasma, which can also nicely be watched outdoors on high-voltage overhead lines at foggy nights. Partial discharges under oil generate favourably H_2, plus some CH_4, without producing remarkable amounts of heat. In opposite, sparks (fault type: D1) have a much higher energy and so heat up small liquid volumes to temperatures above 1000 °C, causing H_2 and C_2H_2. Sparks occur in defective or overstressed insulating arrangements or also on electrodes with floating potential and are indicators of a possible successive flashover, which often matures into a high energy arc (fault type: D2). In the core of an arcing channel, temperatures up to 3000 °C can be reached, causing the oil to carbonize and to produce huge amounts of C_2H_2 and H_2. Around the core, the temperature gradient causes additional heating gases, from C_2H_4 over C_2H_6 to CH_4 with increasing distance. While a flashover does not necessarily destroy the equipment (it can only leave a small arcing mark as root point; see Figure 2), arcs are always disruptive. Depending on the energy released in an arc or flashover, the amounts of C_2H_2 and H_2 vary.

Thermal faults in transformers can be categorized in three ranges: temperatures above the maximum liquid temperature (typically 115 °C) but lower than 300 °C (fault type: T1), temperatures between 300 and 700 °C (fault type: T2), and temperatures above 700 °C (fault type: T3). At temperatures below 300 °C, mainly C_2H_6 is produced, accompanied by C_3H_8. Additional CH_4 and C_2H_4 may show up in low

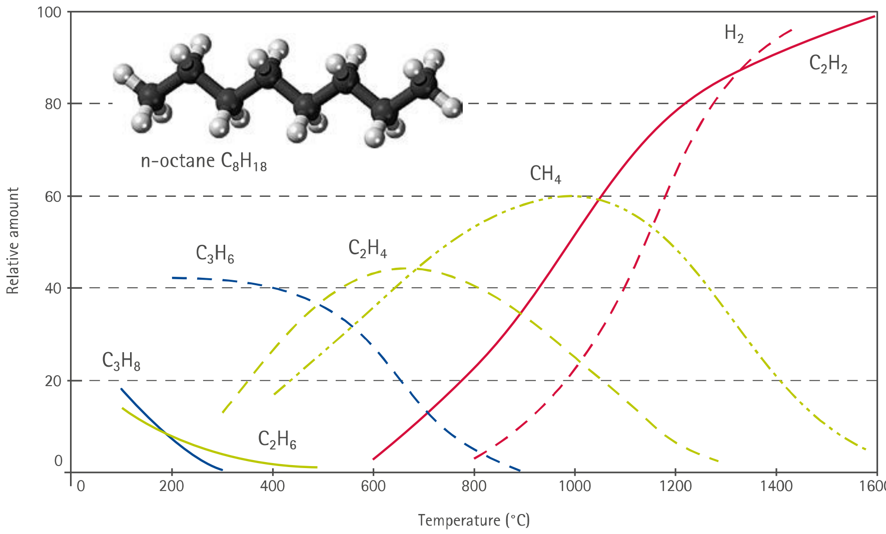


Figure 1. Thermal decomposition of n-octane

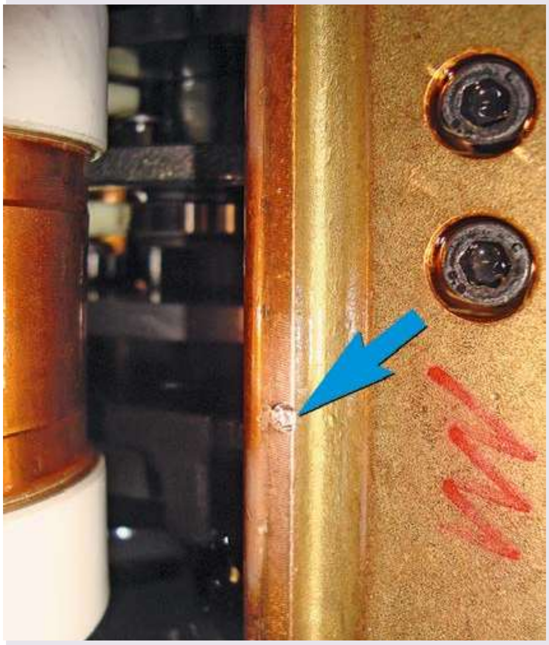


Figure 2. Arcing mark of a low-energy flash-over on OLTC main contact, caused by an overvoltage surge

amounts. Between 300 and 700 °C, the typical gas is C_2H_4, with C_3H_6 and CH_4 as supplemental gases. Above 700 °C, CH_4 is the dominating gas, but also significant amounts of C_2H_2 and H_2 can be expected. From here, there is no sharp borderline to the gases which are produced by sparks (D1) or arcs (D2).

Summed up, there are six basic transformer faults which can be detected by DGA: PD, D1, D2, T1, T2 and T3. These fault types can be evaluated by graphical methods such as Duval Triangle #1 and Duval Pentagon #1 [6], or by quotient methods according to IEC 60599 or IEEE C57.104 (Rogers Method). Figure 3 shows a coarse assignment of faults to the gas evolution over temperature.

The thermal faults T1-T3 can be further subdivided in sub-types: fault type S covers stray-gassing issues at oil temperatures below 200 °C, which are due to a potential chemical instability of the (mineral) oil. Fault type O stands for overheating of oil (or paper) for temperatures below 250 °C, and fault type T3-H represents overheated oil at temperatures beyond 700 °C. These three additional fault types are of minor concern in transformers, because they deteriorate only some oil, but don't harm the solid insulation. Potentially more dangerous is a fault type C, which represents carbonization of paper at temperatures above 300 °C. These four additional sub-types plus fault type PD can be evaluated by Duval Triangles #4 and #5, and Duval Pentagon #2. All have turned out to be quite sensitive methods to detect faults with comparatively low energy content [6].

Free-breathing transformers feature an oil conservator with dehumidifying cartridge (breather), which allows the ingress of O_2, N_2 and CO_2 from the atmosphere. After the initial oil-filling of degassed oil under vacuum, the oil slowly saturates with these environmental gases. In uninhibited oils, oil oxidation starts immediately and so O_2 is consumed. As O_2 is permanently delivered from the atmosphere, the O_2 content should not decrease significantly, but the average value (equilibrium between O_2 consumption and ingress) depends on the intensity of breathing. A clogged breather, for instance, can be detected by very low O_2 values.

The thermal degradation of cellulose generates CO and CO_2 (and water, H_2O). Therefore, the absolute CO_2 and CO values as well as the CO_2/CO ratio are established measures to determine the grade of cellulose degradation. But as already stated above, CO_2 and CO are also generated by oil oxidation processes, and CO_2 can also be introduced by the atmosphere (in free-breathing systems). With this, it is obvious that the evaluation of CO_2 and CO must be done carefully.

2.2 Tap-changers

Not all of the transformer faults described above are also transferable to OLTC. For example, arcing and sparking belong to the normal operation of conventional arc-breaking-in-oil tap-changers (often also called 'arcing type' or 'oil-switching type'; acc. to IEC60214-1: 'non-vacuum type'), as these types make and break the load current by using arc-breaking contacts in oil. With this, the tap-changer oil gets strongly deteriorated and therefore must be exchanged regularly. And it must strictly be separated from the transformer oil to avoid contamination by carbon particles, soot and gases. It has been tried to detect worn contacts or malfunctions of the contact system by analyzing the total amount of arcing gases or their increase rate over time, regrettably without success. That would require a trend analysis with ample data points, which can only be sensibly realized by an online-DGA system which is capable to analyze carbonized oil. Sensors, which separate the gases from the

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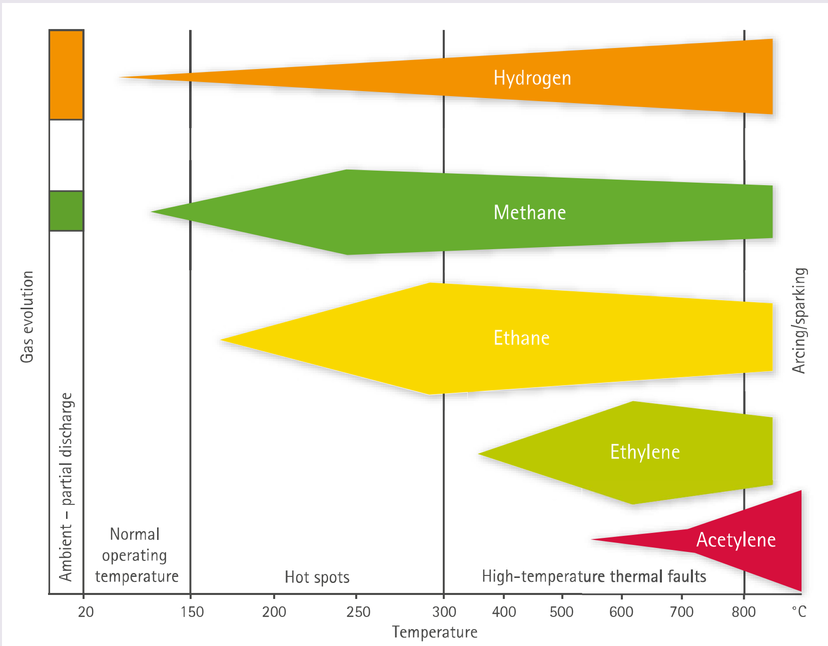

Figure 3. Gas evolution over temperature, assigned to faults

The faults which can be detected by DGA strongly depend on the OLTC type

oil by using a membrane, will not work, as the membrane will get clogged very quickly. So will do upstreamed filters. And it is highly dubious that a malfunction can be detected in time – *before* a tap-changer malfunction causes the transformer to blow up. So better forget that.

Besides the typical arcing gas pattern, conventional arc-breaking-in-oil tap-changers can generate a gas pattern similar to the T2 heating gas pattern in normal service, when the oil gets carbonized. This phenomenon is probably due to a more distributed arc in carbonized oil, which heats up the oil in a different way and so favourably produces C_2H_4 instead of C_2H_2. As a possible root cause, soot and carbon particles cause a higher electrical and thermal conductivity of the oil which could lead to a different arc shape, but a final proof to this theory is still missing. At least, it has been shown in a test that this 'high-ethylene-phenomenon' could be avoided by using an oil filter unit. Tap-changer operations in clean oil always caused the expected typical arcing gas pattern, say: more C_2H_2 than C_2H_4 [7]. It is noticeable that the 'high-ethylene-phenomenon' has been only recognized with in-tank type OLTCs, never with compartment types. This is probably due to the fact that the majority of compartment type OLTCs don't use transition resistors but reactances instead, which are mounted inside the transformer tank. Transition resistors increase the thermal impact on the tap-changer oil and cause additional soot or sludge.

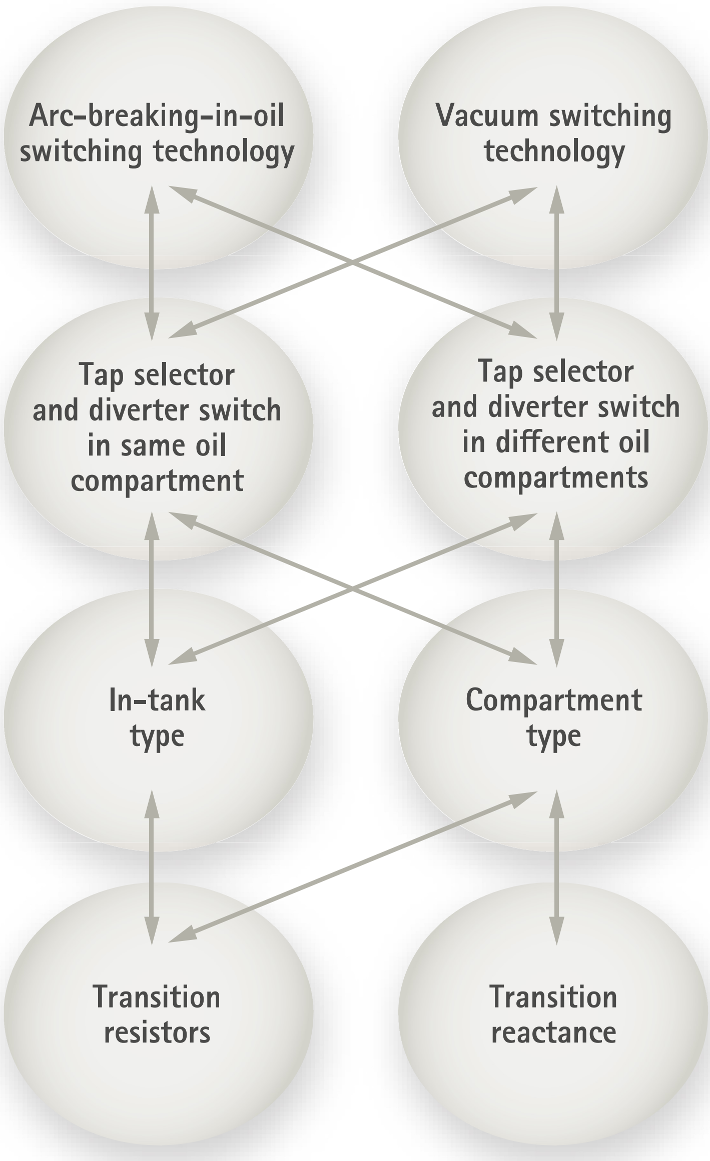

Figure 4. On-load tap-changer diversity

In modern vacuum type OLTCs, the powerful switching arcs are encapsulated inside vacuum interrupters, but there are often by-pass contacts which have to commutate the load current onto the vacuum interrupter path, causing some sparking. Sliding contacts of selector switches act in the same way when carrying the load current while moving. Usually, the amounts of sparking gases are in the one-digit ppm range, so excessive sparking is generally an indicator for irregular behaviour of the contact system, or for electrodes on floating potential. In rare cases, e.g. compartment type OLTCs in arc-furnace applications, C_2H_2 values of more than 50 ppm are reported, without showing any fault.

Resistor type OLTCs contain transition resistors, which can reach peak surface temperatures up to 450 °C during normal operation, depending on the design (which is specific to the respective application) and load conditions. The gases produced by these resistors cover a big range from "almost nothing" to "looks like a T1 fault". Fault types T2 and T3, which represent advanced contact heating, are easily detectable, at least for vacuum type OLTCs and for tap selectors which are mounted inside the transformer tank or inside an extra tap selector compartment, separated from the diverter switch oil.

As reactor type OLTCs don't contain transition resistors, any excessive heating gases represent a fault (T1 to T3).

Tap-changers usually contain only low amounts of cellulose, so a detection of cellulose degradation via CO_2 and CO is invalid. Instead of that, CO and CO_2 can be used as an indicator of beginning thermal oil ageing. CO and CO_2 are produced at much lower temperatures as necessary for hydrocarbon gases, so these gases are sensitive measures to evaluate the thermal impact on the tap-changer oil, brought in by the transition resistors [8]. A continuous evaluation of the CO_2/CO ratio can possibly detect irregularities of the load switching sequence (overheated resistors), or reveal incipient overheating of contacts.

For DGA on the tap-changers working in alternative liquids there is still insufficient operational experience to derive handy interpretation rules

With the above said it becomes apparent that the faults, which can be detected by DGA, strongly depend on the OLTC type. The most difficult case is the resistor arcing type – which does not mean that DGA is generally not possible for these models. It only needs special expertise. Much clearer is the situation for reactor type OLTCs (arcing and vacuum type models), which allows a definite detection of thermal faults. Vacuum type OLTCs show gas patterns similar to transformers (except for the sparking issue) and so allow the evaluation of arcing and thermal faults. Up to now there is no experience if the thermal fault sub-types S, O and T3-H can be used for tap-changer DGA. Sub-type C is definitely not applicable, as it describes carbonization of paper, which is not present in OLTCs in significant amounts.

3. Tap-changer diversity

Worldwide, many different tap-changer models are available. The type variety also includes de-energized tap-changers (DETCs), which may only be operated when the transformer is de-energized. So, arcing or sparking is not an issue. But the contacts have to carry the load current continuously and are operated infrequently. This makes them prone to overheating faults (T1-T3). Contact pressure, number of contact points and material of the contact surface must be carefully selected to ensure a constant minimum contact resistance over the whole lifetime of the transformer. For example, 150 A per contact point can be conducted safely over years, if a copper-silver pairing with appropriate contact pressure is used. Anyhow, such contacts should be operated from time to time to remove tarnish, which can build up by catalytic reactions of the insulating liquid with the contact material.

Concerning the OLTCs, the available type variety is shown in Fig. 4. It must be distinguished between arc-breaking-in-oil models and models with vacuum switching technology. The tap selector can be located in the same oil compartment as the diverter switch, or inside the transformer tank, or in a separate selector compartment. It can be equipped with a change-over selector (reversing switch or coarse-tap selector) or not. All these variants can be constructed as in-tank type or compartment type models. And finally, they can utilize transition resistors or transition reactances. OLTCs with transition reactance are only available as compartment types, whereas resistor type OLTCs are available as in-tank types and compartment types.

All variants produce different gas patterns in their various oil compartments. For a proper DGA evaluation, one has to regard the individual conditions of each architecture and also has to distinguish between the different oil compartments. It is exactly this huge diversity which makes tap-changer DGA so complex.

In the next column, we will discuss different approaches to how this diversity can be controlled. Stay tuned!

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