New frontiers of DGA interpretation for power transformers and their accessories

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ABSTRACT

Dissolved gas analysis is among the most powerful tools for assessing the condition of transformers and their accessories in service. However, several questions still remain today concerning the use of DGA, such as: how much is the equipment at risk, what are the actions recommended, and how can DGA be applied to related equipment such as load tap changers? The latest investigations concerning these questions are presented and discussed in this paper.

Risk of Failure of Transformers

The risk of failure of transformers in service, based on dissolved gas analysis (DGA), depends on three main parameters: the type of fault involved, the location of the fault (in oil or in paper), and the amount of gases formed (concentrations and rates).

The most dangerous faults are: high-energy arcing faults D2 in oil and paper, low-energy arcing faults D1 in paper, and hot spots in paper of high temperatures T3 and T2.

Less dangerous faults are: low-energy arcing faults D1 in oil, hot-spots T3 and T2 in oil, and hot spots in paper of low temperature.

Non-dangerous faults are: hot spots T1 in oil, producing only “stray gassing” of oil, corona partial discharges PD (unless very high levels of hydrogen are formed), catalytic reactions with water, and aging of paper.

Identification of Type and Location of Faults

The general type of fault (PD, D1, D2, T1, T2, T3) can be identified by several methods: e.g., Rogers, Key Gas, IEC ratios, Duval Triangle 1.

It is more difficult, however, to identify the location of the fault (in oil or in paper); the levels of CO, CO_2 and the CO_2/CO ratio are generally used for that purpose. However, it has been shown recently [1] that these gases are not always good indicators. More particularly, large amounts of CO (>1000 ppm) and low values of the CO_2/CO ratio (< 3) are often observed in closed transformers without any fault [2]. This has been attributed at CIGRE to the low availability of O_2, which favours the formation of CO over CO_2.

Also, localized faults involving small volumes of paper often do not produce detectable amounts of CO and CO_2 against the usually large background of these gases in oil. In many cases, local faults with carbonization of paper are more reliably detected by the formation of the other gases (H_2 and hydrocarbon), using for example Duval Triangles 4 and 5 [3].

The Duval Triangles 4 and 5

The “classical” Duval Triangle 1 uses gases (CH_4, C_2H_4 and C_2H_2) that are formed by faults of low to high energy (from low-temperature faults T1 and PD to high energy arcing faults D2).

The Duval Triangle 4 uses gases (H_2, CH_4 and C_2H_6) that are formed more specifically by faults of low energy or temperature (PD, T1 and T2), in order to get more information about these faults in service. An updated (2012) version of Triangle 4 is presented in Figure 1.

Warning: Triangle 4 should be used only for faults identified first with Triangle 1 as faults PD, T1 or T2. It should never be used in case of electrical faults D1 or D2.

Triangle 4 is used mostly to distinguish between:
-stray gassing of oil at T < 200ºC in zone S,
-overheating at T < 250ºC in zone O with “cooking” but no carbonization of paper,
-possible carbonization of paper at T > 300ºC in zone C (in 80% of inspected cases used for Triangle 4 - not 100%),
-corona partial discharges in zone PD. The boundary between zones PD and S has been changed recently from % C_2H_6 = 1 to 0.6, based on stray gassing test results on new types of oil on the market.
-in case of a DGA point in service in the PD zone with a % C_2H_6 slightly < 0.6 (e.g., 0.5 or 0.3%), verify the stray gas formation of the oil used with laboratory stray gassing tests before confirming a fault PD or S.

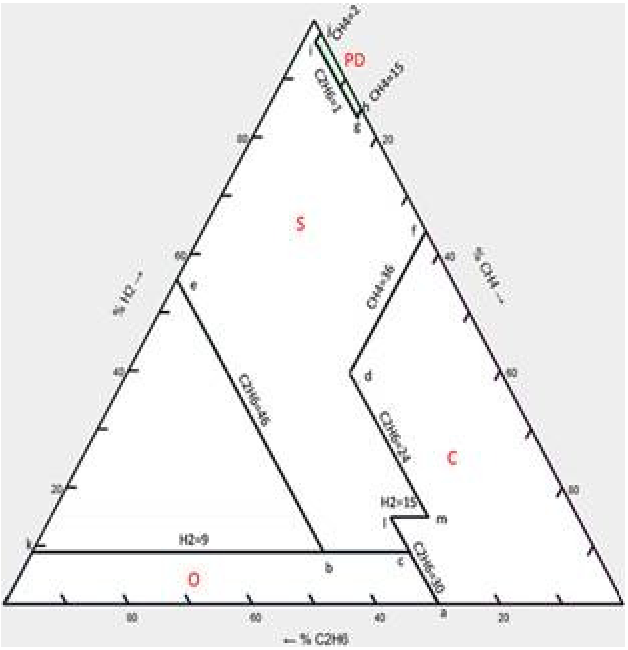


Figure 1: The Duval Triangle 4

(Graph Courtesy Serveron)

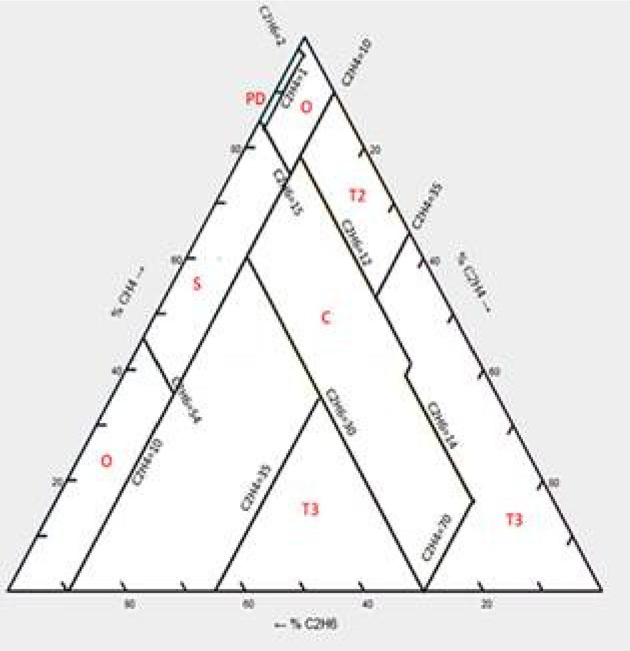


Figure 2: The Duval Triangle 5

The Duval Triangle 5 uses gases (CH_4, C_2H_4 and C_2H_6) that are formed more specifically by faults of high temperature, in order to get more information about thermal faults in paper and in oil. An updated (2012) version of Triangle 5 is presented in Figure 2.

Warning: Triangle 5 should be used only for faults identified first with Triangle 1 as faults T2 or T3. It should never be used in case of electrical faults D1 or D2.

Triangle 5 is used mostly to distinguish between:

-hot spots in oil only in zones T3 (> 700ºC) and T2 (> 300ºC),

-possible carbonization of paper in zone C (in 90% of inspected cases used for Triangle 5 - not 100%).

-for faults O, S and PD, Triangle 4 should be used rather than Triangle 5.

A small, free algorithm is available from duvalm@ireq.ca for Duval Triangles 1 through 7.

Paper aging – Myths and Reality

1 The risk of failure of transformers increases with age and load. Reality.

However, in a large majority of cases this is because of high moisture, gas-producing faults, leaking gaskets or membranes, rusting of tank, loss of dielectric properties of paper and oil, not because of paper aging.

2 *When the degree of polymerization (DP) of paper reaches a value of 200, the risk of failure of the transformer becomes very high*: Myth.

A large number of transformers with DPs between 200 and 100 have been reported to operate quite normally, including by the late V. Sokolov [4].

Furthermore, no convincing cases have been reported so far (to CIGRE WG47 or elsewhere) of transformers with a DP of 200 or 100 where failure could be clearly attributed to the mechanical weakness of paper.

So, based on present observations, the risk of failure of transformers with low DPs appears to be quite low, and not very high as generally believed. Transformers with gas-producing faults are actually much more at risk of failure.

3 *When paper reaches a DP of 200 or 100, it becomes brittle and will be easily torn away from between windings turns, causing short circuits*: Myth.

Paper squeezed between turns will remain in place because of the compression/ clamping forces applied to windings, even when it is brittle and has a low tensile strength.

What is required for paper between turns is compression strength, not tensile strength. Brittle paper can easily resist compression forces down to very low DPs (e.g., 50).

4 *Aged paper loses density and thickness, resulting in loose windings*. Reality.

This, however, can easily be mitigated by re-clamping windings, which by the way should be part of regular maintenance after 20 to 30 years in service.

5 *When paper reaches a DP of 200, external short circuits will result in immediate failure*. Myth.

The following case was reported by ERDF to the MyTransfo Conference in Torino in 2010. One of their transformers with a DP of 150 was transported to the factory and subjected to several external short circuits, but did not fail.

6 *A DP of 200 is a good indicator of the end-of-life of transformers:* Myth.

In the absence of gassing or high moisture, transformers with a DP of 200 in most cases could be left in service several more years, based on present observations above.

7. *Conclusion*:

Priority should be given to the replacement of faulty gassing transformers that cannot be fixed. For replacements based on DP only, a limit value of 100 or 150 appears more realistic than 200.

Gas limits in service

Gas limits in IEEE Gas Guide C57.104 are presently under revision, based on the very large database of DGA results put together recently by the IEEE WG. One very significant change will concern condition 1 values for CO and CO_2, which will be much higher (750 and 7500 ppm, respectively) and closer to CIGRE/ IEC limits. Present IEEE limits are often a cause of false alarms.

A distinction between closed and open type transformer will be attempted by the WG, using the ratio $R = O_2 / (O_2 + N_2)$ which is usually much lower in nitrogen-blanketed types. Low values of the ratio, however, may also be due to oil overheating.

Limits for gas concentrations and rates above IEC typical (condition 1) values have been recommended by CIGRE TF15/WG32 [5], together with more frequent sampling intervals for DGA.

CIGRE WG47 is presently investigating the effect of type and location of faults on these gas limits. The effect on typical (condition 1) values is obtained by calculating 90% percentile values for each type of fault. The effect on prefailure (condition 4) values is deduced from inspected fault cases where high levels of gases are observed without failure or just before failure.

The general type of fault is identified first with Triangle 1 (PD, D1, D2, T1, T2 or T3). Triangles 5 and 4 are then used for further distinctions between faults T3/T2 in oil or with carbonization of paper, overheating, stray gassing and corona PDs.

Examples of the effect of fault type on condition 1 and condition 4 are indicated in Table 1 and summarized in Table 3 for condition 4. Also see Figures 3 and 4.

Typically, condition 1 will require more frequent monitoring by DGA, while condition 4 may require inspection and repair of the transformer.

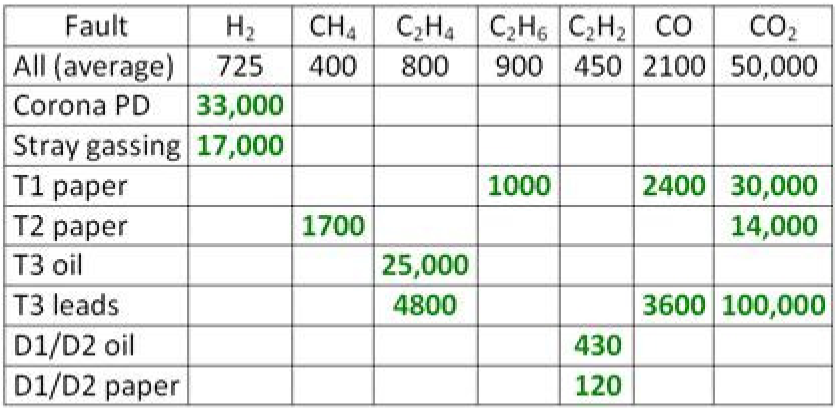
Table 1 Effect of Fault Type and Location on Conditions 1 and 4 (values in ppm)

Type of fault	All	Corona PDs	Type of fault	All	T3 in paper
	H_2	H_2		C_2H_4	C_2H_4
Condition 1	100	15,000	Condition 1	50	300
Condition 4	725	33,000	Condition 4	800	4800
Type of fault	All	Stray gassing	Type of fault	D1 in oil	D1 in paper
	H_2	H_2		C_2H_2	C_2H_2
Condition 1	100	300	Condition 4	430	120
Condition 4	725	17,000	Type of fault	All	T3 in paper
Type of fault	All	T3 in oil			
	C_2H_4	C_2H_4			
Condition 1	50	200			
Condition 4	800	25,000			

Fig. 3: Example of a current transformer with 6400 ppm C_2H_4 and no failure observed in service

Fig. 4: Example of a power transformer with a fault D1 in oil (on a Bakelite plate), 480 ppm C_2H_2 and no failure observed in service

Table 3 Summary of CIGRE Conditions 4 for Different Types of Faults:



Fault	H_2	CH_4	C_2H_4	C_2H_6	C_2H_2	CO	CO_2
All (average)	725	400	800	900	450	2100	50,000
Corona PD	33,000						
Stray gassing	17,000						
T1 paper				1000		2400	30,000
T2 paper		1700					14,000
T3 oil			25,000				
T3 leads			4800			3600	100,000
D1/D2 oil					430		
D1/D2 paper					120		

To confirm results in Table 3, other examples of the following fault cases would be needed; please email such examples to duvalm@ireq.ca.

-arcing faults D1/D2 in oil with high levels of C_2H_2 and no failure,

-arcing faults in paper just before failure,

-thermal faults T1, T2 and T3 in paper with high levels of C_2H_4, C_2H_6 or CH_4 and no failure.

Application of DGA to LTCs

What makes the interpretation of DGA in LTCs more complex than in transformers is that their normal operation involves various combinations of arc-breaking-in-oil between contacts, current dissipation in resistors and sparking in selectors or switches, depending on their type and operating conditions.

Normal gas formation resulting from this normal operation of LTCs must be identified first as precisely as possible in service. Faulty or abnormal operation may then be detected by deviation from normal gas formation.

Normal gas formation in LTCs may be due to:

-arc-breaking-in-oil between contacts, switching of selectors and valves, with the formation of arcing gases D1 (C_2H_2).

-current dissipation in transition resistors, increasing their temperature and producing thermal gases in oil (C_2H_4/ CH_4/ C_2H_6).

-depending on the specific type and design of LTC used (in oil or vacuum, of the compartment type or in-tank type) and its operating conditions (at low or high powers or currents), different mixtures of these gases may be formed during normal operation of the LTC.

Faulty or abnormal gas formation/ operation of LTCs may be due to, among others:

-an increase in the resistance and therefore the temperature of arc-breaking contacts, resulting in carbonization of oil, coking of contacts and formation of thermal gases T3 or T2.

-abnormal arcing on metal plates or components, producing arcing gases D2 or D1.

-abnormal hot spots on LTC enclosures or vacuum bottles, producing thermal gases.

Two main methods are used for the identification of faults in LTCs:

-the C_2H_4/C_2H_2 ratio of IEEE.

-the Duval Triangles 2, allowing to:

-follow visually the evolution from normal to faulty gas formation/ operation of LTCs,

-identify the different types of overheating (T1, T2, T3) that may occur in LTCs.

-more easily distinguish between normal and faulty gas formation/ operation of some types of LTCs where this is not possible by using the C_2H_4/C_2H_2 ratio only, but possible by using a third gas (CH_4).

The original Duval Triangle 2, presented in Figure 5, applies to LTCs of type I (in terms of normal gas formation), either reactive or resistive, operating in oil or in vacuum, and representing a large majority of LTCs presently in service:

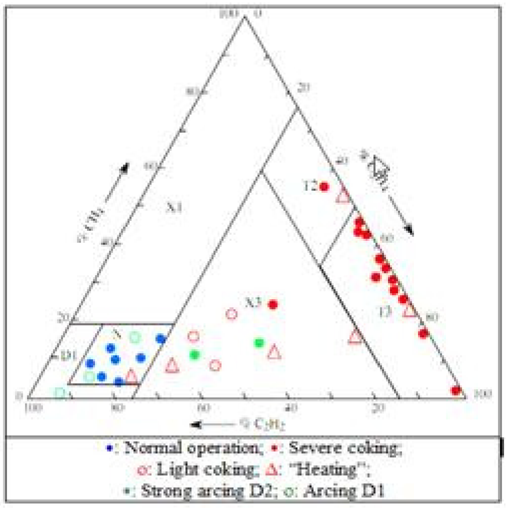


Fig. 5: The Original Duval Triangle 2 for LTCs of Type I

Examples of LTCs of type I include: Westinghouse's UN, UR, UV and UTs; ABB's UB, UC and UZs (except some UZBs, which are of type II); General Electric's LR and LRTs ; McGraw Edison's 390, 490, 550 and 990 series; Siemens' TLHs; MR-Reinhausen's RMs and OilTaps T and Vs; Federal pacific's TCs; Ferranti's RTs; Hyundai's RSs, Cooper's LTCs, etc.

Gases in these LTCs of type I appearing in:

-zone N of Triangle 2 indicate normal operation of the LTC.

-zone T3 and T2, coking of contacts.

-zone X1, mild overheating.

-zone X3, coking in progress or abnormal arcing.

In LTCs of type II (in terms of gas formation), representing a minority of LTCs in service, gas formation may appear in zone N or in another part of Triangle 2, depending on the specific type and operating conditions of the LTC.

Specific zones of normal gas formation N to N5 have thus been defined in Duval Triangles 2a to 2e for different types of LTCs of type II, and are indicated in Figure 6:

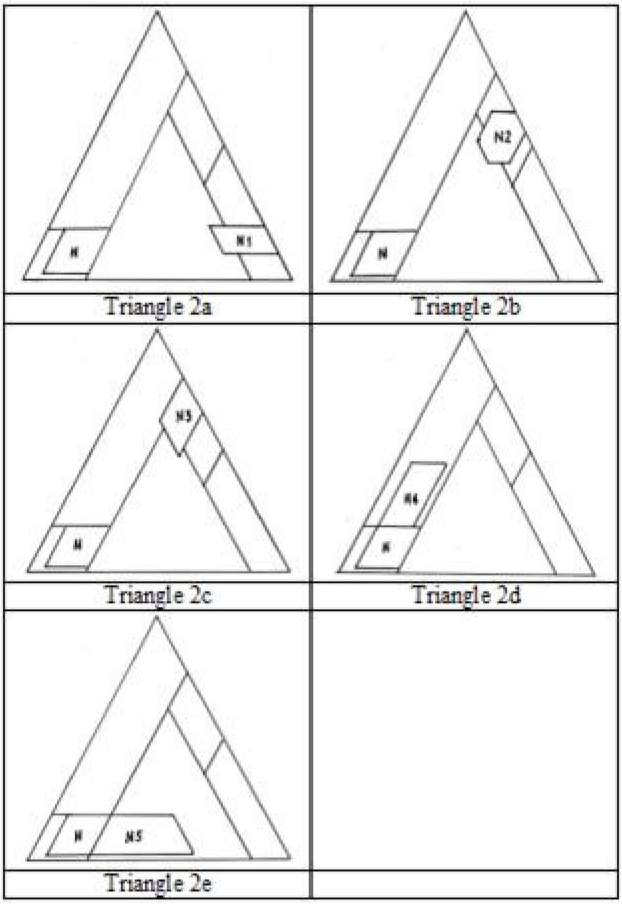


Fig. 6: Zones of Normal Gas Formation N to N5 in Duval Triangles 2a to 2e for LTCs of Type II

-Triangle 2a applies to LTCs such as MR’s OilTaps M and D.

Normal gas formation appears either in zone N or zone N1 depending on operating conditions, and should be determined in service first. Faulty or abnormal operation is indicated by gas formation in zones X3 or T3 (from zone N), or in zones T3 or T2 (from zone N1).

-Triangle 2b applies to LTCs such as MR’s VacuTaps VR.

Normal gas formation appears in zone N2 (not in zone N so far).

-Triangle 2c applies to LTCs such as MR’s VacuTaps VV.

Normal gas formation appears either in zone N or zone N3 (at high powers), and should be determined in service first. Faulty or abnormal operation is indicated by gas formation in zones X3 or T3 (from zone N), or in zone T3 (from zone N3).

-Triangle 2d applies to LTCs such as MR’s OilTaps R and V.

Normal gas formation appears either in zone N or zone N4 (mild overheating).

-Triangle 2e applies to LTCs such as MR's OilTaps G (operating at high currents), or in a few resistive UZBs of ABB[4], depending on operating conditions. Normal operation appears either in zone N or zone N5, and should be determined in service first.

To confirm the position of these zone boundaries, other examples of normal and faulty operation of the following types of LTCs of type II would be needed; please send such examples to duvalm@ireq.ca.

-resistive MR-Types (M, D, VR and VV),

-MR-Type G and some ABB-UZBs (operating normally in the X3 zone).

On-line gas monitors

There are two main types of on-line monitors:

-hydrogen (and two-gas) monitors, allowing to detect abnormal hydrogen formation. They are less expensive and therefore can be installed on a larger number of transformers. However, they will usually miss the early signs of arcing, the most dangerous fault, because of insufficient hydrogen formation in conjunction with acetylene.

-multi-gas monitors, allowing to detect abnormal gas formation, get a fault diagnosis on-line and take immediate action on the equipment without having to send an oil sample to the lab for complete DGA analysis.

-the recommendation of CIGRE TF15 [6] is to use hydrogen monitors on relatively "healthy" transformers, and multi-gas monitors on transformers where problems are suspected (already gassing or critical transformers).

-the main advantage of on-line gas monitors is to detect faults occurring between regular oil sampling intervals.

References

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