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Edition 4.0   2022-05

INTERNATIONAL STANDARD

NORME INTERNATIONALE

Mineral oil-filled electrical equipment in service – Guidance on the interpretation of dissolved and free gases analysis

Matériels électriques remplis d'huile minérale en service – Recommandations relatives à l'interprétation de l'analyse des gaz dissous et des gaz libres

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MINERAL OIL-FILLED ELECTRICAL EQUIPMENT IN SERVICE – GUIDANCE ON THE INTERPRETATION OF DISSOLVED AND FREE GASES ANALYSIS

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IEC 60599 has been prepared by IEC technical committee 10: Fluids for electrotechnical applications. It is an International Standard.

This fourth edition cancels and replaces the third edition published in 2015. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) revision of Clause A.5 on bushings, at the request of IEC subcommittee 36A, in order to transfer to IEC 60599 the corresponding contents of IEC TR 61464 [1][1] relating to DGA in bushings and include the new information on DGA in bushings available in CIGRE Technical Brochure 771 (2019) [2];

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1 Numbers in square brackets refer to the Bibliography.

b) revision of Clause A.3 on wind turbine transformers, in order to include in IEC 60599 the new information on DGA in wind turbine transformers available in CIGRE Technical Brochure 771 (2019) [2].

The text of this International Standard is based on the following documents:

Draft	Report on voting
10/1164/FDIS	10/1174/RVD

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

• reconfirmed,

• withdrawn,

• replaced by a revised edition, or

• amended.

INTRODUCTION

Dissolved and free gas analysis (DGA) is one of the most widely used diagnostic tools for detecting and evaluating faults in electrical equipment filled with insulating liquid. However, interpretation of DGA results is often complex and should always be done with care, involving experienced insulation maintenance personnel.

This document gives information for facilitating this interpretation. The first edition, published in 1978, has served the industry well, but had its limitations, such as the absence of a diagnosis in some cases, the absence of concentration levels and the fact that it was based mainly on experience gained from power transformers. The second edition (2015) attempted to address some of these shortcomings. Interpretation schemes were based on observations made after inspection of a large number of faulty oil-filled equipment in service and concentrations levels deduced from analyses collected worldwide.

MINERAL OIL-FILLED ELECTRICAL EQUIPMENT IN SERVICE – GUIDANCE ON THE INTERPRETATION OF DISSOLVED AND FREE GASES ANALYSIS

1 Scope

This document describes how the concentrations of dissolved gases or free gases can be interpreted to diagnose the condition of oil-filled electrical equipment in service and suggest future action.

This document is applicable to electrical equipment filled with mineral insulating oil and insulated with cellulosic paper or pressboard-based solid insulation. Information about specific types of equipment such as transformers (power, instrument, industrial, railways, distribution), reactors, bushings, switchgear and oil-filled cables is given only as an indication in the application notes.

This document can be applied, but only with caution, to other liquid-solid insulating systems.

In any case, the indications obtained are given only as guidance with resulting action undertaken only with proper engineering judgment.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60475, *Method of sampling insulating liquids*

IEC 60567:2011, *Oil-filled electrical equipment – Sampling of gases and analysis of free and dissolved gases – Guidance*

IEC 61198, *Mineral insulating oils – Methods for the determination of 2-furfural and related compounds*

3 Terms, definitions and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- IEC Electropedia: available at https://www.electropedia.org/
- ISO Online browsing platform: available at https://www.iso.org/obp

3.1.1
fault
unplanned occurrence or defect in an item which may result in one or more failures of the item itself or of other associated equipment

3.1.2
non-damage fault
fault which does not involve repair or replacement action at the point of the fault

Note 1 to entry: Typical examples are self-extinguishing arcs in switching equipment or general overheating without paper carbonization or stray gassing of oil.

3.1.3
damage fault
fault that involves repair or replacement action at the point of the fault

3.1.4
incident
event of external or internal origin, affecting equipment or the supply system and which disturbs its normal operation

Note 1 to entry: For the purposes of this document "incidents" are related to internal faults.

Note 2 to entry: For the purposes of this document typical examples of "incidents" are gas alarms, equipment tripping or equipment leakage.

3.1.5
failure
loss of ability to perform as required

Note 1 to entry: In electrical equipment, failure will result from a damage fault or incident necessitating outage, repair or replacement of the equipment, such as internal breakdown, rupture of tank, fire or explosion.

3.1.6
electrical fault
partial or disruptive discharge through the insulation

3.1.7
partial discharge
electric discharge that only partially bridges the insulation between conductors

Note 1 to entry: A partial discharge may occur inside the insulation or adjacent to a conductor.

Note 2 to entry: Scintillations of low energy on the surface of insulating materials are often described as partial discharges but should rather be considered as disruptive discharges of low energy, since they are the result of local dielectric breakdowns of high ionization density, or small arcs, according to the conventions of physics.

Note 3 to entry: For the purposes of this document the following consideration can also be added:

– Corona is a form of partial discharge that occurs in gaseous media around conductors that are remote from solid or liquid insulation. This term shall not be used as a general term for all forms of partial discharges.

– As a result of corona discharges, X-wax, a solid material consisting of polymerized fragments of the molecules of the original liquid, can be formed.

3.1.8
disruptive discharge
passage of an arc following the breakdown

Note 1 to entry: The term "sparkover" (in French: "amorçage") is used when a disruptive discharge occurs in a gaseous or liquid dielectric.

The term "flashover" (in French: "contournement") is used when a disruptive discharge occurs over the surface of a solid dielectric surrounded by a gaseous or liquid medium.

The term "puncture" (in French: "perforation") is used when a disruptive discharge occurs through a solid dielectric.

Note 2 to entry: Discharges are often described as arcing, breakdown or short circuits. The following other specific terms are also used in some countries:

– tracking (the progressive degradation of the surface of solid insulation by local discharges to form conducting or partially conducting paths);

– sparking discharges that, in the conventions of physics, are local dielectric breakdowns of high ionization density or small arcs.

3.1.9
thermal fault
excessive temperature rise in the insulation

Note 1 to entry: Typical causes are

– insufficient cooling;

– excessive currents circulating in adjacent metal parts (as a result of bad contacts, eddy currents, stray losses or leakage flux);

– excessive currents circulating through the insulation (as a result of high dielectric losses), leading to a thermal runaway;

– overheating of internal winding or bushing connection lead;

– overloading.

3.1.10
typical values of gas concentrations
gas concentrations normally found in the equipment in service that have no symptoms of failure, and that are exceeded by only an arbitrary percentage of higher gas contents (for example 10 %)

Note 1 to entry: See 8.2.1.

Note 2 to entry: Typical values will differ in different types of equipment and in different networks, depending on operating practices (load levels, climate, etc.).

Note 3 to entry: Typical values, in many countries and by many users, are quoted as "normal values", but this term has not been used in this document to avoid possible misinterpretations.

3.2   Abbreviated terms

3.2.1   Chemical names and formulae

Name	Formula
Nitrogen	N_2
Oxygen	O_2
Hydrogen	H_2
Carbon monoxide	CO
Carbon dioxide	CO_2
Methane	CH_4
Ethane	C_2H_6
Ethylene	C_2H_4
Acetylene	C_2H_2

NOTE   Acetylene and ethyne are both used for C_2H_2; ethylene and ethene are both used for C_2H_4.

3.2.2   General abbreviated terms

CT   current transformer

CTCV   combined transformer (current-voltage)

CIVT   cascade (inductive) voltage transformer

CVT   capacitor voltage transformer

MVT   magnetic voltage transformer

VT   voltage transformer

ONAN	oil natural air natural
OFAF	oil forced air forced
DDB	dodecylbenzene
WTT	wind turbine transformer
D1	discharges of low energy
D2	discharges of high energy
DGA	dissolved gas analysis
CIGRE	Conseil International des Grands Réseaux Électriques
PD	corona partial discharges
S	analytical detection limit
T1	thermal fault, $t < 300$ °C
T2	thermal fault, 300 °C $< t < 700$ °C
T3	thermal fault, $t > 700$ °C
T	thermal fault
D	electrical fault
TP	thermal fault in paper
ppm	parts per million by volume of gas in oil, equivalent to µl (of gas)/l (of oil). See IEC 60567:2011, 8.7, Note 1.
OLTC	on-load tap-changer

4 Mechanisms of gas formation

4.1 Decomposition of oil

Mineral insulating oils are made of a blend of different hydrocarbon molecules containing CH_3, CH_2 and CH chemical groups linked together by carbon-carbon molecular bonds. Scission of some of the C-H and C-C bonds can occur as a result of electrical and thermal faults, with the formation of small unstable fragments, in radical or ionic form, such as $H^\bullet$, $CH_3^\bullet$, $CH_2^\bullet$, $CH^\bullet$ or $C^\bullet$ (among many other more complex forms), which recombine rapidly, through complex reactions, into gas molecules such as hydrogen (H-H), methane (CH_3-H), ethane (CH_3-CH_3), ethylene ($CH_2 = CH_2$) or acetylene (CH $\equiv$ CH). C_3 and C_4 hydrocarbon gases, as well as solid particles of carbon and hydrocarbon polymers (X-wax), are other possible recombination products. The gases formed dissolve in oil, or accumulate as free gases if produced rapidly in large quantities, and can be analysed by DGA according to IEC 60567.

Low-energy faults, such as partial discharges of the cold plasma type (corona discharges), favour the scission of the weakest C-H bonds (338 kJ/mol) through ionization reactions and the accumulation of hydrogen as the main recombination gas. More and more energy and/or higher temperatures are necessary for the scission of the C-C bonds and their recombination into gases with a C-C single bond (607 kJ/mol), C=C double bond (720 kJ/mol) or C≡C triple bond (960 kJ/mol), following processes bearing some similarities with those observed in the petroleum oil-cracking industry.

Ethylene is thus favoured over ethane and methane above temperatures of approximately 500 °C (although still present in lower quantities below these temperatures). Acetylene requires temperatures of at least 800 °C to 1 200 °C, and a rapid quenching to lower temperatures, in order to accumulate as a stable recombination product. Acetylene is thus formed in significant quantities mainly in arcs, where the conductive ionized channel is at several thousands of degrees Celsius, and the interface with the surrounding liquid oil necessarily below 400 °C (above which oil vaporizes completely), with a layer of oil vapour and/or decomposition gases in between. Acetylene can still be formed at lower temperatures (< 800 °C), but in very minor

quantities. Carbon particles form at 500 °C to 800 °C and are indeed observed after arcing in oil or around very hot spots.

Oil can oxidize with the formation of small quantities of CO and CO_2, which can accumulate over long periods of time into more substantial amounts.

4.2   Decomposition of cellulosic insulation

The polymeric chains of solid cellulosic insulation (paper, pressboard, wood blocks) contain a large number of anhydroglucose rings, and weak C-O molecular bonds and glycosidic bonds which are thermally less stable than the hydrocarbon bonds in oil, and which decompose at lower temperatures. Significant rates of polymer chain scission occur at temperatures higher than 105 °C, with complete decomposition and carbonization above 300 °C (damage fault). Carbon monoxide and dioxide, as well as water, is formed, together with minor amounts of hydrocarbon gases, furanic and other compounds. Furanic compounds are analysed according to IEC 61198, and used to complement DGA interpretation and confirm whether or not cellulosic insulation is involved in a fault. CO and CO_2 formation increases not only with temperature but also with the oxygen content of oil and the moisture content of paper.

4.3   Stray gassing of oil

Stray gassing of oil has been defined by CIGRE [3] as the formation of gases in oil heated to moderate temperatures (< 200 °C). H_2, CH_4 and C_2H_6 can be formed in all equipment at such temperatures or as a result of oil oxidation, depending on oil chemical structure. Stray gassing is a non-damage fault. It can be evaluated using methods described in references [3] and [4].

NOTE   Stray gassing of oil has been observed in some cases to be enhanced by the presence in oil of a metal passivator or other additives.

4.4   Other sources of gas

Gases can be generated in some cases not as a result of faults in the equipment, but through corrosion or other chemical reactions involving steel, uncoated surfaces or protective paints.

Hydrogen can be produced by reaction of steel and galvanized steel with water, as long as oxygen is available from the oil nearby. Large quantities of hydrogen have thus been reported in some transformers that had never been energized. Hydrogen can also be formed by reaction of free water with special coatings on metal surfaces, or by catalytic reaction of some types of stainless steel with oil, in particular oil containing dissolved oxygen at elevated temperatures. Hydrogen, acetylene and other gases can also be formed in new stainless steel, absorbed during its manufacturing process, or produced by welding, and released slowly into the oil. Internal transformer paints, such as alkyd resins and modified polyurethanes containing fatty acids in their formulation, can also form gases.

Gases can also be produced, and oxygen consumed, by exposure of oil to sunlight.

These occurrences, however, are very unusual, and can be detected by performing DGA analyses on new equipment which has never been energized, and by material compatibility tests. The presence of hydrogen with the total absence of other hydrocarbon gases, for example, can be an indication of such a problem.

NOTE   The case of gases formed at a previous fault and remnant in the transformer is dealt with in 5.4.

5   Identification of faults

5.1   General

Any gas formation in service, be it minimal, results from a stress of some kind, even if it is a very mild one, like normal temperature ageing. However, as long as gas concentration is below

typical values and not significantly increasing, it should not be considered as an indication of a "fault", but rather as the result of typical gas formation (see Figure 1). Typical values are specific for each kind of equipment.

5.2 Dissolved gas compositions

Although the formation of some gases is favoured, depending on the temperature reached or the energy contained in a fault (see 4.1), in practice mixtures of gases are almost always obtained. One reason is thermodynamic: although not favoured, secondary gases are still formed, albeit in minor quantities. Existing thermodynamic models derived from the petroleum industry, however, cannot predict accurately the gas compositions formed, because they correspond to ideal gas and/or temperature equilibria that do not exist in actual faults. Large temperature gradients also occur in practice, for instance as a result of oil flow or vaporization along a hot surface. This is particularly true in the case of arcs with power follow-through, which transfer a lot of heat to the oil vapour and/or decomposition gas layer between the arc and the oil, probably explaining the increasing formation of ethylene observed in addition to acetylene. In addition, existing thermodynamic models do not apply to paper that turns irreversibly to carbon above 300 °C.

5.3 Types of faults

Internal inspection of hundreds of faulty equipment has led to the following broad classes of visually detectable faults:

- partial discharges (PD) of the cold plasma (corona) type, resulting in possible X-wax deposition on paper insulation;

- discharges of low energy (D1), in oil and/or paper, evidenced by larger carbonized perforations through paper (punctures), carbonization of the paper surface (tracking) or carbon particles in oil (as in tap changer diverter operation); also, partial discharges of the sparking type, inducing pinhole, carbonized perforations (punctures) in paper, which, however, may be difficult to find;

- discharges of high energy (D2), in oil and/or paper, with power follow-through, evidenced by extensive destruction and carbonization of paper, metal fusion at the discharge extremities, extensive carbonization in oil and, in some cases, tripping of the equipment, confirming the large current follow-through;

- thermal faults, in oil and/or paper, below 300 °C if the paper has turned brownish (T1), and above 300 °C if it has carbonized (T2);

- thermal faults of temperatures above 700 °C (T3) if there is strong evidence of carbonization of the oil, metal coloration (800 °C) or metal fusion (> 1 000 °C).

5.4 Basic gas ratios

Each of the six broad classes of faults leads to a characteristic pattern of hydrocarbon gas composition, which can be translated into a DGA interpretation table, such as the one recommended in Table 1 and based on the use of three basic gas ratios:

$$\frac{C_2H_2}{C_2H_4} \qquad\qquad \frac{CH_4}{H_2} \qquad\qquad \frac{C_2H_4}{C_2H_6}$$

Table 1 applies to all types of equipment, with a few differences in gas ratio limits depending on the specific type of equipment.

Table 1 – DGA interpretation table

Case	Characteristic fault	$\dfrac{C_2H_2}{C_2H_4}$	$\dfrac{CH_4}{H_2}$	$\dfrac{C_2H_4}{C_2H_6}$
PD	Partial discharges (see Notes 3 and 4)	NS [a]	< 0,1	< 0,2
D1	Discharges of low energy	> 1	0,1 to 0,5	> 1
D2	Discharges of high energy	0,6 to 2,5	0,1 to 1	> 2
T1	Thermal fault t < 300 °C	NS [a]	> 1 but NS [a]	< 1
T2	Thermal fault 300 °C < t < 700 °C	< 0,1	> 1	1 to 4
T3	Thermal fault t > 700 °C	< 0,2 [b]	> 1	> 4

NOTE 1   In some countries, the ratio C_2H_2/C_2H_6 is used, rather than the ratio CH_4/H_2. Also in some countries, slightly different ratio limits are used.

NOTE 2   Conditions for calculating gas ratios are indicated in 6.1 c).

NOTE 3 CH_4/H_2 < 0,2 for partial discharges in instrument transformers. CH_4/H_2 < 0,07 for partial discharges in bushings.

NOTE 4   Gas decomposition patterns similar to partial discharges have been reported as a result of stray gassing of oil (see 4.3).

[a]   NS = Non-significant whatever the value.

[b]   An increasing value of the amount of C_2H_2 can indicate that the hot spot temperature is higher than 1 000 °C.

Typical examples of faults in the various types of equipment (power transformers, instrument transformers, etc.), corresponding to the six cases of Table 1, can be found in Table A.1, Table A.5, Table A.8 and Table A.12.

Some overlap between faults D1 and D2 is apparent in Table 1, meaning that a dual attribution of D1 or D2 should be given in some cases of DGA results. The distinction between D1 and D2 has been kept, however, as the amount of energy in the discharge can significantly increase the potential damage to the equipment and necessitate different preventive measures. Table 1 applies to transformers. For switching equipment see Clause A.7 and reference [5] in the bibliography.

NOTE   Combinations of gas ratios that fall outside the range limits of Table 1 and do not correspond to a characteristic fault of this table can be considered a mixture of faults, or new faults that combine with a high background gas level (see 6.1).

In such a case, Table 1 cannot provide a diagnosis, but the graphical representations given in Annex B can be used to visualize which characteristic fault of Table 1 is closest to the case.

The less detailed scheme of Table 2 can also be used in such a case in order to get at least a rough distinction between partial discharges (PD), discharges (D) and thermal fault (T), rather than no diagnosis at all.

Table 2 – Simplified scheme of interpretation

Case	$\dfrac{C_2H_2}{C_2H_4}$	$\dfrac{CH_4}{H_2}$	$\dfrac{C_2H_4}{C_2H_6}$
PD		< 0,2	
D	> 0,2		
T	< 0,2		

5.5 CO_2/CO ratio

The formation of CO_2 and CO from oil-impregnated paper insulation increases rapidly with temperature. High values of CO (e.g. 1 000 ppm) and CO_2/CO ratios less than 3 are generally considered as an indication of probable paper involvement in a fault, with possible carbonization, in the presence of other fault gases.

However, in some recent transformers of the closed-type or open (free breathing) transformers operating at constant load (i.e. with low breathing), CO can accumulate in the oil, leading to ratios CO_2/CO < 3, without any irregularities or faults if no other gases such as H_2 or hydrocarbons are formed [6].

High values of CO_2 (> 10 000 ppm) and high CO_2/CO ratios (> 10) can indicate mild (< 160 °C) overheating of paper [3], [5] or oil oxidation, especially in open transformers. CO_2 can accumulate more rapidly than CO in open transformers operating at changing loads because of their different solubilities in oil. This, and the long term degradation with time of paper at low temperatures (< 160 °C), can lead to higher CO_2/CO ratios in aged equipment.

In some cases, localized faults in paper do not produce significant amounts of CO and CO_2 and cannot be detected with these gases (the same for furanic compounds).

Involvement of faults in paper therefore shall not be based only on CO and CO_2, but shall be confirmed by the formation of other gases or other types of oil analysis.

In order to get reliable CO_2/CO ratios in the equipment, CO_2 and CO values should be corrected (incremented) first for possible CO_2 absorption from atmospheric air, and for the CO_2 and CO background values (see 6.1 and Clause 9), resulting from the ageing of cellulosic insulation, overheating of wooden blocks and the long term oxidation of oil (which will be strongly influenced by the availability of oxygen caused by specific equipment construction details and its way of operation).

Air-breathing equipment, for example, saturated with approximately 9 % to 10 % of dissolved air, can contain up to 300 µl/l of CO_2 coming from the air. In sealed equipment, air is normally excluded but can enter through leaks, and CO_2 concentration will be in proportion of air present.

When excessive paper degradation is suspected, it is recommended to ask for further analysis (e.g. of furanic compounds) or a measurement of the degree of polymerization of paper samples, when this is possible.

NOTE 1   In case of equipment containing negligible amounts of paper (e.g. most modern types of on-load tap-changers (OLTCs)), CO and CO_2 can increase with oil oxidation under thermal stress. CO_2/CO ratios can have values quite different from those in transformers.

NOTE 2   High levels of CO can also be formed in case of high energy discharges in oil only.

NOTE 3   In instrument transformers and some bushing types, low ratios < 3 are observed without any paper degradation.

5.6 O_2/N_2 ratio

Dissolved O_2 and N_2 are found in oil as a result of contact with atmospheric air in the conservator of air-breathing equipment, or through leaks in sealed equipment. At equilibrium with air, the concentrations of O_2 and N_2 in oil are approximately 32 000 ppm and approximately 64 000 ppm, respectively [5], and the O_2/N_2 ratio is approximately 0,5.

In service, this ratio can decrease as a result of oil oxidation and/or paper ageing, if O_2 is consumed more rapidly than it is replaced by diffusion. Factors such as the load and

preservation system used can also affect the ratio, but with the exception of closed systems, ratios less than 0,3 are generally considered to indicate excessive consumption of oxygen.

5.7 C_2H_2/H_2 ratio

In power transformers, on-load tap-changer (OLTC) operations produce gases corresponding to discharges of low energy (D1). If some oil or gas communication is possible between the OLTC compartment and the main tank, or between the respective conservators, these gases can contaminate the oil in the main tank and lead to wrong diagnoses. The pattern of gas decomposition in the OLTC, however, is quite specific and different from that of regular D1s in the main tank.

C_2H_2/H_2 ratios higher than 2 to 3 in the main tank are thus considered as an indication of OLTC contamination. This can be confirmed by comparing DGA results in the main tank, in the OLTC and in the conservators. The values of the gas ratio and of the acetylene concentration depend on the number of OLTC operations and on the way the contamination has occurred (through the oil or the gas).

If contamination by gases coming from the OLTC is suspected, interpretation of DGA results in the main tank should be made with caution by subtracting background contamination from the OLTC, or should be avoided as unreliable.

NOTE   Modern OLTCs are designed not to contaminate oil in the main tank.

5.8 C_3 hydrocarbons

The interpretation method of gas analysis indicated in 5.1 to 5.7 takes into account only C_1 and C_2 hydrocarbons. Some practical interpretation methods also use the concentrations of C_3 hydrocarbons, and their authors believe that they are liable to bring complementary information that is useful to make the diagnosis more precise. Because the C_3 hydrocarbons are very soluble in oil, their concentrations are practically not affected by a possible diffusion into ambient air. Conversely, and because they are very soluble, they are difficult to extract from the oil and the result of the analysis can greatly depend on the extraction method used. Moreover, experience has shown that, in most cases, a satisfactory diagnosis can be made without taking into account these hydrocarbons and for the sake of simplification, they have been omitted from the interpretation method indicated in 5.1 to 5.7.

5.9   Evolution of faults

Faults often start as incipient faults of low energy, which can develop into more serious ones of higher energies, leading to possible gas alarms, breakdowns and failures.

When a fault is detected at an early stage of development, it can be quite informative to examine not only the increase in gas concentrations, but also the possible evolution with time toward a more dangerous high-energy fault resulting in failure.

For example, some current transformers have operated satisfactorily for long periods of time with very high levels of hydrogen produced by partial discharges. However, partial discharges can also cause the formation of X-wax. When the X-wax is present in sufficient quantity to increase the dissipation losses in the paper-oil insulation, a thermal fault can occur, eventually leading to catastrophic thermal runaway and breakdown.

In other occurrences, however, instant final breakdown can occur without warning.

5.10   Graphical representations

Graphical representations of gas ratios are convenient to follow this evolution of faults visually. Annex B gives examples of graphical representation of faults.

These representations are also useful in cases that do not receive a diagnosis using Table 1, because they fall outside the gas ratios limits. Using Figure B.1 or Figure B.2, the zone or box that is closest to such an undiagnosed case can be easily visualized and attributed with caution to this case. Figure B.3 is particularly useful since it always provides a diagnosis in such cases.

6 Conditions for calculating ratios

6.1 Examination of DGA values

DGA sampling and analysis shall be done in accordance with the recommendations of IEC 60475 and IEC 60567, respectively.

a) Values of 0 µl/l on a DGA report or below the analytical detection limits S shall be replaced by "below the S value for this gas" (see IEC 60567 for recommended S values).

b) If successive DGA analyses have been performed over a relatively short period of time (days or weeks), it is possible that inconsistent variations (e.g. large decreases of concentrations) have to be eliminated as an indication of a sampling or analytical problem.

c) Gas ratios are significant and should be calculated only when at least one of the gases is at a concentration and a rate of gas increase above typical values (see Clause 9). Nevertheless, it is recommended to also calculate them in cases where one or more gases show increasing or abnormal concentrations, even if they are lower than typical values. Avoid calculating ratios when gas concentrations are not high enough to be reasonably accurate according to IEC 60567.

d) If gas ratios are different from those for the previous analysis, a new fault can superimpose itself on an old one or normal ageing. In order to get only the gas ratios corresponding to the new fault, subtract the previous DGA values from the last ones and recalculate ratios. This is particularly true in the case of CO and CO_2 (see 5.4). Be sure to compare DGA values of samples taken at the same place and preferably in moving oil. Interpretation should also take into account treatments previously made on the equipment, such as repair, oil degassing or filtering, which can affect the level of gases in the oil.

NOTE   In the case of air-breathing power transformers, losses occur very slowly with time by diffusion through the conservator or as a result of oil expansion/temperature cycles, with the result that the measured gas levels can be slightly less than the gas levels actually formed in the transformer. However, there is no agreement concerning the magnitude of this diffusion loss in service, some considering it as totally negligible, others as potentially significant, depending on the type of equipment used. Typical values in open and closed transformers are relatively similar, suggesting that either gas loss in open transformers is lower than suspected, or that gas production is higher (because of higher oxygen availability) and compensated by higher gas loss. In any case, this has not been observed to significantly affect the identification of faults in open transformers.

6.2 Uncertainty on gas ratios

Because of the uncertainty on DGA values, there is also an uncertainty on gas ratios, which can be calculated using the uncertainty on DGA values described in IEC 60567.

Above 10 × S (S being the analytical detection limit), the uncertainty (precision and accuracy) is typically ±15 % on DGA values and this can also effect the uncertainty on gas ratios. Below 10 × S, the uncertainty on DGA values increases rapidly, to typically ±30 % at 5 × S.

Caution should therefore be exercized when calculating gas ratios at low gas levels (lower than 10 × S), keeping in mind the possible variations resulting from the higher uncertainty.

7 Application to free gases in gas relays

During a fault, the production rate of gases of all types is closely linked to the rate of energy liberation. Thus, the low rate of energy liberation in partial discharges, or in a low-temperature thermal fault, will cause gases to evolve slowly and there is every probability that all the gas produced will dissolve in the oil. The higher rate of energy liberation of a high-temperature core fault, for example, can cause an evolution of gas rapid enough to result in gas bubbles. These will usually partially dissolve in the oil (and exchange with gases already dissolved) but some

gas can well reach the gas collecting relay or gas cushion; this gas can approach equilibrium with the gases dissolved in the oil.

A very high rate of energy liberation associated with a power arcing fault causes a rapid and substantial evolution of gas (the resulting pressure surge normally operates the surge element of the gas collecting relay). The large gas bubbles rise quickly to the relay and exchange little gas with the oil so that the gas that collects in the relay is initially far from being in equilibrium with the gases dissolved in the oil. However, if this gas is left for a long time in the relay, some constituents will dissolve, modifying the composition of the gas collected. Acetylene, which is produced in significant quantities by an arcing fault, and which is very soluble, is a noteworthy example of a gas that can dissolve comparatively quickly to produce misleading results.

In principle, the analysis of free gases from a gas-collecting relay or from a gas cushion can be evaluated in the same way as the analysis of gases dissolved in the oil. However, where the surge element has operated and gas has accumulated in substantial quantities, there is a possibility of having a serious fault, and analyses of the gases should be undertaken to identify the fault. If the rate of gas production is low, gases formed will usually dissolve entirely in oil. If it is high, or if the oil is over-saturated with gas, gas bubbles will rise rapidly in the oil and accumulate in the gas relay. The less soluble gases in bubbles (H_2, CO and CH_4) will not have time to dissolve in oil during their ascent and will be over-represented in the top oil of the tank and the gas relay, resulting in wrong fault identification.

After a Buchholz alarm it is recommended to collect the gas at the relay as soon as possible and sample the oil in the relay and in the top and bottom oil of the main tank. This will allow first to verify that the alarm is indeed due to a fault in the transformer and not to air accumulation following a combination of warm days and sudden temperature drops at night, or because of faults in oil pumps.

Where gas has accumulated slowly (e.g. as a result of coking of selector contacts or of core overheating), assessment of the gases dissolved in the oil is more informative than that of the free gases; this gas-in-oil analysis is also essential in order to determine the total rate of evolution of gases and thus check whether the fault is growing, which is the most important matter to investigate. When analysis of free gases is undertaken, it is necessary to convert the concentrations of the various gases in the free state into equivalent concentrations in the dissolved state, using Table 3, before applying the gas ratio method of Table 1, and to compare them to the dissolved gas concentrations in the oil of the relay and the main tank.

Applying the principles set out above, comparison of the actual concentrations in the oil with the equivalent concentrations in the free gas can give valuable information on how far gas bubbles can have risen through the oil and, hence, on the rate of gas evolution.

The calculation of dissolved gas concentrations equivalent to free gas concentrations is made by applying the Ostwald solubility coefficient for each gas separately. For a particular gas, the Ostwald solubility coefficient k is defined as follows:

$$k = \frac{\text{concentration of gas in liquid phase}}{\text{concentration of gas in gas phase}}$$

with concentrations in microlitres per litre.

Table 3 contains the Ostwald solubility coefficients of various gases in mineral insulating oils as given in IEC 60567:2011, Table A.1.

**Table 3 – Ostwald solubility coefficients
for various gases in mineral insulating oils**

Gas	k at 25 °C
N_2	0,091
O_2	0,172
H_2	0,056
CO	0,132
CO_2	1,09
CH_4	0,429
C_2H_6	2,82
C_2H_4	1,84
C_2H_2	1,24
Data given in this table represent mean values obtained on some of the current types of transformer mineral insulating oils. Actual data can differ a little from these figures. Nevertheless, data given in this table can be used without influencing conclusions drawn from recalculated test results.	

The Ostwald solubility coefficient is independent of the actual partial pressures of the gas concerned. The gas and liquid phases are assumed to be at the same temperature; this is rarely the case but the error introduced by any difference will not invalidate the conclusions reached.

If only free gas in the relay is analysed, gas content in oil of the relay at equilibrium can be calculated using the above equation and Ostwald solubility coefficients k for each gas given in Table 3.

When gas accumulates in the gas relay, collect and analyse as soon as possible the free gases in the relay, convert into gases in the relay oil, using k, then compare to gases in oil in the main tank. If results are comparable, this indicates equilibrium has been reached and gas has accumulated slowly. If they do not compare, this indicates that equilibrium has not been reached and gas has accumulated rapidly.

8 Gas concentration levels in service

8.1 Probability of failure in service

8.1.1 General

The probability or risk of having an incident or a failure in service is related to gas concentration levels and rates of gas formation [5].

Below certain concentration levels (quoted as typical values or normal values), the probability of having a failure is low (typically 10 % according to CIGRE [3] when using oil sampling). The equipment is considered healthy, although a failure cannot be totally ruled out, even at these low levels, but it is improbable. A first rough screening between healthy and suspect analyses can therefore be obtained by calculating typical values for the equipment.

The probability of having a failure can increase significantly at values much above typical concentration levels. The situation is then considered critical, for even though a failure can never occur at these high levels, the risk of having one is high. For detecting such failures, see [7] in the bibliography.

8.1.2 Calculation methods

Utilities with large DGA and equipment maintenance databases are able to calculate the probability of failure in service for a given type of equipment and at a given concentration level of a gas. This can be obtained by calculating the number of DGA analyses that have led to an actual failure or incident in service (gas alarm, failure, repair, outage, etc.), and comparing it to the total number of DGA analyses on this type of equipment and at this gas concentration level.

A large number of analyses is necessary to get reliable values of failure probability. Knowledge of these values, however, is useful when choosing the normality percentage most appropriate for a given network and type of equipment (see 8.2.3). Pre-failure values have thus been proposed by CIGRE [3], [5], above which the probability of failure increases very rapidly.

8.2 Typical concentration values

8.2.1 General

Typical concentration values are the acceptable gas quantities that are exceeded by only an arbitrarily low percentage of higher gas contents, for example 10 %. Typical concentration values will be referred to in such an example as the 90 % typical values. This allows concentrating maintenance efforts on the 10 % of transformers most at risk.

However, typical concentration values shall be considered as initial guidelines for decision making, when no other experience is available. They shall not be used to ascertain whether or not a fault exists within the equipment. They should be viewed as values above which the rate of gas formation can permit the detection of a probable fault.

Typical concentration values are affected by a number of factors, chiefly the operating time since commissioning, the type of equipment and the nature of the fault (electrical or thermal). For power transformers, the type of oil protection, load factor and operation mode are other influencing factors.

Typical concentration values can be calculated as indicated in 8.2.2 to 8.3 and should preferably be obtained by the equipment users on the specific types of equipment.

8.2.2 Calculation methods

The simplest method of calculation consists in gathering all the DGA results concerning a specific type of equipment. For each characteristic gas considered, the cumulative number of DGA analyses where the gas concentration is below a given value is calculated, then plotted as a function of gas concentration. Using the plotted curve, the gas concentration corresponding to a given percentage of the total cumulative number of analyses (for instance 90 %) is the 90 % typical concentration value for that gas and type of equipment.

8.2.3 Choice of normality percentages

Most organizations worldwide (IEC, IEEE) use a normality percentage of 90 % for typical values. However, other percentages can also be used.

If adequate databases are not available to calculate typical values, users can also adopt as a first step, values observed on other networks and indicated in the application notes. It is apparent from these values that, in general, typical values are lower in instrument transformers and bushings than in power transformers, especially those with a communicating OLTC.

8.2.4 Alarm concentration values

Alarm concentration values are those values of concentration above which the probability of an incident is sufficiently high to require urgent competent decisions and/or actions. Pre-failure concentration values have thus been proposed by CIGRE [5], and more recently as a function of type and location of faults [2].

Alarm concentration values should be set by users, manufacturers or independent experts, based on previous experience with equipment with similar characteristics (voltage, type, manufacturer, loading practices, age, etc.).

8.3   Rates of gas increase

If there is no increase in gas concentration over the last analysis, chances are that the fault has disappeared (or that a very small one is still there, in the case of air-breathing equipment, compensated by diffusion losses through the conservator (see 6.1).

What should be considered as a typical or alarm rate of gas increase depends very much on equipment type and age, type of identified faults, air-breathing and load patterns, and volume of the insulation involved. Ultimately the rate of increase should be decided by the user of the equipment, the manufacturer and/or other experts.

Typical rates of gas increase can be calculated as in the case of typical gas concentrations and are indicated in Table A.3. Pre-failure rates of increase have also been proposed by CIGRE [5].

On-line gas monitors, including those for hydrogen, can be particularly well-suited for detecting non-typical rates of gas increase occurring within minutes, hours or weeks, which is generally not possible with routine oil samplings done at monthly or yearly intervals [7]. However, when such increases are detected by a gas monitor, complete DGA analyses shall be made at the laboratory to confirm the monitor readings.

9   Recommended method of DGA interpretation

See Figure 1. For specific types of equipment, see Annex A. The procedure shall be as follows:

a) Reject or correct inconsistent DGA values (see 6.1). Calculate the rate of gas increase since the last analysis, taking into account the precision on DGA results.

If all gases are below typical values of gas concentrations and rates of gas increase, report as "Normal DGA/healthy equipment".

If at least one gas is above typical values of gas concentrations and rates of gas increase, calculate gas ratios and identify the fault using Table 1 (see 5.4). Check for eventual erroneous diagnosis (see 4.3).

If necessary, subtract last values from present ones before calculating ratios, particularly in the case of CO, CO_2 (see 6.1).

If DGA values are above typical values but below $10 \times S$ (S = analytical detection limit), see 6.2.

b) Determine if gas concentrations and rates of gas increase are above alarm values. Verify if the fault is evolving towards a final stage (see 5.9). Determine if paper is involved (see 4.2 and 5.5).

c) Take proper action according to best engineering judgment and/or with the help of Figure 1.

It is recommended to:

1) increase sampling frequency (quarterly, monthly or other) when the gas concentrations and their rates of increase exceed typical values;

2) consider performing complementary tests (acoustic, electrical, infrared) or reduce loading;

3) consider removing the transformer from service for inspection or repair depending on the results of complementary and other tests and on the advice of transformer experts;

4) consider immediate action when gas concentrations and rates of gas increase exceed alarm values.

10 Report of results

The report should be adapted to the specific type of equipment considered.

The DGA interpretation report should include the following, when available:

a) analysis report, including S values, method of analysis (see IEC 60567:2011, Table A.1) and date of analysis;

   NOTE   Values of 0 ppm or µl/l on a DGA report or below the S values are replaced by "below the S value for this gas".

b) specific information on the equipment such as:

   1) date of commissioning, voltage, general type (e.g. power or instrument transformer), rated power;

   2) special features (e.g. sealed or air-breathing, type of OLTC (see A.2.1);

   3) oil volume;

   4) oil or gas sampling date;

   5) oil or gas sampling location;

c) special operations or incidents just before the oil or gas sampling, such as tripping, gas alarm, degassing, repair, outage;

d) previous DGA on the equipment;

e) indication of typical values for this specific equipment, if known;

f) indication of "Typical DGA/healthy equipment" or "Fault";

g) in case of "Fault", identification of the fault using Table 1 (see 5.4), with values of the calculated gas ratios indicated;

h) indication of paper involvement or not, with value of the CO_2/CO ratio or other methods (see 5.5);
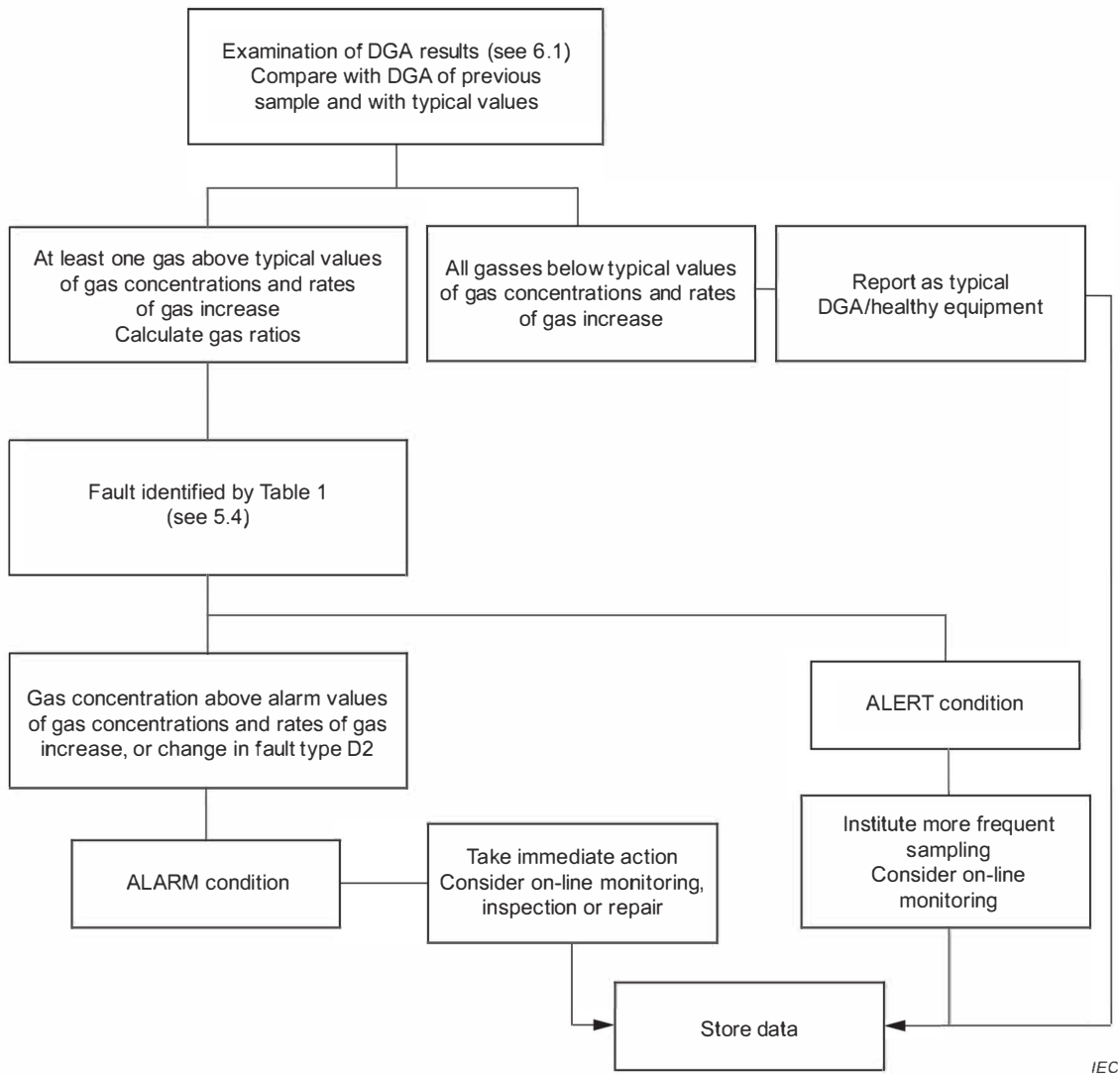
i) recommended actions: (see Clause 9 c)).

Figure 1 – Flow chart

Annex A
(informative)

Equipment application notes

A.1   General warning

"Limit values" of gas concentrations and rates of gas increase in service are not the responsibility of TC 10 but of IEC equipment committees.

"Typical values" in the following application notes are not limit values. They are given for information only, as a maintenance and predictive tool. In a given transformer population, they indicate for example that 90 % of DGA values in service are below the 90 % typical values and 10 % are above. When typical values are exceeded, the only action recommended in this document is to increase the frequency of DGA analyses.

Typical values depend on several parameters (age, type and manufacturer of equipment, operating and loading practices, climate, etc.), and are not exactly the same for all electrical networks. Ranges of typical values are therefore indicated in the following application notes, covering the different individual values observed worldwide and surveyed by IEC and CIGRE.

Individual networks are strongly encouraged to calculate the typical values corresponding to their own specific transformer population, using DGA data meeting IEC 60567 specifications for accuracy and following the methods indicated in Clause 8 and [3].

The ranges of typical values indicated in these application notes should be used only by default, when individual values are not available, and should not be used in a contract without a special agreement between the user and manufacturer of the equipment.

A.2   Power transformers

A.2.1   Specific subtypes

Specific subtypes of power transformers are as follows:

-   air-breathing (open conservator type);
-   sealed or nitrogen-blanketed;
-   inter-tie transmission versus generation step-up;
-   no OLTC communicating with main tank versus communicating OLTC;
-   core-type or shell-type;
-   reactors.

A.2.2   Typical faults

See Table A.1.

Table A.1 – Typical faults in power transformers

Type	Fault	Examples
PD	Partial discharges	Discharges in gas-filled cavities resulting from incomplete impregnation, high-humidity in paper, oil super saturation or cavitation, and leading to X-wax formation
D1	Discharges of low energy	Sparking or arcing between bad connections of different or floating potential, from shielding rings, toroids, adjacent disks or conductors of winding, broken brazing or closed loops in the core
		Discharges between clamping parts, bushing and tank, high voltage and ground within windings, on tank walls
		Tracking in wooden blocks, glue of insulating beam, winding spacers. Breakdown of oil, selector breaking current
D2	Discharges of high energy	Flashover, tracking, or arcing of high local energy or with power follow-through
		Short circuits between low voltage and ground, connectors, windings, bushings and tank, copper bus and tank, windings and core, in oil duct, turret. Closed loops between two adjacent conductors around the main magnetic flux, insulated bolts of core, metal rings holding core legs
T1	Thermal fault $t < 300\ °C$	Overloading of the transformer in emergency situations
		Blocked item restricting oil flow in windings
		Stray flux in clamping beams of yokes
T2	Thermal fault $300\ °C < t < 700\ °C$	Defective contacts between bolted connections (particularly between aluminium busbar), gliding contacts, contacts within selector switch (pyrolitic carbon formation), connections from cable and draw-rod of bushings
		Circulating currents between yoke clamps and bolts, clamps and laminations, in ground wiring, defective welds or clamps in magnetic shields
		Abraded insulation between adjacent parallel conductors in windings
T3	Thermal fault $t > 700\ °C$	Large circulating currents in tank and core
		Minor circulation currents in tank walls created by a high uncompensated magnetic field
		Shorting links in core steel laminations

A.2.3   Identification of faults by DGA

Table 1 (see 5.4) applies directly to all transformer subtypes, except those equipped with a communicating OLTC. In the latter cases, if C_2H_2/H_2 is higher than 2 to 3, there can be contamination from the OLTC into the main tank, in which case Table 1 does not apply or applies with care, after subtracting background contamination from the OLTC (see 5.7).

Any gas formation below typical values of gas concentration and rates of gas increase should not be considered as an indication of "fault", but rather as "normal gas formation". Ratios are not significant in such a case (see Note 2 of Table 1).

In the case of air-breathing power transformers, losses of gas occur very slowly with time by diffusion through the conservator or as a result of oil expansion cycles, with the result that the measured gas levels can be slightly less than the gas levels actually formed in the transformer. However, there is no agreement concerning the magnitude of this diffusion loss in service, some considering it as totally negligible, others as potentially significant, depending on the type of equipment considered. In case of doubt, to get an idea of the volume ventilated it can be expedient to measure the gas concentration in the conservator as well. Significant diffusion losses can affect gas ratios, typical values of gas concentrations and rates of gas increase (see 6.1).

A.2.4   Typical concentration values

Clause A.1 (General warning), shall be consulted before applying A.2.4.

Ranges of 90 % typical gas concentration values observed in power transformers, from about 25 electrical networks worldwide and including more than 20 000 transformers, are given in Table A.2. For hydrogen, for example, one network reported a typical value of 50 µl/l, another one 150 µl/l and the 23 others reported values between 50 µl/l and 150 µl/l. These ranges of values have been reported by CIGRE Study Committees D1 and A2 (TF11) and approved by IEC TC 10 and TC 14.

**Table A.2 – Ranges of 90 % typical gas concentration values
observed in power transformers**

Values in microlitres per litre

	C_2H_2	H_2	CH_4	C_2H_4	C_2H_6	CO	CO_2
All transformers		50 to 150	30 to 130	60 to 280	20 to 90	400 to 600	3 800 to 14 000
No OLTC	2 to 20						
Communicating OLTC	60 to 280						

"Communicating OLTC" in Table A.2 and Table A.3 means that some oil and/or gas communication is possible between the OLTC compartment and the main tank or between the respective conservators. Gases produced in the OLTC compartment can contaminate the oil in the main tank and affect concentration values in these types of equipment. "No OLTC" refers to transformers not equipped with an OLTC, or equipped with a tap changer not communicating with or not leaking to the main tank.

Typical values in Table A.2 apply to both breathing and sealed transformers, and correspond mostly to core-type transformers. Values in shell-type transformers are likely to be higher. In two countries, values for C_2H_6 are higher. In one country where transformers are operated below nominal load, values for CH_4 and CO and particularly for C_2H_4 are lower. In one country, values of 0,5 µl/l for C_2H_2 and 10 µl/l for C_2H_4 are reported. Values for H_2 can be higher in transformers where reactions between oil and transformer components (paints, metals) are occurring. Values in transformers frequently degassed, a practice used in a few countries, should not be compared with values of Table A.2.

A.2.5 Typical rates of gas increase

Clause A.1 (General warning), shall be consulted before applying A.2.5.

Ranges of 90 % typical rates of gas increase observed in power transformers, from four electrical networks and including more than 20 000 DGA analyses, are given in Table A.3. These ranges of values have been reported by CIGRE Study Committees D1 and A2 (TF11) and approved by IEC TC 10 and TC 14.

**Table A.3 – Ranges of 90 % typical rates of gas increase
observed in power transformers (all types)**

Values in microlitres per litre per year

	C_2H_2	H_2	CH_4	C_2H_4	C_2H_6	CO	CO_2
All transformers		35 to 132	10 to 120	32 to 146	5 to 90	260 to 1 060	1 700 to 10 000
No OLTC	0 to 4						
Communicating OLTC	21 to 37						

Typical values in Table A.3 are valid for large power transformers with an oil volume > 5 000 l. Values in small transformers (< 5 000 l) are usually lower. Values in the early and late years of the equipment tend to be higher than the average values of Table A.3.

Values of Table A.3 can be converted into ml/day when the transformer oil volume is known. In some countries, it is preferred to express rates of gas increase in ml/day. Values in Table A.3 should not be used to calculate concentration values after several years and compare them to values in Table A.2, since values in these two tables are affected differently by the shape of their respective cumulative curves and gas losses.

When calculating typical rates of increase of individual networks, intervals should be chosen to provide an acceptable accuracy of results.

A.2.6   Specific information to be added to the DGA report

See Clause 10. Specific information to be added to the DGA report is as follows:

- power rating;
- transformer subtype: air-breathing or sealed;
- oil temperature;
- type of cooling system: ONAN (oil natural air natural), OFAF (oil forced air forced), etc.;
- date of manufacturing;
- type of OLTC and whether it is communicating with the main tank or not;
- number of OLTC operations, if known;
- load since last DGA.

NOTE   OLTCs are often composed of a selector switch, located in the oil of the main tank, and of a diverter switch, located in a separate tank but on the same operating axle.

A.3   Industrial and special transformers

A.3.1   Specific subtypes

Specific subtypes of industrial and special transformers are as follows:

- furnace transformers;
- rectifier transformers;
- railway transformers;
- distribution transformers (only industrial and service transformers, below 10 MVA, not from utilities);
- submersible distribution transformers;
- wind turbine transformers (WTTs) installed directly on the wind turbines.

  Collector and step-up transformers connecting WTTs to the grid should be treated in terms of gas formation like the power transformers of Table A.2 and Table A.3.

A.3.2   Typical faults

See Table A.1.

Typical faults in wind turbine transformers depend on their specific types:

- padmount transformers (switchgear in the transformer oil);
- distribution transformers (switchgear outside);
- indoor built at the top of tower, highly thermally stressed due to restricted clearance and proximity of rotating machines and converter;

- indoor built at the base of tower, medium thermal stress;
- outdoor installations, standard thermal stress;
- connected to asynchronous or synchronous generators, since the AC/DC converter can generate severe harmonic disturbances with high impact on dielectric performances.

NOTE   It has been reported in CIGRE Technical Brochure 771 (2019) [2] that faults in wind turbine transformers are mostly of the corona PD and T1 types, sometimes T3.

A.3.3   Identification of faults by DGA

See A.2.3.

A.3.4   Typical concentration values

See Table A.4.

Typical values are highly dependent on the specific type of WTT, as can be seen in Table A.5 and should therefore be calculated accordingly by their users.

The values given in Table A.4 and Table A.5 are for information only. They are not limit values. See Clause A.1.

**Table A.4 – Examples of 90 % typical concentration
values observed on individual networks**

Values in microlitres per litre

Transformer subtype	H_2	CO	CO_2	CH_4	C_2H_6	C_2H_4	C_2H_2
Furnace	200	800	6 000	150	150	200	a
Distribution	100	200	5 000	50	50	50	5
Submersible	86	628	6 295	21	4	6	$< S$ [b]

NOTE   The values listed above were obtained from one particular network. Values on other networks can differ.

[a]   The data are influenced by the design and assembly of the on-load tap-changer. For this reason, no statistically significant value can be proposed for acetylene.

[b] $< S$ means less than the detection limit.

Table A.5 – Ranges of 90 % typical concentration values observed in WTTs

Values in microlitres per litre

Transformer subtype	H_2 [c]	CO	CO_2	CH_4	C_2H_6	C_2H_4	C_2H_2
WTT [a]	1 026 to 5 600	521 to 977	1 592 to 5 173	184 to 788	53 to 162	8 to 47	$< S$ [b] to 5

[a]   90 % typical values in WTTs above have been reported in CIGRE TB 771 [2] in 2019, based on very large numbers of DGA values (thousands +). The ranges reported here were observed in WTTs from four electrical networks (in Europe and North America). For hydrogen, for example, one network reported a typical value of 1 026 µl/l, another one 5 600 µl/l and the two other reported values between 1 026 µl/l and 5 600 µl/l. In the reported ranges, values of distribution-type transformers are usually lower than values of padmount-type transformers. Owing to the wide variability of observed 90 % typical concentrations, it is highly recommended to each utility to calculate its own values, considering the homogeneity of the population and the observed failure rate.

[b] $< S$ means less than the detection limit.

[c]   Hydrogen values obtained statistically can be due to the high electrical stress (transients and harmonics) to which those units are exposed. For this reason, the values for hydrogen can be considered "typical" for statistical purposes, but they could not be inherently attributable to fault absence. Available experience worldwide on wind turbine units is not sufficiently large, yet, to define which statistical values can be considered as fault-free.

A.4   Instrument transformers

A.4.1   Specific subtypes

CT: Current transformers (eyebolt or hairpin design);

VT: Voltage transformers;

CTCV: Combined transformers (current-voltage);

CIVT: Cascade (inductive) voltage transformers;

CVT: Capacitor voltage transformers;

MVT: Magnetic voltage transformers (see [8]).

NOTE   Definitions of these specific subtypes can be found in [9].

A.4.2   Typical faults

See Table A.6.

Failure rates have been reported as being about 1 % of the total population (see [8]), although much higher rates were observed on a limited number of subgroups.

The most frequent final failures involve local or catastrophic dielectric breakdown of paper insulation, following lengthy partial discharge activity and/or thermal runaways.

Table A.6 – Typical faults in instrument transformers

Type	Fault	Examples
PD	Partial discharges	Discharges in gas-filled cavities resulting from poor impregnation, humidity in paper, oil supersaturation, puckers or folds in paper, leading to X-wax deposition and increased dielectric losses Discharges related to switching operations from a nearby substation bus system (in the case of CTs) or to overvoltages at the edges of capacitor unit sections (case of CVTs)
D1	Discharges of low energy	Sparking around loose connections or floating metal strips Tracking in paper Arcing in static shielding connections
D2	Discharges of high energy	Local short circuits between capacitive stress grading foils, with high local current densities able to melt down foils General short circuits with power follow-through are often destructive, resulting in equipment breakage or explosion, and a DGA is not always possible after failure
T2	Thermal fault $300\ °C < t < 700\ °C$	Circulating currents in paper insulation resulting from high dielectric losses, related to X-wax contamination, moisture or incorrect selection of insulating materials, and resulting in dielectric heating and thermal runaways Bad contacts in connections or welds Overheating due to the ferroresonant circuit in MVTs
T3	Thermal fault $t > 700\ °C$	Circulating currents on steel lamination edges

A.4.3   Identification of faults by DGA

Table 1 (see 5.4) applies to all subtypes, with CH_4/H_2 lower than 0,2 instead of lower than 0,1 for partial discharges.

A.4.4   Typical concentration values

Ranges of 90 % typical values observed in instrument transformers are given in Table A.7. The 90 % normality percentage is the most frequently used. Factors of influence are equipment subtype, fault type, and age.

The values given in Table A.7 are for information only.

**Table A.7 – Ranges of 90 % typical concentration
values observed in instrument transformers**

Values in microlitres per litre

Transformer subtype	H_2	CO	CO_2	CH_4	C_2H_6	C_2H_4	C_2H_2
CT	6 to 300	250 to 1 100	800 to 4 000	11 to 120	7 to 130	3 to 40	1 to 5
VT	70 to 1 000					20 to 30	4 to 16

NOTE 1   The values listed in this table were obtained from several networks. Values on other networks can differ.

NOTE 2   The value for H_2 in CTs is much lower for rubber seals (±20 µl/l) than for metal seals (±300 µl/l).

Table A.8 provides the maximum admissible values for sealed instrument transformers without any action to be taken on the transformer, which have been proposed by IEC TC 38.

Table A.8 – Maximum admissible values for sealed instrument transformers

Values in microlitres per litre

H_2	CO	CO_2	CH_4	C_2H_6	C_2H_4	C_2H_2
300	300	900	30	50	10	2

A.5   Oil-impregnated paper bushings

A.5.1   Specific subtypes

Specific subtypes of bushings are as follows:

– capacitance graded;
– non-capacitance graded.

A.5.2   Typical faults

See Table A.9.

In a number of instances, partial discharges result in increased dielectric losses, thermal runaway and final breakdown.

Most frequent final failures are related to the breakdown of core insulation between short-circuited layers (as a result of partial discharges or thermal runaway), flashovers along the internal surface of the porcelain (often resulting in explosions) and flashovers along the core surface.

Table A.9 – Typical faults in bushings

Type	Fault	Examples
PD	Partial discharges	Discharges in gas-filled cavities resulting from humidity in paper, poor impregnation, oil supersaturation or contamination, or X-wax deposition. Also in loose insulating paper displaced during transportation with puckers or folds in paper
D1	Discharges of low energy	Sparking around loose connections at capacitive tap Arcing in static shielding connections Tracking in paper
D2	Discharges of high energy	Localized short-circuits between capacitive stress grading foils, with high local current densities able to melt down foils (see definition of D2 in 5.3), but not leading to the explosion of the bushing
T2	Thermal fault 300 °C < t < 700 °C	Circulating currents in paper insulation resulting from high dielectric losses, related to contamination or improper selection of insulating materials, and resulting in thermal runaways Circulating currents in poor connections at bushing shield or high voltage lead, with the temperature transmitted inside the bushing through conduction by the conductor

A.5.3   Identification of faults by DGA

A simplified table of interpretation is proposed as shown in Table A.10.

Table A.10 – Simplified interpretation scheme for bushings

Fault	$\dfrac{C_2H_2}{C_2H_4}$	$\dfrac{CH_4}{H_2}$	$\dfrac{C_2H_4}{C_2H_6}$	$\dfrac{CO_2}{CO}$
PD		< 0,07		
D	> 1			
T			> 1	
TP				< 1, > 20

NOTE 1   The ratio C_2H_2/H_2 > 1 can be used as an indication of high energy discharge.

NOTE 2   A ratio of $H_2/ \Sigma C_nH_m$ > 30 (n = 1, 2; m = 2, 4, 6) can indicate generation of hydrogen caused by non-fault related chemical reactions and it is possible it does not indicate an electrical failure.

In cases where a single characteristic fault cannot be attributed using this simplified table, or when a more precise diagnosis is required, the general Table 1 should be used.

NOTE 3   Some modern bushings contain mixtures of mineral oil and dodecylbenzene (DDB), in proportions not known. Gas compositions evolved from DDB are not the same as from mineral oil, and DDB absorbs more gas than mineral oil.

A.5.4   Typical concentration values

The following ranges of 90 % typical values are proposed.

The values given in Table A.11 are for information only. They are not limit values, see Clause A.1. Typical values are highly dependent on the type and age of bushings, as can be seen in Table A.11, and should therefore be calculated accordingly by their users.

Table A.11 – Ranges of 90 % typical concentration values in bushings

<div align="right">Values in microlitres per litre</div>

H$_2$	CO	CO$_2$	CH$_4$	C$_2$H$_6$	C$_2$H$_4$	C$_2$H$_2$
69 to 392	229 to 927	484 to 11 578	37 to 216	17 to 121	2 to 70	< S[a] to 5
[a] < S means less than the detection limit.						

NOTE 1 Ranges of values in Table A.11 were observed in three different countries and reported in CIGRE Technical Brochure 771 [2] in 2019. See this technical brochure for details and references. Within these ranges are values from a large European utility, based on 992 DGA results from oil/air bushings, and on 1 442 DGA results from oil/sulphur hexafluoride bushings, operated at 400 kV.

Statistically obtained typical values can be influenced by the irregular sampling frequency to which bushings are usually subjected; the common practice of many utilities does not include bushings' oil sampling on a regular time base. Often the sampling is largely more frequent on bushings belonging to families where fault conditions were already observed; this can alter the normality of the population leading to the overestimation of typical values.

NOTE 2 In case of corona PDs and stray gassing of oil, very high values of H$_2$ have been observed in some countries without failure of the bushing (see CIGRE Technical Brochure 771 [2] and Note 5 below). Evaluation of such exceptional cases by appropriate experts is preferred, as some of these high values can have incipient faults. The ratio of oil to paper in oil impregnated bushings is different to that of transformers, and absolute levels are therefore not directly comparable.

NOTE 3 Condition assessment of bushings consists of a consolidation of information on type and performance of the product, voltage, age, routine test information, service conditions, application, previous events in the grid, dissipation factor and capacitance as well as the rate of changes for all parameters. It has been concluded lately that in particular the type of application is of high importance to the generation of hydrogen, see CIGRE Technical Brochure 771 [2].

NOTE 4 It has been reported by L. Jonsson et al. in [10] that reactor bushings generate more hydrogen. Secondly, the nature and presence of X-wax in bushings was thoroughly described in [11].

NOTE 5 Preferred for actions on bushings are Clause 9 and Figure 1, using the typical concentration values of Table A.11 for bushings (particularly for C$_2$H$_2$), Table A.10 rather than Table 1 for the identification of faults in bushings, the alarm and alert values for bushings versus type of fault of CIGRE Technical Brochure 771 [2]. Also preferred for any actions on bushings are appropriate engineering judgment and contacting the bushings manufacturer for advice, particularly in cases of discharges D in Table A.10.

A.6 Oil-filled cables

A.6.1 Typical faults

Discharges and hot spots at cable terminations or junctions.

A.6.2 Identification of faults by DGA

Table 1 applies.

DGA is difficult to apply in cables due to the lack of representative oil samples (sampling sometimes possible only a long distance from the fault; lack of oil convection; gas trapped in paper insulation).

Also, modern cables often contain mixtures of mineral oil and dodecylbenzene (DDB), in proportions not known. Gas compositions evolved from DDB are not the same as from mineral oil, and DDB absorbs more gas than mineral oil under electric stress.

A.6.3 Typical concentration values

The values given in Table A.12 are for information only.

The data come from one particular network and only 95 % values are available. The following 95 % typical concentration values have been observed on cables.

Table A.12 – Ranges of 95 % typical concentration values observed on cables

H_2	CO	CO_2	CH_4	C_2H_6	C_2H_4	C_2H_2
150 to 500	40 to 100	220 to 500	5 to 30	10 to 25	3 to 20	2 to 10

NOTE   These values are examples taken from one particular network. Values on other networks and with different types of cable designs can differ.

A.7   Switching equipment

A.7.1   Specific subtypes

Specific subtypes of switching equipment are as follows:

– on-load tap-changers (OLTCs) (vacuum and non-vacuum), including selector switches;

– switchgear.

A.7.2   Normal operation

The large majority of non-vacuum on-load tap-changers (OLTCs) of the reactive or resistive type produce gases of the arcing type D1 or D2 during their normal operation, because of the arc-breaking-in-oil activity on the switching contacts. Change-over selector contacts or commutation contacts of vacuum type models can produce low amounts of D1 gases.

Some vacuum or non-vacuum resistive type models can produce T2 or T3 gas patterns, respectively under certain load conditions, not indicating any thermal irregularities.

A.7.3   Typical faults

See Table A.13.

Table A.13 – Typical faults in switching equipment

Type	Fault	Examples
D1	Discharges of low energy	Normal operation of OLTCs, selectors Arcing on off-load selector switch ring, OLTC connections
D2	Discharges of high energy	Switch contacts do not reach their final position but stop halfway, due to a failure of the rotating mechanism, inducing a sparkover discharge Arcing on off-load selector switch ring, OLTC connections, of high energy or with power follow-through, with failure often transmitted to transformer windings
T2, T3	Thermal fault	Increased resistance between contacts of OLTC or change-over selector, as a result of pyrolitic carbon growth, selector deficiency or a very large number of operations Transition resistor temperatures > 700 °C due to faulty (prolonged) switching sequence

NOTE 1   In this table are given examples of faults detected by DGA of oil samples taken from the switching compartment.

NOTE 2   Switching equipment attached to transformers is complex and of various designs. The detailed description of these systems and the interpretation of DGA results can be obtained from the equipment manufacturer, particularly concerning the types of discharges and degree of heating that is normal for the specific equipment.

A.7.4   Identification of faults by DGA

Two methods are used for the identification of faults in OLTCs:

1) The C_2H_4/C_2H_2 ratio represents an individual fingerprint of the application. It is up to users to define ratio value ranges for normal operation, depending on the OLTC model and operation mode. Deviations of the found range indicate irregularities.

2) The Duval-triangle-2 method (see Annex B): for the large majority of OLTCs, normal operation will show coordinates in the "N" zone. Nevertheless, some applications will show coordinates in the X3, T2 or T3 zone for normal operation [13], as described in A.7.2. As long as coordinates do not move significantly, these fingerprints do not indicate a fault. With this, the triangle method can be used to track the evolution of gas formation graphically to detect excessive arcing or heating.

NOTE   All DGA interpretations for OLTC are strongly model type and operation dependent. In case of suspect DGA results, the manufacturer is contacted.

## A.8   Equipment filled with non-mineral fluids

Gases formed in equipment filled with non-mineral fluids (natural esters, synthetic esters, silicones) are the same as with mineral oils, however, some adjustments to zone boundaries used for mineral oils are necessary to identify faults in non-mineral oils, as indicated in [5].

Examples of typical values observed with such fluids are also indicated in [5].

Annex B
(informative)

Graphical representations of gas ratios

See 5.10. Graphical representations of gas ratios are given in Figure B.1, Figure B.2, Figure B.3 and Figure B.4.
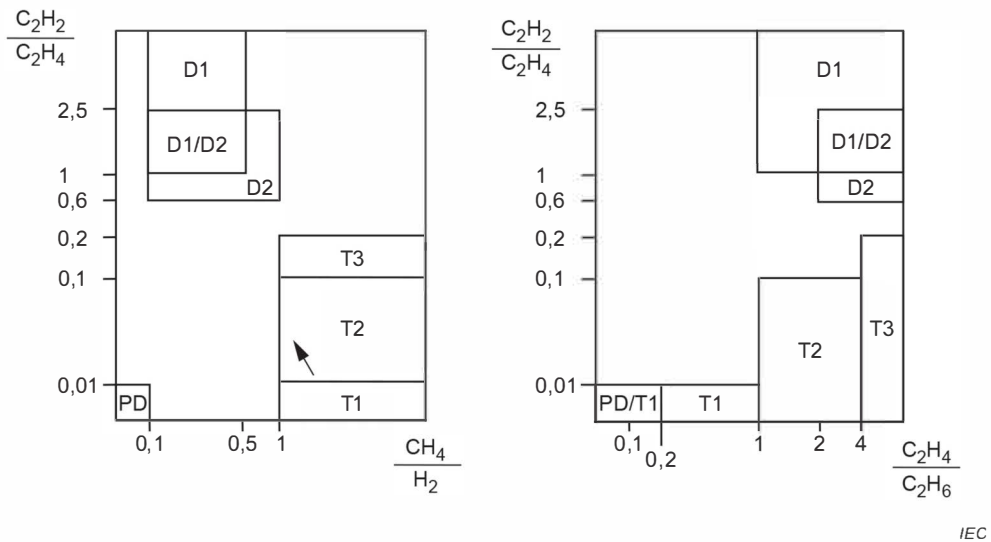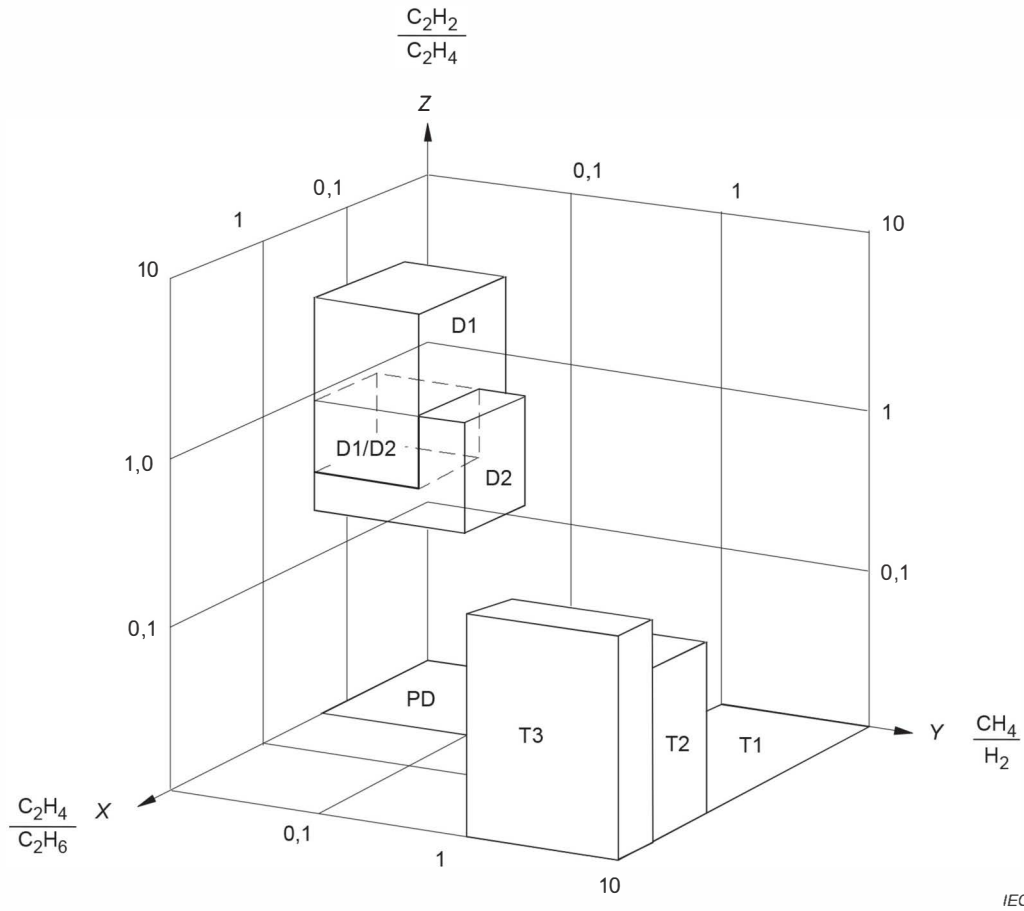

Key

PD　partial discharges

D1　discharges of low energy

D2　discharges of high energy

T1　thermal fault, t < 300 °C

T2　thermal fault, 300 °C < t < 700 °C

T3　thermal fault, t > 700 °C

NOTE 1　The arrow indicates increasing temperature.

NOTE 2　The axes are limited to values of 10 for clarification of presentation, but actually extend to unlimited values. The coordinates of each zone are the same as in Table 1 and Figure B.2.

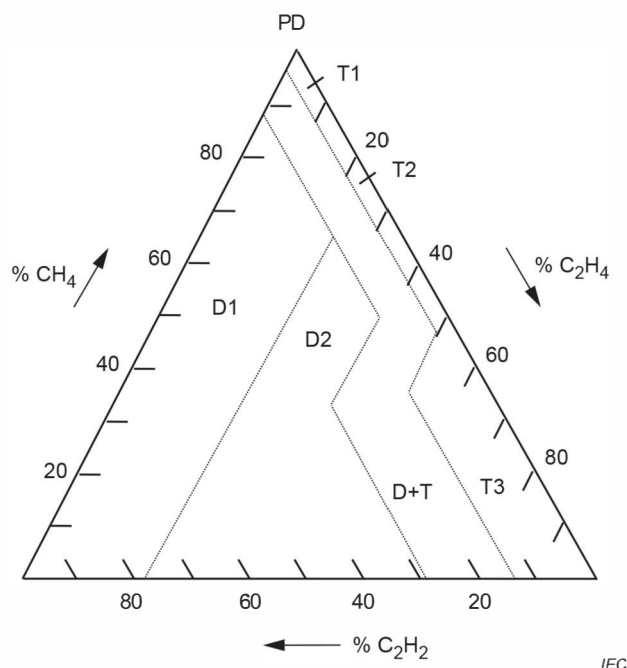**Figure B.1 – Graphical representation 1 of gas ratios**

Key

PD   partial discharges

D1   discharges of low energy

D2   discharges of high energy

T1   thermal fault, $t < 300\ °C$

T2   thermal fault, $300\ °C < t < 700\ °C$

T3   thermal fault, $t > 700\ °C$

NOTE 1   Each of the cases defined in Table 1 is represented by a volume or "box" on the 3-D graphic.

NOTE 2   The coordinates of each box are the same as in Figure B.1 and Table 1. It is more convenient to use this representation with the help of a computer software package.

Figure B.2 – Graphical representation 2 of gas ratios

where

$$\%C_2H_2 = \frac{100x}{x+y+z}$$ for x = [C_2H_2] in microlitres per litre

$$\%C_2H_4 = \frac{100y}{x+y+z}$$ for y = [C_2H_4] in microlitres per litre

$$\%CH_4 = \frac{100z}{x+y+z}$$ for z = [CH_4] in microlitres per litre

**Key**

PD   partial discharges

D1   discharges of low energy

D2   discharges of high energy

T1   thermal fault, t < 300 °C

T2   thermal fault, 300 °C < t < 700 °C

T3   thermal fault, t > 700 °C

Limits of zones				
PD	98 % CH_4			
D1	23 % C_2H_4	13 % C_2H_2		
D2	23 % C_2H_4	13 % C_2H_2	40 % C_2H_4	29 % C_2H_2
T1	4 % C_2H_2	20 % C_2H_4		
T2	4 % C_2H_2	20 % C_2H_4	50 % C_2H_4	
T3	15 % C_2H_2	50 % C_2H_4		

SOURCE: Reference [12], reproduced with the permission of the authors.

**Figure B.3 – Graphical representation 3 of gas ratios –
Duval's triangle 1 for transformers, bushings and cables**
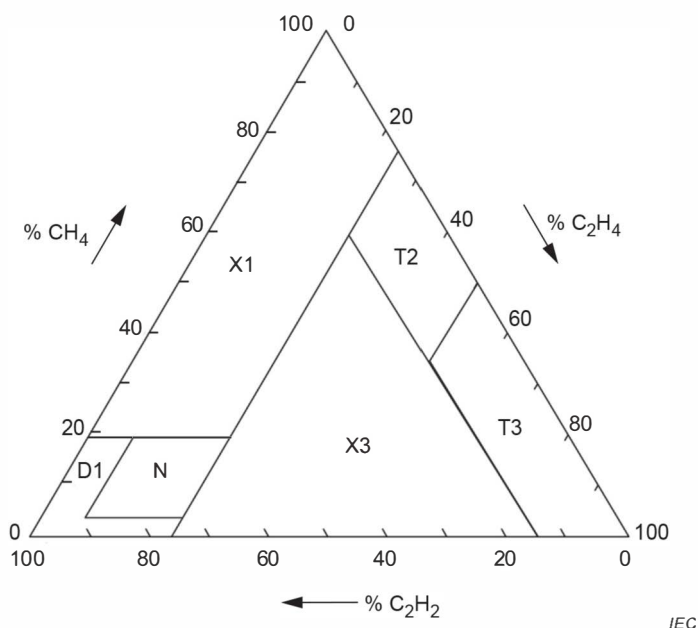
Key

N   normal operation

T3 severe coking of contacts at t > 700 °C

T2 severe coking of contacts at t > 300 °C

X3 coking in progress or abnormal arcing D2

D1 abnormal arcing D1

X1 overheating at t < 300 °C

NOTE   See Figure B.3 for calculation of triangular coordinates.

	Limits of zones			
N	19 % CH_4	23 % C_2H_4	2 % CH_4	6 % C_2H_4
T3	50 % C_2H_4	15 % C_2H_2		
X3	23 % C_2H_4	15 % C_2H_2		
T2	23 % C_2H_4	15 % C_2H_2		
D1	19 % CH_4	6 % C_2H_4	2 % CH_4	23 % C_2H_4
X1	19 % CH_4	23 % C_2H_4		

SOURCE: Reference [13], reproduced with the permission of the authors.

**Figure B.4 – Graphical representation 4 of gas ratios –
Duval's triangle 2 for OLTCs (see A.7.2)**

NOTE   For some OLTCs mentioned in A.7.2 and A.7.3, normal gassing occurs either in zone N, T3, T2 or X3, depending on specific OLTCs models and operating conditions [13].

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