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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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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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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:

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

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