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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 – Lignes directrices pour l'interprétation de l'analyse des gaz dissous et des gaz libres

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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

FOREWORD

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

This third edition cancels and replaces the second edition published in 1999 and Amendment 1:2007. This edition constitutes a technical revision.

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

a) revision of 5.5, 6.1, 7, 8, 9, 10, A.2.6, A.3, A.7;
b) addition of new sub-clause 4.3;
c) expansion of the Bibliography;
d) revision of Figure 1;
e) addition of Figure B.4.

The text of this standard is based on the following documents:

FDIS	Report on voting
10/967/FDIS	10/973/RVD

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

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication 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- withdrawn,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 International Standard 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 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 International Standard describes how the concentrations of dissolved gases or free gases may be interpreted to diagnose the condition of oil-filled electrical equipment in service and suggest future action.

This standard 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 (see Annex A).

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

In any case, the indications obtained should be viewed only as guidance and any resulting action should be undertaken only with proper engineering judgment.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050-191:1990, *International Electrotechnical Vocabulary – Chapter 191: Dependability and quality of service* (available at http://www.electropedia.org)

IEC 60050-192:2015, *International Electrotechnical Vocabulary – Part 192: Dependability* (available at http://www.electropedia.org)

IEC 60050-212:2010, *International Electrotechnical Vocabulary – Part 212: Electrical insulating solids, liquids and gases* (available at http://www.electropedia.org)

IEC 60050-604:1987, *International Electrotechnical Vocabulary – Chapter 604: Generation, transmission and distribution of electricity – Operation* (available at http://www.electropedia.org)

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 abbreviations

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions, some of which are based on IEC 60050-191, IEC 60050-192, IEC 60050-212 and IEC 60050-604, apply.

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

[SOURCE: IEC 60050-604:1987, 604-02-01]

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.

[SOURCE: IEC 60050-604:1987, 604-02-09]

3.1.3
damage fault

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

[SOURCE: IEC 60050-604:1987, 604-02-08]

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 the present standard “incidents” are related to internal faults.

Note 2 to entry: For the purposes of the present standard typical examples of “incidents” are gas alarms, equipment tripping or equipment leakage.

[SOURCE: IEC 60050-604:1987, 604-02-03]

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.

[SOURCE: IEC 60050-192:2015, 192-03-01]

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 standard the following consideration may 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.

[SOURCE: IEC 60050-212:2010, 212-11-39]

3.1.8

discharge (disruptive)

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.

[SOURCE: IEC 60050-604:1987, 604-03-38]

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 % (see 8.2.1))

Note 1 to entry: Typical values will differ in different types of equipment and in different networks, depending on operating practices (load levels, climate, etc.).

Note 2 to entry: Typical values, in many countries and by many users, are quoted as "normal values", but this term has not been used here to avoid possible misinterpretations.

3.2 Abbreviations

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 abbreviations

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 may 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 may 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 needed 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). 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/decomposition gases in between. Acetylene may 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 may 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 [6][1] as the formation of gases in oil heated to moderate temperatures (<200 °C). H_2, CH_4 and C_2H_6 may 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 reference [6] and [12].

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

Hydrogen may 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 may 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 may also be formed in new stainless steel, absorbed during its manufacturing process, or produced by welding, and released

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[1] Numbers in square brackets refer to the Bibliography.

slowly into the oil. Internal transformer paints, such as alkyd resins and modified polyurethanes containing fatty acids in their formulation, may also form gases.

Gases may 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, may 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/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/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 or/and 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 not be easy to find;
- discharges of high energy (D2), in oil or/and 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 or/and 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).