



# Power Transformer Fault Diagnosis via Gas Chromatography: A Comprehensive Review of Techniques and Standards

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## Abstract

Gas Chromatography (GC) serves as a pivotal technique for the detection and diagnosis of faults in oil-immersed power transformers (OIPTs). This method relies on the identification and analysis of the gases dissolved in insulating oil, which are produced because of the degradation of insulating materials under thermal and/or electrical stresses. Key fault indicators such as hydrogen, methane, ethylene, ethane, and acetylene are separated and accurately quantified using GC equipment. The qualitative and quantitative analysis of these gases facilitates the precise identification of various fault types and severities, including partial discharge, overheating, and electrical arcing. Due to its high sensitivity, accuracy, and capability for early fault detection, GC is widely employed in preventive maintenance programs within the electricity industry to enhance the OIPTs reliability and prolong their operational lifespan. This paper offers a comprehensive review of established methods for gas chromatography and, through an examination of prior research, aims to propose standardized approaches and diagnostic criteria for accurate fault detection in the OIPTs.

**Keywords:** Gas chromatography, Dissolved gases analysis, Condition monitoring, Oil-immersed power transformer

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## Nomenclature

Symbol/Term	Description	D1, D2 R <sub>1</sub> , R <sub>2</sub> , R <sub>3</sub> , R <sub>4</sub> Duval Triangle/Pentagon FID TCD ECD	Low and high energy discharge faults, respectively Ratios of key gases used in fault diagnosis Graphical tools for fault diagnosis using gas concentration ratios Flame Ionization Detector Thermal Conductivity Detector Electron Capture Detector
GC	Gas Chromatography		
OIPT	Oil Immersed Power Transformer		
H <sub>2</sub>	Hydrogen		
CH <sub>4</sub>	Methane		
C <sub>2</sub> H <sub>2</sub>	Acetylene		
C <sub>2</sub> H <sub>4</sub>	Ethylene		
C <sub>2</sub> H <sub>6</sub>	Ethane		
CO	Carbon Monoxide		
CO <sub>2</sub>	Carbon Dioxide		
DGA	Dissolved Gas Analysis		
IEEE C57.104	Standard for the interpretation of dissolved gases in transformer oil		
TDCG	Total Dissolved Combustible Gas		
Symbol/Term	Description		
PD	Partial Discharge		
T1, T2, T3	Thermal faults classified by temperature ranges (<300°C, 300–700°C, >700°C respectively)		

## 1. INTRODUCTION

Analyzing dissolved gases in the oil of the OIPTs is a crucial method for detecting faults in them. GC technique involves examining the combustible gases dissolved in the oil, which are identified and quantified using gas chromatography tests. These analyses provide valuable insights into the condition of the OIPTs in operation, allowing for early detection of faults and monitoring their development [1-8]. The faults in the OIPTs are identified in a timely manner using this method, allowing us to address issues before they cause significant damage. This proactive approach helps ensure that the OIPTs operate without interruption and their service life is extended. The frequency of the GC tests for monitoring the transformer conditions depends on

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several factors, including the type of equipment, operating conditions, and organizational maintenance policies. Generally, GC tests may be performed in several intervals as follows [9-10]:

- **Monthly or Quarterly:** For advanced monitoring systems and OIPTS operating under high stresses or in critical conditions, gas analysis may be scheduled monthly or quarterly. This approach ensures meticulous monitoring of equipment health and early detection of changes in gas patterns that could indicate potential faults.
- **Every Six Months:** For many OIPTS, a six-month interval for GC analysis is a common practice within preventive maintenance programs. This schedule is designed to maintain equipment reliability, prevent severe failures, and identify changes in gas composition to address potential issues promptly.
- **Annually:** GC analysis may be performed annually in cases where equipment operates under stable conditions with a lower incidence of faults. This approach is suited for routine maintenance programs and less stressful environments, providing sufficient insight into the equipment's condition.
- **As Needed or in Emergencies:** Some organizations may apply GC analysis only when abnormal situations or specific events occur, such as a sudden temperature rise or frequent failures. This strategy is used in emergency situations or following significant issues that require detailed analysis and immediate intervention.

The frequency of GC analysis for transformer oil should be determined by a combination of several factors, including risk assessments, environmental conditions, and the specific needs of the transformer and its monitoring system. Risk assessments play a key role in deciding how often GC analysis should be performed. The likelihood of faults and the potential consequences of failure are critical. For instance, transformers in high-risk environments, such as those with high loads or critical applications, may require more frequent monitoring. Additionally, older transformers or those with a history of previous faults may need more regular analysis [11-12].

Environmental conditions also significantly influence the frequency of analysis. Transformers located in harsh environments—such as areas with high humidity, extreme temperatures, or industrial pollution—are subject to greater stress and accelerated aging, which can lead to an increased risk of faults. In such cases, more frequent GC analysis is necessary to ensure the early detection of any

developing issues. Similarly, transformers exposed to extreme weather conditions or regions prone to electrical surges may require additional monitoring due to the possible impacts of these environmental factors on the transformer's health. The specific needs of the equipment should also be taken into account. Larger and more critical transformers typically require more frequent analysis to ensure their reliability and to detect faults at an early stage. Additionally, the type of monitoring equipment used—such as advanced online monitoring systems or traditional manual sampling—can influence the frequency. Automated systems with real-time data collection can reduce the need for frequent sampling, while less advanced systems may necessitate more regular analysis to maintain accurate fault detection. Ultimately, the frequency of GC analysis should be customized based on these factors, ensuring that monitoring is optimized to detect faults early without unnecessary procedures. This approach helps improve transformer reliability, optimize maintenance schedules, and reduce the risk of unexpected failures [13-15].

To ensure the accuracy and reliability of the GC results, it is crucial that sample preparation, instrument performance, and data analysis are conducted with high precision, and the results are compared against established standards and reference methods [16-19].

The GC analysis is widely used for identifying and analyzing various internal faults in the OIPTS. This method is particularly effective in detecting the following issues:

- **Partial Discharge:** Partial discharge involves localized electrical sparks within the insulation and generates gases like  $H_2$  and  $C_2H_4$ . A high hydrogen-to-other-gas ratio in the oil often indicates partial discharge [20].
- **Electrical Arc:** Electrical arcs result from continuous and intense sparking, producing gases such as  $C_2H_2$  and  $C_2H_4$ . A high acetylene-to-other-gas ratio typically points to an electrical arc. Weak discharges, including partial discharges and low-energy intermittent arcs, generate more hydrogen, less methane, and minimal acetylene. Intense discharges transitioning to continuous arcs in temperatures ranging from  $700^{\circ}C$  to  $1800^{\circ}C$  produce significant amounts of acetylene [21].
- **Overheating:** Overheating of the insulation leads to the formation of gases like  $C_2H_4$  and  $C_2H_6$ . A high ethylene-to-methane and ethane ratio usually signals overheating [22].

- **Thermal Decomposition:** Thermal decomposition caused by high temperatures can generate gases such as methane, ethylene, and ethane. Variations in the ratios of these gases can help identify the type of thermal decomposition. Decomposition of oil at temperatures between 150°C to 500°C produces significant amounts of low molecular weight gases like hydrogen and methane, while generating only small quantities of higher molecular weight gases such as ethylene and ethane. As the fault temperature increases to moderate levels, hydrogen becomes more prevalent than methane, and the concentrations of higher molecular weight gases also rise, including acetylene. In contrast, the thermal decomposition of cellulose occurs at much lower temperatures, producing CO, CO<sub>2</sub>, and water vapor. During normal operating conditions, hundreds of ppm of CO and thousands of ppm of CO<sub>2</sub> can be generated. The CO/CO<sub>2</sub> ratio is often used as an indicator of paper thermal decomposition, with a typical ratio greater than 7 considered reliable if CO<sub>2</sub> and CO levels exceed 5000 and 500 ppm, respectively [23].
- **Chemical Decomposition:** Chemical decomposition, resulting from chemical reactions within the oil, can produce gases such as CO<sub>2</sub> and CO. A higher ratio of CO<sub>2</sub> to CO is typically an indicator of chemical decomposition [24].
- **Insulation Failure:** Insulation failure indicates the loss of insulating properties, leading to abnormal levels of gases like hydrogen and ethylene. An increase in these gases can signal issues with the insulation [25].
- **Excessive Pressure:** Excessive pressure within the transformer can result in the production of gases such as hydrogen and methane. Analyzing the ratios of these gases provides insights into pressure conditions and potential mechanical issues [26-27].

In the process of analyzing dissolved gases in the transformer oil using GC, a series of precise and specialized steps are undertaken to separate and identify different gases. This is crucial for assessing the insulation condition and detecting internal faults within the OIPTs.

First, oil sampling is conducted following strict standards to prevent contamination and unauthorized changes in the gas composition. Proper sampling is vital to ensure the accuracy of the analysis results. After collecting the sample, the preparation process involves removing suspended particles and adjusting the sample volume to make it ready for analysis. This

preparation stage may include filtration and other pre-conditioning techniques to ensure the sample is in optimal condition for the GC analysis [28-29].

In the next step, the dissolved gases in the oil are subjected to heat to facilitate their evaporation and separation from the oil. This process typically takes place in an evaporator device, where the gases are extracted from the oil and then transferred to the GC system, where the gas absorption is achieved through a bubbling technique, while Argon gas is injected to separate the dissolved gases. The inert carrier gas, Argon, is used to carry H<sub>2</sub>, O<sub>2</sub>, N<sub>2</sub>, and CH<sub>4</sub> through the system, while another inert gas, such as Helium, acts as the second carrier gas to transport other dissolved gases like C<sub>2</sub>H<sub>4</sub>, C<sub>2</sub>H<sub>6</sub>, C<sub>3</sub>H<sub>8</sub>, C<sub>3</sub>H<sub>6</sub>, CO<sub>2</sub>, and CO [30].

It is important to note that to extract the gas from the oil, the oil is placed in a vacuum chamber with a specific volume, and the separated gases are then pressurized to reach one atmosphere. The volume of the gas is measured, and the type of gas is identified using an absorption spectrum detector based on photoionization. These detectors convert changes in the physical or chemical properties of the gases into measurable signals. The data obtained is processed by chromatography analysis software, producing chromatograms that display gas retention times and the areas under the curves, which are used for qualitative and quantitative analysis [31].

Finally, the analyzed results are compared with reference standards to identify and evaluate the types and concentrations of gases present. This analysis is crucial for detecting OIPTs internal issues and accurately assessing the condition of their insulation. The precise and regular execution of these steps is essential for achieving valid and reliable results in the GC analysis approach [32].

## 2. Equipment for GC Analysis

As mentioned before, GC is a critical technique for analyzing dissolved gases in transformer oil. It is widely used to identify and quantify gases, such as H<sub>2</sub>, CH<sub>4</sub>, C<sub>2</sub>H<sub>4</sub>, C<sub>2</sub>H<sub>2</sub>, and others, which can indicate specific fault types within a transformer. To perform accurate and reliable DGA, high-quality GC equipment and associated detectors are essential. Below is an overview of the key equipment used in GC analysis for transformer oil:

### 2.1. Gas Chromatographs (GC Units)

Gas chromatographs are the core equipment used in the analysis of dissolved gases. These devices separate and identify different gas components in a mixture, based on their interaction with a stationary phase inside a column. Some of the most commonly used GC units include [33-34]:

- **Agilent Technologies 7890B GC System:** This high-performance gas chromatograph is widely used in DGA for transformer oil analysis. The 7890B offers superior sensitivity, precision, and high-speed data acquisition, which are essential for detecting low-concentration gases in transformer oil. Its flexibility allows for simultaneous analysis of multiple gases using various detectors.
- **Thermo Fisher Scientific TRACE 1300 Series:** Known for its reliability and accuracy, the TRACE 1300 Series offer fast response times, high sensitivity, and robustness in multi-gas analysis. It is commonly used in laboratories for routine DGA testing due to its user-friendly interface and high throughput capabilities.
- **PerkinElmer Clarus 590 GC:** This advanced GC system is designed for both qualitative and quantitative analysis, providing excellent separation of gases and high repeatability. It is suitable for DGA, where the rapid analysis of multiple samples is often required, ensuring precise monitoring of transformer health.

## 2.2. Detectors

The selection of detectors is crucial in determining the sensitivity and specificity of gas detection. Several types of detectors are commonly used in GC analysis for DGA [35-37]:

- **TCD:** The TCD is one of the most widely used detectors in DGA because of its ability to detect a broad range of gases, particularly those with different thermal conductivities compared to the carrier gas. It is especially useful for detecting gases like hydrogen, methane, and ethylene in low concentrations. TCD is favored in cases where the measurement of multiple gases with varying properties is necessary.
- **FID:** The FID is highly sensitive to hydrocarbons, particularly ethylene and acetylene, which are key indicators of high-temperature thermal faults or electrical discharges. This detector is frequently used when analyzing organic compounds due to its high sensitivity and low detection limits.
- **ECD:** The ECD is sensitive to electronegative gases such as halogenated compounds but is also used in DGA for detecting gases like acetylene. It provides excellent sensitivity for low-concentration gases and is often used in high-resolution DGA analysis to ensure precise fault detection.

## 2.3. Sample Preparation Equipment

Proper sample collection and preparation are essential for ensuring accurate DGA results. The following equipment is commonly used for preparing oil samples for GC analysis [38]:

- **Headspace Samplers:** These devices are used to extract gases from the headspace of transformer oil samples. Headspace samplers allow for the collection of dissolved gases without contamination, preserving the integrity of the sample. The gas extracted from the headspace is then injected into the GC for analysis. This method ensures an accurate representation of the dissolved gases in the oil, which is critical for fault detection.
- **Gas Sampling Bags:** Gas sampling bags are used to collect and transport transformer oil samples to laboratories for analysis. These bags are designed to prevent any contamination or loss of volatile gases during transport, ensuring that the sample's dissolved gases remain intact for accurate analysis.

## 2.4. Application and Importance in Transformer Diagnostics

The equipment used for GC analysis plays a vital role in transformer diagnostics. Accurate detection and quantification of dissolved gases enable the identification of potential faults such as partial discharge, thermal faults, and electrical discharges. Real-time data from these instruments can help diagnose issues before they lead to catastrophic failures. Moreover, the ability to analyze a wide range of gases at low concentrations is crucial for the early detection of faults in transformers, preventing costly downtime and damage [39]. In addition, the combination of GC analysis with online condition monitoring systems enhances the diagnostic capabilities of transformer monitoring programs, providing continuous data and enabling proactive maintenance strategies [40].

## 3. Different Methods of Dissolved Gas Analysis in Oil

In this section, we discuss some of the common methods used for evaluating dissolved gases in oil to assess the condition of the OIPTS. The transformers considered in this study operate within the voltage range of 11 kV to 765 kV. This range includes OIPTS commonly used in industrial, transmission, and distribution networks. While the methods discussed in this paper are applicable across this entire voltage spectrum, they are particularly crucial for high-voltage transformers, such as those operating at 110

kV and above, where the risks of insulation failures and potential faults are more significant and their impact more severe. Each of these methods is widely employed in the industry and is recognized as an established technique:

### 3.1. Analysis of Total Dissolved Combustible Gas in Oil

The analysis of TDCG in the oil is a key technique used to assess the condition of lubricating oils and hydraulic fluids. This method focuses on the detection and identification of combustible gases dissolved in the oil, including hydrogen, methane, ethylene, propane, and other similar gases. Table 1 gives the TDCG levels in the oil across four distinct conditions. Below are detailed explanations of the TDCG method according to its four distinct conditions [41-42]:

- Condition 1: Normal Status

If the TDCG levels are below this range, the transformer is considered to be in normal condition. No special inspections are required. However, any increase in the gas concentrations beyond this normal range should be examined more closely.

- Condition 2: Potential for Fault

An increase in the TDCG level compared to its normal levels may cause falling into this condition. This suggests a potential fault in the transformer and a need for more detailed inspections; any significant rise in the TDCG amounts should be carefully examined and analyzed.

- Condition 3: Significant Degradation

When TDCG levels fall within this range, it indicates significant degradation in the oil and/or cellulosic insulation. This suggests the presence of one or more faults in the transformer. A new oil sample should be taken, and a thorough inspection and analysis are necessary to identify and address the issues.

- Condition 4: Severe Degradation

If the TDCG levels fall within this range, it indicates severe degradation of the oil and/or cellulosic insulation. Continued operation could lead to transformer failure. Immediate corrective actions are required, and the transformer may need repair or replacement. It is crucial to stop the operation and conduct a detailed assessment of the condition.

TABLE 1. Levels of dissolved gases in oil across the four conditions

Status	H <sub>2</sub>	CH <sub>4</sub>	C <sub>2</sub> H <sub>2</sub>	C <sub>2</sub> H <sub>4</sub>	C <sub>2</sub> H <sub>6</sub>	CO	CO <sub>2</sub> *	TDCG
1	100	120	35	50	65	350	2500	720
2	101 to 700	121 to 400	36 to 50	51 to 100	66 to 100	351 to 570	2500 to 4000	721 to 1920
3	701 to 1800	401 to 1000	51 to 80	101 to 200	101 to 150	571 to 1400	4001 to 10000	1921 to 4630
4	1800<	1000<	80<	200<	150<	1400<	10 <sup>4</sup> <	<4630

\*Since CO<sub>2</sub> is not flammable, it is not included in the category of combustible gases

### 3.2. IEEE C57.104 Gas Analysis Method

The IEEE C57.104 gas analysis method is intended for evaluating dissolved gases in the OIPT oil and helps assess the insulation condition and performance of the transformers. According to this method, a sample of the transformer oil is collected and its dissolved gases are released using related techniques, first. Then, the gases are subsequently analyzed using analytical tools such as gas chromatography. The results obtained from the gas analysis are interpreted according to the IEEE standards to identify potential issues and make necessary predictions. Finally, based on the analysis results, appropriate corrective actions are taken to improve the condition and performance of the transformer [43-44].

The application of the IEEE gas analysis method for analyzing dissolved gases in the OIPT oil typically involves some tables to facilitate result interpretation. These tables, such as Table 2, include reference gas values and various operational conditions of the transformer.

TABLE 2. Levels of dissolved gases in oil for the IEEE C57.104 gas analysis method

Gas Type	Reference Values (ppm)	Description
H <sub>2</sub>	100-500	Higher values indicate high thermal activity or insulation degradation.
CH <sub>4</sub>	10-50	High values may suggest more severe thermal degradation or insulation problems.
C <sub>2</sub> H <sub>4</sub>	10-100	Indicates degradation of cellulose insulation; high values point to more serious degradation.
C <sub>2</sub> H <sub>6</sub>	10-50	High values typically indicate moderate thermal degradation.

C <sub>3</sub> H <sub>8</sub>	10-20	May suggest more extensive thermal degradation.
C <sub>3</sub> H <sub>6</sub>	1-10	High values point to more severe insulation degradation and thermal activity.
CO	100-500	Higher values can indicate severe degradation of cellulose insulation.
CO <sub>2</sub>	1000-5000	Indicates degradation of cellulose insulation and more intense thermal activity.

### 3.3. Gas Ratios Methods (Dorneneburg and Rogers Methods)

The use of gas ratios for identifying potential faults is an empirical method based on diverse research and industrial work on a large number of transformers. This approach was first established and popularized by Dorneneburg and Rogers and uses key gas ratios from the thermal decomposition of the oil and the cellulose insulation as indicators of the OIPT faults. In the Dorneneburg method, the values of the gas concentrations are determined by comparing them to specific threshold values for the gases (corresponding to the values in state 1 of the TDCG method). However, the Rogers method does not require high concentrations of these gases, although it is recommended that this method only be employed when the gas concentrations in the system exceed a minimum threshold [45-46].

TABLE 3. Dorneneburg ratio method table

Gas Ratios	Standard Value	Description
CO/CO <sub>2</sub>	>0.5	Indicates cellulose degradation
CH <sub>4</sub> /H <sub>2</sub>	>0.1	Indicates oil degradation
C <sub>2</sub> H <sub>6</sub> /C <sub>2</sub> H <sub>4</sub>	>0.1	Refers to both cellulose and oil degradation
C <sub>2</sub> H <sub>4</sub> /CH <sub>4</sub>	Typically >0.5	Indicates oil degradation and degradation resulting from electrical discharges
C <sub>2</sub> H <sub>2</sub> /CH <sub>4</sub>	Typically <0.1	High levels may indicate severe electrical discharges

TABLE 4. Rogers ratio method table

Gas Ratios	Standard Value	Description
CO/CH <sub>4</sub>	>1.0	Indicates cellulose decomposition and the presence of electrical discharges
CO <sub>2</sub> /CH <sub>4</sub>	>1.0	Indicates oil and cellulose decomposition
H <sub>2</sub> /CH <sub>4</sub>	>0.5	Associated with electrical discharges
C <sub>2</sub> H <sub>2</sub> /CO <sub>2</sub>	Typically < 0.1	Indicates the presence of severe electrical discharges
C <sub>2</sub> H <sub>2</sub> /CH <sub>4</sub>	Typically >0.1	High values may indicate the presence of electrical discharges

### 3.4. Gas Ratios According to IEC 60599 Standard

This method uses a combination of gas ratios based on the Rogers method, gas concentration, and gas growth. The IEC 60599 standard specifies six types of faults, which include:

- **Partial Discharge:** This fault can be of the cold plasma (corona) type, which may lead to potential oxide accumulation in paper insulation or of the spark type which causes puncturing of the paper.
- **Low Energy Discharge:** This occurs in the oil and/or paper with signs such as carbonization on the surface and inside the paper or carbon particles in the oil (e.g. in a disconnecter oil).
- **High Energy Discharge:** This occurs in the oil and/or paper with signs including extensive paper degradation and carbonization, metal melting at the beginning and end of the discharge location, extensive carbonization in the oil.
- **Thermal Faults:** If the paper has turned brown, the temperature is less than 300°C. If the paper is carbonized, the temperature is above 300°C.
- **High-Temperature Faults above 700°C:** this include oil carbonization, metal discoloration (at 800°C), and metal melting (above 1000°C).

#### 3.4.1. Fundamental Gas Ratios According to IEC 60599 Standard

Each of the six types of faults can be identified by analyzing the composition of hydrocarbon gases using the dissolved gas analysis table. An example of this analysis is provided in Table 5, which relies on three key ratios [47]:

- C<sub>2</sub>H<sub>2</sub>/C<sub>2</sub>H<sub>4</sub>
- CH<sub>4</sub>/H<sub>2</sub>
- C<sub>2</sub>H<sub>4</sub>/C<sub>2</sub>H<sub>6</sub>

In Table 5, there is an overlap between fault types D1 and D2, meaning that in some cases, the analysis of dissolved gases in oil may need to address both types of faults. The difference between these two faults, which relates to the amount of energy present in the discharge, can affect the extent of potential equipment damage and necessitate different preventive actions. If the gas ratios fall outside the range of Table 5 and a specific fault cannot be inferred from this table, it should be analyzed as a combination of faults or a new fault combined with high background gas levels. In such cases, using Table 6 for approximate separation of partial discharge, discharge, and thermal fault is preferable to not identifying the fault at all.

TABLE 5. Gas ratios and equipment fault types

Fault type	Fault description	C <sub>2</sub> H <sub>2</sub> /C <sub>2</sub> H <sub>4</sub>	CH <sub>4</sub> /H <sub>2</sub>	C <sub>2</sub> H <sub>4</sub> /C <sub>2</sub> H <sub>6</sub>
PD	Partial Discharge	no effect	0.1>	0.2>
D1	Low Energy Discharge	1<	0.1-0.5	1<
D2	High Energy Discharge	0.6-2.5	0.1-1	2<
T1	Thermal Faults Below 300 <sup>o</sup> C	no effect	>1 but has no effect	1>
T2	Thermal Faults Between 300 <sup>o</sup> C and 700 <sup>o</sup> C	0.1>	>1	1-4
T3	Thermal Faults Above 700 <sup>o</sup> C	0.2*>	>1	>4

a) In some countries, instead of the CH<sub>4</sub>/H<sub>2</sub> ratio, the C<sub>2</sub>H<sub>2</sub>/C<sub>2</sub>H<sub>6</sub> ratio is used. Additionally, the thresholds for the ratios may vary slightly in different countries.

b) The ratios mentioned are very important and should only be calculated if at least one of the gases has a concentration that exceeds the normal range.

c) The ratio threshold of CH<sub>4</sub>/H<sub>2</sub> < 0.2 is used for partial discharge in transformers, while CH<sub>4</sub>/H<sub>2</sub> < 0.07 is used for partial discharge in bushings.

\*An increase in acetylene (C<sub>2</sub>H<sub>2</sub>) may indicate a hotspot temperature exceeding 1000<sup>o</sup>C.

TABLE 6. Simplified gas ratio analysis

Fault type	C <sub>2</sub> H <sub>2</sub> /C <sub>2</sub> H <sub>4</sub>	CH <sub>4</sub> /H <sub>2</sub>	C <sub>2</sub> H <sub>4</sub> /C <sub>2</sub> H <sub>6</sub>
PD		0.2>	
D	>0.2		
T	0.2>		

### 3.4.2. CO<sub>2</sub>/CO ratio

With an increase in temperature, carbon dioxide and carbon monoxide are produced from paper impregnated with oil. A corrected CO<sub>2</sub>/CO ratio of less than 3 usually indicates the presence of faults in the paper and slight carbonization.

To achieve a reliable CO<sub>2</sub>/CO ratio in the equipment, the amounts of carbon dioxide and carbon monoxide should be corrected considering the carbon dioxide absorbed from the environment and the previous amounts of these two gases resulting from the aging of cellulose, overheating of wooden beams, and prolonged oxidation of the oil. The oxidation of oil is heavily influenced by the amount of oxygen present due to the design and operation of the equipment.

For example, breathing equipment, which contains about 10% dissolved air in the oil, has up to 300 µl/l of carbon dioxide gas. In sealed equipment, air enters the system through existing leaks, and the amount of carbon dioxide is proportional to the air entering. When paper degradation is suspected (CO<sub>2</sub>/CO ratio

is less than three), it is recommended measure the degree of polymerization of the paper sample [48].

### 3.4.3. O<sub>2</sub>/N<sub>2</sub> Ratio

Due to the direct contact of oil with air in the expansion tank of breathing equipment or due to the presence of leaks in sealed equipment, oxygen and nitrogen are found dissolved in the oil. In equilibrium, considering the solubility of oxygen and nitrogen, the O<sub>2</sub>/N<sub>2</sub> ratio is approximately similar to the ratio of these gases in the air, being close to 0.5.

During operation, this ratio decreases due to oil oxidation and/or paper aging, which requires that the rate of oxygen consumption be higher than the rate of its diffusion into the oil. Factors such as the load and the protective system of the equipment also influence this ratio; however, a ratio of less than 0.3 can be considered indicative of excessive oxygen consumption [49].

### 3.4.4. C<sub>2</sub>H<sub>2</sub>/H<sub>2</sub> Ratio

The operation of the tap changer under load in the OIPT produces gases that correspond to low-energy discharge faults (D1). If there is the possibility of oil or gas communication between the diverter switch compartment of the tap changer and the main transformer tank or between the expansion sources of the two, these gases may transfer to the oil in the main tank which leads to erroneous analysis. However, the gas generation process in the tap changer is specific and differs from low-energy discharge faults in the main tank. A C<sub>2</sub>H<sub>2</sub>/H<sub>2</sub> ratio greater than 2 to 3 in the main tank may indicate oil leakage from the diverter into the main tank oil.

If oil leakage from the tap changer to the transformer is suspected, dissolved gas analysis in the transformer oil should be performed by subtracting the gases introduced from the tap changer to the main tank gases. Otherwise, the analysis should be disregarded due to its unreliability [50].

### 3.4.5. C<sub>3</sub> Hydrocarbons

The gas analysis method mentioned above only includes C<sub>1</sub> and C<sub>2</sub> hydrocarbons. Some analysts also consider the amount of C<sub>3</sub> hydrocarbons and believe that these gases provide additional accurate information. Since C<sub>3</sub> hydrocarbons dissolve extensively in the oil, their amount is not affected by potential escape into the environment. Due to this high solubility, separating these gases from the oil is challenging, and the analysis results greatly depend on the extraction method used. Moreover, experience has shown that in most cases, satisfactory analysis is possible even without considering these hydrocarbons. To avoid complexity, these gases have

not been included in the analytical method used in this standard [51].

### 3.5. Duval Triangle Method

The basis for this method is the use of three gases: CH<sub>4</sub>, C<sub>2</sub>H<sub>4</sub>, and C<sub>2</sub>H<sub>2</sub>. This method is precise and its accuracy has been proven over the years. To use the Duval Triangle by Figure 1, it is first necessary to determine whether there is a fault in the transformer using the IEEE method [52]. When a fault is present, the total gases of the Duval Triangle are calculated and the percentage of each gas is determined. By plotting the gas percentages on the sides of the triangle and identifying their intersection point, the relevant area is defined which helps in determining the type of fault. The types of faults that can be identified are as follows [52]:

- Partial Discharge (PD)
- Thermal Faults Below 300°C (T1)
- Thermal Faults Between 300°C and 700°C (T2)
- Thermal Faults Above 700°C (T3)
- Low-Energy Discharges (D1)
- High-Energy Arcs (D2)
- Combination of Thermal and Electrical Faults (D+T)

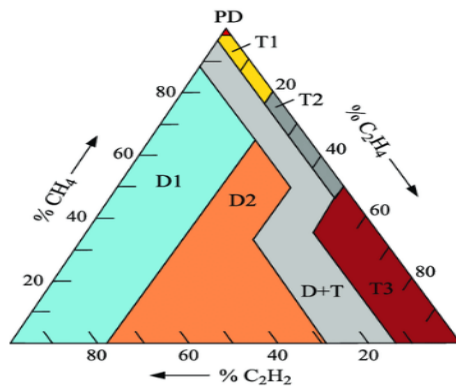


Fig.1. Duval triangle for fault diagnosis based on the percentage of gases

The amount of the three gases used in the Duval Triangle is calculated from the time of the sudden increase in gases. This is done by subtracting the amount of gas produced before the sudden increase from the total amount of gas produced. The fault identified from the total produced gases is compared with the fault identified using only the increased gases. If the fault has existed for some time or if the production rates are high, the results of the two diagnostics will be the same. Otherwise, if the results of the two diagnostics differ, the diagnosis based on

the increased gases will be used which is usually more severe.

It should be noted that in most cases, the amount of acetylene is zero, so the intersection point will be on the right side of the Duval Triangle. It is important to mention that the Duval Triangle is not used to determine whether there is a fault in the transformer. There is no area on the triangle that indicates the transformer is fault-free. The Duval Triangle always indicates a fault for any transformer, whether healthy or faulty. Therefore, before using the Duval Triangle, it must first be determined whether a fault exists in the transformer using the IEEE method. The Duval Triangle is used only to identify the type of fault, not to detect whether a fault is present. Compared to other methods, a certain amount of gas must be present before the Duval Triangle can be used.

### 3.6. Duval Pentagon Method

The Duval Pentagon method is a significant advancement in DGA for diagnosing transformer faults. Unlike the Duval Triangle, which relies on three gases, the Pentagon method incorporates five key gases— H<sub>2</sub>, CH<sub>4</sub>, C<sub>2</sub>H<sub>4</sub>, C<sub>2</sub>H<sub>2</sub>, and C<sub>2</sub>H<sub>6</sub>—to provide a more detailed and accurate fault classification. Each of these gases plays a distinct role in identifying specific fault types: H<sub>2</sub> indicates low-energy discharges, CH<sub>4</sub> is associated with low-temperature thermal faults, C<sub>2</sub>H<sub>4</sub> represents high-temperature thermal faults, C<sub>2</sub>H<sub>2</sub> signals high-energy electrical discharges, and C<sub>2</sub>H<sub>6</sub> corresponds to moderate thermal decomposition [53].

In the Duval Pentagon, the concentrations of these five gases are normalized as percentages of their total sum using the following equation:

$$G_i\% = \frac{C_i}{\sum C_i} \times 100 \quad (1)$$

Here, C<sub>i</sub> is the concentration of gas i, and  $\sum C_i$  represents the sum of all five gas concentrations. The calculated percentages are then plotted within a pentagonal diagram. The Duval Pentagon surpasses the Triangle method in diagnostic accuracy by addressing overlapping fault conditions and complex fault types. For instance, the addition of H<sub>2</sub> and C<sub>2</sub>H<sub>6</sub> enables better differentiation of fault conditions that involve combined electrical and thermal effects. Furthermore, its graphical representation simplifies fault classification by visualizing the gas interactions and their relationship to fault types [54].

This method is particularly valuable for diagnosing larger and more complex transformers where multiple faults may coexist. However, its effectiveness relies on accurate gas sampling and precise measurement. Errors during data acquisition

or normalization can lead to misclassification of faults.

Figure 2 illustrates the Duval Pentagon, highlighting the regions corresponding to different fault types. Compared to traditional methods, the Pentagon provides a more comprehensive framework for analyzing dissolved gases, making it a vital tool for improving the reliability and operational lifespan of power transformers [55].

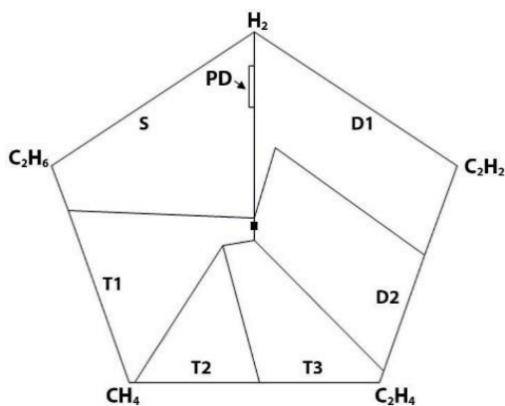


Fig.2. Duval pentagon for fault diagnosis

#### 4. Fuzzy Logic for Dissolved Gas Analysis in Oil

Fuzzy logic, as an advanced method for data analysis and processing, can effectively handle uncertainty and incomplete information. These features make the fuzzy logic widely applicable in various fields like the dissolved gas analysis in oil [56-57].

In the process of dissolved gas analysis in the oil, there are several stages where fuzzy logic can enhance accuracy and efficiency. The first stage involves defining fuzzy variables. In this context, variables such as gas concentration, temperature, pressure, and oil quality are defined as fuzzy sets. Instead of using precise values, these variables are categorized into fuzzy sets like "low", "medium" or "high".

The next step is constructing fuzzy rules. These rules, typically written in "if-then" format, are based on experience and expert knowledge. For example, a rule might be defined as follows: "If the hydrogen gas concentration is high and the temperature is elevated, then the likelihood of a fault in the oil is high". Subsequently, a membership function is defined for each fuzzy variable. These functions indicate how much a specific value belongs to a fuzzy set. For instance, a membership function might express that a hydrogen gas concentration of 300 ppm belongs to the "high" set with a degree of 0.7.

Then, the fuzzy inference stage is performed using these functions and rules. In this stage, the fuzzy

rules are applied to the input values to produce fuzzy results. The outcomes are typically in the form of fuzzy sets and need to be converted into precise values. This process, known as "defuzzification", often uses methods such as midpoint or weighted average to transform the fuzzy results into specific values. Ultimately, the precise results aid in interpretation and practical decision-making. These decisions might include identifying the need for maintenance, predicting the oil's lifespan, or optimizing operational conditions. Fuzzy logic, with its ability to handle ambiguity and uncertainty, serves as a valuable tool for enhancing the analysis and management of dissolved gases in oil [58-59].

#### 4.1. Roger's Fuzzy Method

In many cases, Roger's method is not capable of identifying the type of fault based on the dissolved gas values in the oil. The conventional Roger method uses AND - OR operators based on the codes in Table 7 for the fault detection (see Table 8) [60].

TABLE 7. CODES RELATED TO RATIO RANGES

$R_1 = \frac{CH_4}{H_2}$	$R_1 \leq 0.1$	5	$R_3 = \frac{C_2H_4}{C_2H_6}$	$R_3 < 1$	0
	$0.1 < R_1 < 1$	0		$1 \leq R_3 < 3$	1
	$1 \leq R_1 < 3$	1		$R_3 \geq 3$	2
	$R_1 \geq 3$	2	$R_4 = \frac{C_2H_2}{C_2H_4}$	$R_4 < 0.5$	2
$R_2 = \frac{C_2H_6}{CH_4}$	$R_2 < 1$	0		$0.5 \leq R_4 < 3$	1
		$R_2 \geq 1$	1	$R_4 \geq 3$	2

For example, the process of detecting a partial discharge fault is as follows:

$$f(1) = code_5(R_1) \text{ AND } code_0(R_2) \text{ AND } code_0(R_3) \text{ AND } code_0(R_4) \quad (2)$$

Where  $f(1)$  has three values: zero (no fault) and one (fault present). In the mentioned conventional Roger method, the threshold values have abrupt changes between the defined codes, which is a major and important issue for values near the threshold codes. So here, codes 2, 1, 0, and 5 replace the fuzzy sets "high" and "medium", "low" and "very low" respectively. Accordingly, the ratio  $R_1$  is shown by the

vector  $[\mu_{verylow}(R_1), \mu_{low}(R_1), \mu_{medium}(R_1), \mu_{high}(R_1)]$  and other ratios are represented as  $[\mu_{low}(R_1), \mu_{medium}(R_1), \mu_{high}(R_1)]$ , where  $\mu_{verylow}$ ,  $\mu_{low}$ ,  $\mu_{medium}$ , and  $\mu_{high}$  are the membership functions of the fuzzy sets "very low", "low", "medium" and "high" respectively. Figure 3 illustrates how the codes related to the ratio  $R_1$  are fuzzified.

TABLE 8. Fault detection by fuzzy ratio ranges

Fault Detection	Codes			
	R <sub>1</sub>	R <sub>2</sub>	R <sub>3</sub>	R <sub>4</sub>
Normal	0	0	0	0
Partial Discharge	5	0	0	0
Low-Level Overheating (Below 150°C)	1&2	0	0	0
Low-Level Overheating (150-200°C)	1&2	1	0	0
Low-Level Overheating (200-300°C)	0	1	0	0
General Overheating	0	0	1	0
Circulating Current in the Conductor	1	0	1	0
Circulating Current in the Tank and Core	1	0	2	0
Spark without Power Transfer	0	0	0	1
Electric Arc with Power Transfer	0	0	1&2	1&2
Low-Energy Electric Arc	0	0	2	2
Low-Energy Partial Discharge	5	0	0	1&2

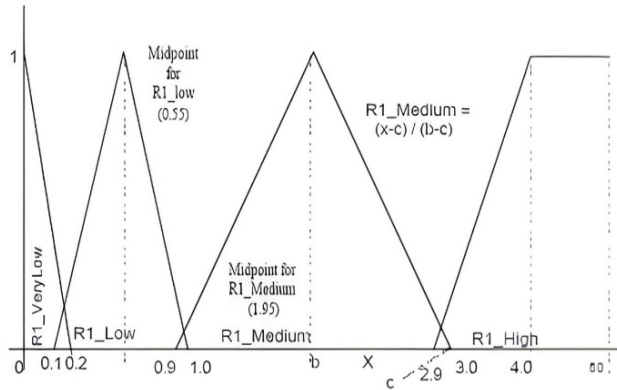


Fig.3. Fuzzification of the codes related to the ratio R<sub>1</sub>

Tables 9 to 12 show how the values of each ratio R<sub>1</sub>, R<sub>2</sub>, R<sub>3</sub>, and R<sub>4</sub> are converted into fuzzy values in the fuzzy sets "very low", "low", "medium" and "high".

TABLE 9. Range of fuzzified values for ratio R<sub>1</sub>

Fuzzified Roger			Traditional Roger	
range	code	midpoint	Range	code
R <sub>1</sub> ≤ 0.2	R <sub>1</sub> -Very low	0	R <sub>1</sub> ≤ 0.1	5
0.1 < R <sub>1</sub> < 1	R <sub>1</sub> -Low	0.55	0.1 < R <sub>1</sub> < 1	0
0.9 ≤ R <sub>1</sub> < 3	R <sub>1</sub> -Medium	1.55	1 ≤ R <sub>1</sub> < 3	1
R <sub>1</sub> ≥ 2.9	R <sub>1</sub> -High	0	R <sub>1</sub> ≥ 3	2

TABLE 10. Range of fuzzified values for ratio R<sub>2</sub>

Fuzzified Roger			Traditional Roger	
range	code	midpoint	Range	code
R <sub>2</sub> < 1	R <sub>2</sub> - low	0	R <sub>2</sub> < 1	0
R <sub>2</sub> > 0.9	R <sub>2</sub> -High	0.55	R <sub>2</sub> > 1	1

TABLE 11. Range of fuzzified values for ratio R<sub>3</sub>

Fuzzified Roger			Traditional Roger	
range	code	midpoint	Range	code
R <sub>3</sub> < 1	R <sub>3</sub> -Low	0	R <sub>3</sub> < 1	0
0.9 < R <sub>3</sub> < 3	R <sub>3</sub> -Medium	1.95	1 < R <sub>3</sub> < 3	1
R <sub>3</sub> > 2.9	R <sub>3</sub> -High	0	R <sub>3</sub> ≥ 3	2

TABLE 12. Range of fuzzified values for ratio R<sub>4</sub>

Fuzzified Roger			Traditional Roger	
range	code	midpoint	Range	code
R <sub>4</sub> > 1	R <sub>4</sub> -Low	0	R <sub>4</sub> < 0.5	0
0.4 < R <sub>4</sub> < 3	R <sub>4</sub> -Medium	1.7	0.5 < R <sub>4</sub> < 3	1
R <sub>4</sub> > 2.9	R <sub>4</sub> -High	0	R <sub>4</sub> ≥ 3	2

Finally, according to the rules provided in Table 8 and by substituting the AND operators with min and OR operators with max, the type of fault in the transformer insulation system is identified. For example, the applied rules for detecting partial discharge would be as follows:

$$F(1) = \min[\mu_{verylow}(R_1), \mu_{low}(R_2), \mu_{low}(R_3), \mu_{low}(R_4)] \quad (3)$$

#### 4.2. Fuzzy IEC

In this case, the same method used in the fuzzy Roger is employed. The difference in this method is the use of three ratios: R<sub>1</sub> = C<sub>2</sub>H<sub>2</sub>/C<sub>2</sub>H<sub>4</sub>, R<sub>2</sub> = CH<sub>4</sub>/H<sub>2</sub>, and R<sub>5</sub> = C<sub>2</sub>H<sub>4</sub>/C<sub>2</sub>H<sub>5</sub> to determine the type of fault. The fuzzy sets used include low, medium, and high, and all three ratios used in this method are represented by  $[\mu_{low}(R_1), \mu_{medium}(R_1), \mu_{high}(R_1)]$ , where  $\mu_{low}$ ,  $\mu_{medium}$ , and  $\mu_{high}$  are the membership functions for the fuzzy sets "low", "medium" and "high" respectively [61].

Figure 4 shows the membership functions used for the ratio R<sub>1</sub> in this method. The rules required to determine the type of fault will be applied exactly as in the Roger method, according to Table 8. For example, according to Table 13, the probability of a partial discharge fault occurring is described as  $F(1) = \min[\mu_{low}(R_1), \mu_{low}(R_2), \mu_{low}(R_5)]$ . Similarly, the probability of occurrence for other faults defined in the IEC method is carried out using the same approach. Finally, a brief comparison of the DGA method is available in Table 14.

TABLE 13. Ranges associated with faults in the IEC method

Fault Type	R <sub>1</sub> = $\frac{C_2H_2}{C_2H_4}$	R <sub>2</sub> = $\frac{CH_4}{H_2}$	R <sub>3</sub> = $\frac{C_2H_4}{C_2H_6}$
Partial Discharge	Very little amount	0.2 >	0.2 >

Low Energy Discharge	1<	0.1-0.5	1<
High Energy Discharge	0.6-2.5	0.1-1	2<
Low-Level Excess Heat	0.2>	Very little amount	1>
Medium-Level Excess Heat	0.1>	1<	1-4
High-Level Excess Heat	0.2>	1<	4<

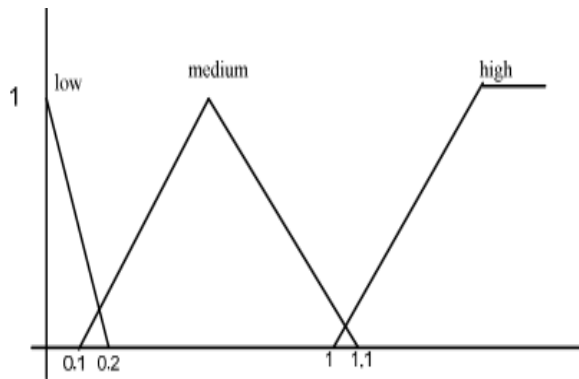


Fig.4. Membership functions related to the ratio  $R_1$  (in the fuzzy IEC method)

### 5. CONCLUSION

In this paper, several widely adopted DGA methods were reviewed, including the Duval Triangle, IEC 60599, Duval Pentagon, Gas Ratio Methods, and Fuzzy Logic Approaches, with a focus on their strengths and limitations. While these methods are essential tools for fault detection and transformer diagnostics, their practical applications in the industry are equally important. Each method discussed offers distinct advantages in real-world transformer monitoring systems. In summary, this article not only reviewed established DGA methods but also emphasized their direct applicability in transformer monitoring and diagnostics, bridging the gap between theory and practice. The methods discussed offer a comprehensive toolkit for industry professionals, enabling them to enhance the accuracy of fault detection, optimize maintenance schedules, and improve the overall reliability of transformer systems.

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TABLE14. Advantages and disadvantages of each method

Method	Advantages	Disadvantages	Best Application
Duval Triangle	<ul style="list-style-type: none"> <li>- Simple, easy-to-use, graphical representation.</li> <li>- Quick fault identification.</li> <li>- Widely adopted in industry for basic fault diagnosis.</li> </ul>	<ul style="list-style-type: none"> <li>- Limited precision for complex or mixed faults.</li> <li>- Does not account for gas concentration trends over time.</li> </ul>	<ul style="list-style-type: none"> <li>- Best for quick diagnostics and simpler fault conditions.</li> <li>- Suitable for field engineers.</li> </ul>
IEC 60599 Method	<ul style="list-style-type: none"> <li>- Structured, standardized approach.</li> <li>- Quantitative analysis with gas concentration ratios.</li> <li>- Reliable for detailed fault diagnosis.</li> </ul>	<ul style="list-style-type: none"> <li>- Requires precise gas sampling and measurement.</li> <li>- Less intuitive than graphical methods.</li> <li>- More complex and requires training.</li> </ul>	<ul style="list-style-type: none"> <li>- Ideal for detailed condition monitoring.</li> <li>- Useful for analyzing complex or overlapping fault scenarios.</li> </ul>
Gas Ratio Methods (Dornenburg & Rogers)	<ul style="list-style-type: none"> <li>- Empirical method based on large datasets.</li> <li>- Useful for identifying fault types quickly.</li> <li>- Simple to implement.</li> </ul>	<ul style="list-style-type: none"> <li>- May lack precision in certain fault conditions.</li> <li>- Requires accurate threshold values for effective diagnosis.</li> </ul>	<ul style="list-style-type: none"> <li>- Ideal for identifying faults when gas ratios exceed certain thresholds.</li> <li>- Good for routine inspections.</li> </ul>
Duval Pentagon	<ul style="list-style-type: none"> <li>- More detailed and accurate fault diagnosis than the Duval Triangle.</li> <li>- Incorporates five gases for enhanced precision.</li> <li>- Suitable for complex or mixed faults.</li> </ul>	<ul style="list-style-type: none"> <li>- More complex to interpret than the Duval Triangle.</li> <li>- Requires accurate gas sampling and precise calculations for reliable results.</li> </ul>	<ul style="list-style-type: none"> <li>- Best for diagnosing complex and mixed faults.</li> <li>- Useful for larger or critical transformers with multiple fault conditions.</li> </ul>
Fuzzy Logic Approaches	<ul style="list-style-type: none"> <li>- Handles uncertainty and incomplete information.</li> <li>- Can combine various methods for enhanced diagnosis.</li> <li>- Can be integrated with AI and machine learning.</li> </ul>	<ul style="list-style-type: none"> <li>- More complex to implement.</li> <li>- Requires expert knowledge to develop fuzzy rules.</li> <li>- Maybe computationally intensive.</li> </ul>	<ul style="list-style-type: none"> <li>- Ideal for systems where uncertainty or incomplete data exist.</li> <li>- Used for more advanced or integrated diagnostic systems.</li> </ul>

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