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REVIEW

Traditional fault diagnosis methods for mineral oil-immersed power transformer based on dissolved gas analysis: Past, present and future

Arnaud Nanfak[1] | Eke Samuel[1] | Issouf Fofana[2] | Fethi Meghnefi[2] | Martial Gildas Ngaleu[1] | Charles Hubert Kom[1]

[1]Laboratory of Energy, Materials, Modelling and Methods, National Higher Polytechnic School of Douala, University of Douala, Douala, Cameroon

[2]Canada Research Chair Tier 1, in Aging of Oil-Filled Equipment on High Voltage Lines (ViAHT), University of Quebec at Chicoutimi, Chicoutimi (UQAC), Chicoutimi, Quebec, Canada

Correspondence
Eke Samuel.
Email: samueeke@gmail.com

Abstract
A key factor in ensuring the efficient and safe operation of power transformers is the early and accurate diagnosis of incipient faults. Among the tools available to achieve this goal, dissolved gas analysis (DGA) is widely used by power transformers' maintenance professionals. It is a preventive maintenance tool, used for condition monitoring, fault diagnosis and unplanned outage prevention. With the development of artificial intelligence (AI), many intelligent-based methods using AI tools have been proposed in the literature for DGA data interpretation. Although these methods achieve high diagnostic accuracies and improve DGA efficiency, they are generally complicated and the research documented in these publications is difficult to replicate. Traditional DGA-based methods are simple, easy to understand and implement, and widely used by power transformers' maintenance professionals. Many methods proposed in recent years overcome the limitations of the pioneer methods and are increasingly effective. The authors present a detailed and comprehensive literature review of the traditional DGA-based methods for mineral oil-immersed power transformer faults diagnosis. This review also addresses ways to improve the efficiency of the available traditional methods. Some pitfalls that need to be taken into account to improve the efficiency of the DGA-based diagnostic methods are also presented.

KEYWORDS
power transformer insulation, transformer oil

1 | INTRODUCTION

Considered as the heart of electrical power transmission and distribution networks, the power transformer is an essential part of the electricity transmission chain [1]. Indeed, they represent a major investment for power network operators. Their failure can result in significant financial losses due to interruptions in the transmission and distribution of electricity, environmental damage, risks of explosion and fire, and costly repairs or replacements [2]. Therefore, as a major piece of equipment of the electricity network, its reliability is essential to the reliable delivery of electricity in the network [3]. Their maintenance strategy has shifted from time-based maintenance to condition-based maintenance and now to a predictive maintenance strategy based on extrapolation of transformer health indicators, due to high repair costs, loss of production due to prolonged and unplanned outages, and their importance in the power system [4, 5]. To implement such a maintenance policy, condition monitoring, fault diagnosis, and failure prognosis are the main processes to be mastered. Among them, fault diagnosis is an essential practice for maintenance policy. In fact, fault diagnosis is the logical step after condition monitoring and a prognosis step as preventive diagnosis. Early and correct diagnosis of faults should be conducted to ensure an efficiency operation of power transformers [6]. To achieve this objective, several diagnostic methods have been proposed in the literature, such as partial discharge measurement, furans analysis, frequency response analysis, degree polymerisation measurement, vibro-acoustic analysis, moisture analysis or dissolved gas analysis (DGA) [7, 8].

Among them, DGA is one of the most widely used techniques and has proven effective in detecting faults in active parts of power transformers at an early stage [9, 10]. Its popularity stems from the fact that it is non-intrusive and can be used for real-time monitoring [11]. Several DGA-based methods are proposed in the literature for power transformers faults diagnosis and can be classified in two main categories: traditional and intelligent methods [12]. Intelligent DGA-based methods rely on artificial intelligence (AI) tools to interpret DGA data. Several intelligent DGA-based methods are proposed in the literature for this purpose. These methods are based, among others, on artificial neural networks [13], fuzzy logic [14], deep learning [15], or machine learning [16–19]. Although the fault diagnosis accuracy of AI-based methods is relatively high, they are generally dataset-dependent. This means that they may suffer from reproducibility of research results, which may limit their use to solve generalised problem of power transformer fault diagnosis in real-world utilities [20, 21]. As a result, power transformer maintenance professionals are increasingly turning to traditional methods such as the Duval triangle [22] or IEC 60599 method [23].

Traditional DGA-based methods are those in which the process of interpreting fault-related gas concentrations depends on the experience of the expert rather than on mathematical tools or formulations. In these methods, experts produce rules relating concentrations, concentration ratios and/or percentages of gases to the various faults. Simple, easy to understand and implement, these methods are widely used by power transformer maintenance professionals. Several traditional DGA-based methods have been proposed by researchers for accurately diagnose power transformer faults. Table 1 provides a comparative analysis of traditional and intelligent DGA-based methods.

The lack of a detailed and thorough review of the literature relating to traditional DGA-based methods prevents an overview of the progress made in this area of research. A review paper has recently been published [24], but the authors have limited themselves to advances in traditional DGA-based methods over the last decade. In this article, the authors present a more comprehensive, detailed and in-depth review of these methods used to diagnose faults in oil-immersed power transformers. In the present review, these methods are grouped in four main categories: the key gas methods, the gas ratio methods, the graphical methods and combined methods. The following key points characterise the originality of this contribution:

- This paper shows how the thinking behind the implementation of traditional DGA methods has evolved over time.
- This paper identifies and analyse the main reasons why traditional DGA-based methods are less effective.
- This paper presents and propose new directions that will enable more effective traditional methods to be proposed.

The remaining of this paper is organised as follows: Section 2 describes the DGA principle and the type of faults it can detect and identify. In Section 3, a schematic view of the steps involved in the implementation of traditional DGA-based methods is presented. The review of traditional DGA-methods organised into key gas methods, gas ratio methods, graphical methods and combined methods is presented in Section 4. In addition, the summary of this review and the future of DGA-methods are presented. Section 5 presents some pitfalls and Section 6 concludes the paper.

2 | DISSOLVED GAS ANALYSIS

2.1 | DGA principle

Insulating oil of in-service oil-immersed power transformers contains the by-products of the degradation and ageing reactions of the insulation system and associated components within the transformer. In addition to sludge, water and acids, gaseous products are also generated inside the transformer [25]. The identities and quantities of the gases generated are very useful information in any preventive maintenance policy for power transformers. DGA is a preventive maintenance tool for power transformers, used for condition monitoring, fault diagnosis and unplanned outage prevention [26]. It is a non-invasive monitoring technique that extracts information on the condition of the insulation system in particular and the internal parts in general from the oil as a source of information [3]. Periodic investigation process that is part of the maintenance policy for oil-immersed power transformers, the DGA procedure essentially consists of four steps: sampling, extraction, analysis and interpretation.

At the sampling step, oil insulating samples are collected from the power transformers. Oil samples should preferably be taken from moving oil so that gases generated somewhere are easily and quickly transported from the point of production to the sampling point [27]. IEC 60475 [28], ASTM D-923 [29] and IS 6855 [30] are reference standards for sampling methods. Following sampling, the sample is handled in order to extract the gas mixture it contains. Three techniques can be used for this purpose, namely vacuum extraction, stripping or head-space methods. After sampling and extraction, the gas mixture is analysed to identify and quantify the different components. Several gas detection and quantification methods are available to analyse the gas mixture. Gas chromatography is used in many laboratory assessment systems, as well as in on-line monitoring systems. Other possibilities are offered by photo-acoustic spectroscopy or the use of semiconductor sensors as well as electrochemical sensors [31]. IEC 60567 [32], ASTM D-3612 [33] and IS 9434 [34] are reference standards for extraction of gases and analysis methods. The interpretation of

TABLE 1 Comparative analysis of traditional and intelligent DGA-based methods.

Comparison criteria	Traditional methods	Intelligent methods	Comments
Size of the dataset used to implement the method	▶	▲	The size of the database used to implement intelligent methods is much larger than that used for traditional methods. This is mainly due to the fact that intelligent methods use AI tools to analyse the data, whereas traditional methods rely on human expertise.
Dataset-dependent	▼	▼	Both approaches are highly data dependent. Information about the nature of the faults is contained in the data.
Expert-dependent	▼	▲	Intelligent methods do not rely on human expertise. Traditional methods, on the other hand, essentially rely on the expert's ability to analyse the data when they are implemented. However, it is important to note that once the method has been implemented, the result obtained no longer requires the expert's confirmation.
Reproducibility of the method	▲	▼	Due to the tools used for intelligent methods, the latter suffer from the difficult reproducibility of the method by a third party, which hinders their use in solving transformer fault diagnosis problems in real-world utilities.
Accuracy of the method	▶	▲	Intelligent methods are generally more efficient than traditional methods. However, recent advances in the implementation of traditional methods have led to the proposal of increasingly efficient methods that rival intelligent methods in terms of accuracy.
Use for online diagnosis	✓	✓	In an on-line diagnostic system, both approaches can be used.
Presence in standards	✓	x	Intelligent methods are absent from the standards governing the analysis and interpretation of power transformer fault gases.
Assessing of the fault's severity	▶	▲	The assessment of the severity of faults depends mainly on the dataset used in the implementation of the method. Under these conditions, both approaches can be used to assess the severity of faults. However, it should be noted that many traditional methods are limited to assessing the type of defect and not its severity.

▲ High or Strong ▲ Low or Weak ▶ Medium ▼ or ▼ Means that this is a bad point for the method. ▲ or ▲ Means that this is a good point for the method.

the results obtained allows the health state of the transformer to be assessed. Even though the physical reasons for gas formation have a firm technical basis, interpretation of that data in terms of the specific cause or causes is not an exact science [22]. As underscored in the IEEE standard C57.104, the analysis of the gases and interpretation of their significance is an art subject to variability. IEC 60599 [23], IEEE C57.104 [22] and IS 10593 [35] are reference standards for interpretation.

2.2 | Fault types and fault gas formation

Faults in power transformers due to deterioration of their insulation system (oil and paper) are grouped into two main categories, namely electrical faults and thermal faults. These faults can be reliably identified by visual inspection after the fault has occurred in service [36]. Electrical faults result from the deterioration of the insulation system caused by high electrical stress. This category includes partial discharges and arcing. Thermal faults result from deterioration of the insulation system caused by an abnormal rise in temperature. Based on IEC 60599, the two main types of faults can, according to their severity, be divided into six types of faults as summarised in Table 2.

In addition to the six basic IEC faults shown in Table 2, the additional fault subtypes shown in Table 3 are commonly used.

Depending on the type of fault and its location, different fault-related gases can be produced. Hydrogen (H_2), methane (CH_4), ethane (C_2H_6), ethylene (C_2H_4), acetylene (C_2H_2), propane (C_3H_8) and propylene (C_3H_6) result from faults (electrical and thermal) occurring in the transformer oil [37, 38]. Through oxidation or hydrolysis, the oil molecules degrade generating these combustible gases. When cellulose insulation is involved in the occurrence of faults, carbon monoxide (CO) and carbon dioxide (CO_2) are generated. These gases indicate a thermal fault. Other gases such as oxygen (O_2) and nitrogen (N_2) are also produced [38]. Table 4 summarises the main gases produced according to the type of transformer faults.

The nature of the gases formed and their relative proportions provide information on the incipient fault, its intensity and the type of materials affected [22, 23, 39]. Each fault has a distinctive signature in terms of the quantity and combination of different gases associated with the fault. In addition, the particular combination of gases generated depends on the temperature level and/or the energy produced by the fault [22, 23, 39]. Figure 1 shows the influence of temperature on the production of fault-related gases.

The acceptable limits of the concentrations of the various fault-related gases make it possible to distinguish between normal and abnormal operating conditions and constitute an alarm signal that should trigger an in-depth analysis by the

TABLE 2 Fault classification according to IEC 60599 and IEEE Std C57.104.

Acronyms	Faults
PD	Partial discharge
D_1	Low-energy discharge
D_2	High-energy discharge
T_1	Thermal fault, $T < 300°C$
T_2	Thermal fault, $300°C < T < 700°C$
T_3	Thermal fault, $T > 700°C$

TABLE 3 Other fault types according to IEEE Std C57.104.

Acronyms	Faults
S	Stray gassing, $T < 200°C$
O	Overheating, $T < 250°C$ without carbonisation of paper
C	Possible paper carbonisation
T_3–H	Thermal fault, $T > 700°C$ in mineral oil only
R	Catalytic reaction
DT	Mix of thermal and discharge faults

TABLE 4 Gas generated according to power transformer's fault type [38].

Fault type	Major gas (es)	Minor gas (es)
PD	H_2, CH_4, CO	C_2H_6, C_2H_2, CO_2
D_1	H_2, C_2H_2	/
D_2	H_2, C_2H_2, CO, CO_2	CH_4, C_2H_4, C_2H_6
T_1	CH_4, C_2H_6, CO, CO_2	H_2, C_2H_4
T_2	C_2H_4, CH_4	H_2
T_3	C_2H_4	H_2, C_2H_6

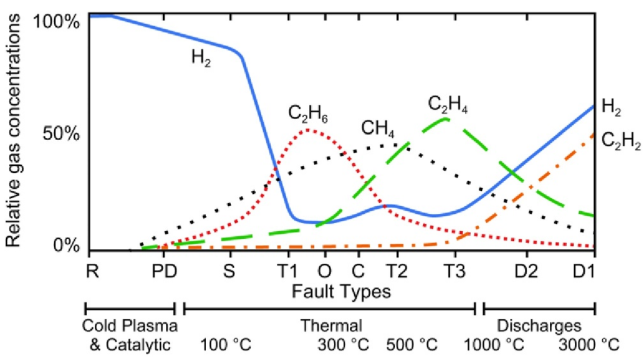

FIGURE 1 Comparative proportion of dissolved gas concentrations in mineral oil as a function of temperature [22].

DGA-based diagnostic methods. Table 5 below gives the permissible limits proposed in the literature.

3 | SYNTHESIS OF TRADITIONAL METHODS

Figure 2 shows a schematic view of the procedure used to implement traditional DGA-based methods for fault diagnosis in power transformers. The first stage is the collection of labelled data. These data are collected by the maintenance departments, which carry out physicochemical analyses of the oil and correlate the results with observations in the field or visual inspection of the transformer. Once collected, these labelled data are sent to the expert for the analysis phase, which includes data mining and fault signature identification.

The data mining stage consists of making observations about the relationships that exist between the DGA results and the faults reported. These relationships include [22, 23, 39]:

- The proportion of a gas or a group of gases is an indication of a type or a group of faults;
- Specific values of gas ratios are an indication of a type or a group of faults;
- The accumulation in a data plane space is an indication of a type or a group of faults;
- The presence or absence of one or more gases is an indication of a type or group of faults.

These relationships allow the expert to explore the labelled dataset. All these observations are then processed to identify all the signatures for each type of fault. Taken together, these signatures allow the expert to propose a fault diagnosis model for the power transformers.

4 | REVIEW OF TRADITIONAL DGA-BASED METHODS

Traditional DGA-based methods can be classified into three main categories: key gas methods, gas ratios methods and graphical methods. This section reviews them in detail.

4.1 | Methods based on key gas approach

Methods based on the key gas approach use the correlation between gases predominantly generated and the different kinds of fault. The use of this approach for power transformer's fault diagnosis dates back to the mid-1950s with the works of Howe [48]. In his book entitled "the identity and significance of gases collected in the Buchholz protectors", carbon monoxide, acetylene and hydrogen are used to assess the fault in the Buchholz relay. Other methods based on this approach have been developed and proposed in the literature, including the IEEE key gas method [22], the LCIE method [49], the California State University of Sacramento (CSUS) method [46], the total dissolved combustible gas (TDCG) method [22], the characteristic gas ensembles (CGE) method of Davidenko et al. [50] or key gas method of Muller et al. [51].

TABLE 5 Acceptable limits of fault-related gases in ppm.

	Limit concentration (in ppm)							
Ref.	**H_2**	**CH_4**	**C_2H_6**	**C_2H_4**	**C_2H_2**	**CO**	**CO_2**	**TDCG**
IEEE C57.104–1991 [40]	100	120	65	50	35	350	2500	-
IEEE C57.104–2019 [22]	100	120	65	50	1	350	2500	720
IEC 60599:1999 [41]	60–150	40–110	50–90	60–280	3–50	540–900	5100–13000	-
IEC 60599:2015 [23]	50–150	30–130	20–90	60–280	2–20	400–600	3800–14000	-
CIGRE, 1999 [42]	90	150	330	150	15	1420	12500	-
STO 34.01-23-003-2019 [43]	20–50	7–30	10	30	10	150–180	1700–2600	80–200
RD 153-34.0-46.302-00-2001 [44]	100	100	50	100	10	500–600	6000–8000	-
BUREC [45]	500	125	75	175	15	750	11000	-
CSUS [46]	150	25	10	20	15	500	10000	-
NTT [47]	1500	80	35	150	7	1000	10000	-

Abbreviations: BUREC, US Bureau of reclamation; CSUS, Californian state university of Sacramento; NTT, Northen Technology & Testing.

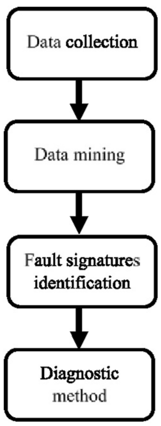

FIGURE 2 The steps involved in implementing conventional DGA-methods for power transformer fault diagnosis.

The IEEE key gas method whose basic formulation was developed in the Doble Engineering Company in 1973 is based on the proportion of each gas generated by the thermal and/or electrical stresses to which the power transformer is subjected. Initially proposed by David Pugh in 1974 [52], the final version included in IEEE Std C57.104 uses the individual concentrations of hydro, hydrocarbon and carbon monoxide gases produced by the degradation of oil and paper as diagnosis criteria. Table 6 shows the key gases used and their associated faults, and Table 7 shows the gas proportions of the four fault types identified by this method. These percentages are based on the practical experience of various experts [53]. The IEEE key gas method results in many inconclusive or wrong fault diagnosis. In addition, the predominant gas is still not one of the four key gases and carbon monoxide is often incorrectly used as an indicator of paper involvement in faults [54].

Like the IEEE key gas method, the TCDG method is included in IEEE Std C57.104 and used to classify risks to power transformers where there is no history of dissolved gas. First proposed in 1978 and revised in 1991, the TDCG uses not only the individual concentrations of the main gases, but also the total amount of combustible gases to assess the condition of power transformers. With this method, four states can be determined and are summarised in Table 8.

TABLE 6 Key gas generated according to a fault type [22].

Key gas	Fault type	Typical proportions
C_2H_4	Overheating, oil	Mainly C_2H_4; Smaller proportions of C_2H_6, CH_4, and H_2; Traces of C_2H_2 at very high fault temperature
CO	Overheating, paper and oil	Mainly CO; much smaller quantities of hydrocarbon gases (predominantly C_2H_4 with smaller proportions of C_2H_6, CH_4, and H_2)
H_2	Partial discharge	Mainly H_2; small quantities of CH_4; Traces of C_2H_4 and C_2H_6
H_2 & C_2H_2	Arcing	Mainly H_2 and C_2H_2; minor traces of CH_4, C_2H_4, and C_2H_6; also, CO if cellulose is involved

TABLE 7 Key gas generated according to a fault type [22].

	Key gas percentages (%)					
Fault type	**H_2**	**CH_4**	**C_2H_6**	**C_2H_4**	**C_2H_2**	**CO**
Partial discharges	85	13	1	1	-	-
Arcing	60	5	2	3	30	-
Overheating, oil	2	16	19	63	-	-
Overheating, paper	-	-	-	-	-	92

In condition 1, the power transformer operates satisfactorily. In condition 2, there is a possible fault and further investigation is recommended. Condition 3 indicates a high level of degradation of the cellulose insulation and/or oil, with the likelihood of one or more faults. Condition 4 refers to excessive decomposition of the insulation system. Continued operation of the power transformer may lead to its failure.

Condition	Permissible concentration values (ppm)							
	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO	CO_2	TDCG
Condition 1	100	120	1	50	65	350	2500	720
Condition 2	101–700	121–400	2–9	51–100	66–100	351–570	2501–4000	721–1920
Condition 3	701–1800	401–1000	10–35	101–200	101–150	571–1400	4001-10000	1921–4630
Condition 4	>1800	>1000	>35	>200	>150	>1400	>10000	>4630

TABLE 8 Permissible concentration values of dissolved gases in oil according to IEEE Std C57.104 [22].

Immediate shut down for maintenance is strongly recommended [22].

Another key gas method proposed by Muller et al. [51] is presented in Table 9. In this method, six types of faults are identified based on the primary and secondary key gases of the fault. More used as indicative method, the Muller's key gas method is based on comparative proportion of dissolved gas concentrations. For example, for a sample with H_2 and C_2H_2 as major gases following CH_4 and C_2H_4, the fault type is arcing. Unlike the IEEE key gas method, the key gas proportions of the different faults identified are not specified and carbon monoxide is not included.

The key gas quantity method or CSUS method is another key gas method developed by the California State University of Sacramento in cooperation with the Pacific Gas and Electric Company [46]. This method is based on the direct and individual comparison between the concentration of hydrocarbon and carbon gases and their respective permissible concentration values. For each gas, Table 10 shows the normal and abnormal limit values. When the concentrations are all below those indicated in the column of normal values, the transformer is in good condition. By direct and individual comparison, the type of fault is determined. In addition of poor diagnosis accuracy, one of the main drawbacks of this method is the possibility of several fault diagnoses at the same time.

In the same way, the CIGRE key gas method is based on direct comparison of measured key gas concentrations with permissible concentration values. Proposed in CIGRE TF 15.01.01 [39], it allows to diagnose, in addition to the three main types of faults, the paper degradation fault. Table 11 shows the normal concentrations of key gases and corresponding fault when exceeded.

This method is rarely used alone to assess the condition of the transformer. The CIGRE TF 15.01.01 guideline includes in the interpretation procedure the gas ratios. Similar to the CSUS method the main drawback of this method is the possibility of several fault diagnoses at the same time.

Another key gas method based on experimental data on gassing of mineral oils under electrical and thermal stress was published in 1975 by CIGRE [55]. This experiment is conducted by Fallou. In this method, carbon dioxide and hydrocarbons with three carbon atoms are also considered here when evaluating the percentage concentration of each gas as shown in Table 12.

Up to date, the most recent key gas method was proposed in 2018 by Davidenko and Ovchinnikov [50]. The CGE method is based on relative concentrations of key gases obtained by the following equation:

TABLE 9 Relationship between the key gases and fault type according to Muller et al. [51].

Fault type	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2
Low-energy discharge	■	△	▽	▽	△
High-energy discharge	■	△	▽	△	■
Disruptive discharge (arcing)	■	□	▽	□	■
Overheating <300°C	▽	△	■	△	▽
Overheating 300°C–1000°C	▽	△	▽	■	▽
Overheating >1000°C	△	□	▽	■	△

■ Key gas for the respective fault type.
□ Secondary characteristic gas (high concentration).
△ Secondary characteristic gas (low concentration).
▽ Gas not typical for the respective fault type.

TABLE 10 Fault diagnosis by CSUS method [46].

Key gas	Limit concentrations		Fault type
	Normal	Anormal	
H_2	150	1000	Corona discharges, arcing
CH_4	25	80	Corona discharges
C_2H_6	10	35	Local overheating
C_2H_4	20	150	Severe overheating
C_2H_2	15	70	Arcing
CO	500	1000	Overload, paper decomposition
CO_2	10000	15000	Overload, paper decomposition

TABLE 11 Fault diagnosis by CIGRE method [39].

Key gas	Limit concentration	Fault
C_2H_2	>20	Arcing
H_2	>100	Partial discharges
$\sum C_xH_y$	>1000	Thermal fault
$\sum CO_x$	>10 000	Cellulosic degradation

$$c_r^i = C^i / C_{\text{lim}}^i \quad (1)$$

where c_r^i, C^i and C_{lim}^i are the relative concentration, the measured concentration and permissible value of ith key gas respectively.

The principle of this method can be summarised in three steps. In the first step, the relative concentrations of the different key gases are calculated. In the second step, the letter-coding of key gases is constructed from the relative concentrations. This is done on the basis of the importance of the different key gases in the ensemble. Table 13 shows the meaning of the letters. In the final step, the faults are identified using the letter codes shown in Table 14.

To improve the fault diagnosis accuracy and to reduce the cases of non-decision, in case of non-coincidence between the codes found and those given in Table 14, the code of the table closest to the code found must be determined and used to identify the fault. For this purpose, the authors recommend selecting codes from the table first according to the coincidence of the position of the letter A with the fault code found. If there is more than one possibility, the code with the coincidence in the position of the second most significant letter should be selected and so on.

The methods based on key gas approach are rarely used for fault severity evaluation. They present the following drawbacks [54]:

- They can only be used manually by experienced personnel;
- The main gas in the sample is often not one of the key gases in the method;
- It is often difficult to determine which is the main gas and how minor gases should be taken into account;
- The diagnostic process for these methods is a one-step process.

TABLE 12 Key gas method proposed by Fallou [55].

	Key gas percentage (%)							
Fault type	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	C_3H_x	CO	CO_2
Low-energy discharge (PD1)	88	7	2	-	-	1	1	1
High-energy discharge (PD2)	55	7	5	6	15	6	1	6
Arcing	39	10	-	6	35	3	4	2
Overheating, oil 300°C	-	37	13	19	-	31	-	-
Overheating, oil 500°C	17	25	8	25	-	23	-	-
Overheating, oil 800°C	16	16	6	41	-	21	-	-
Overheating, paper 300°C	26	1	-	-	-	-	-	73
Overheating, paper 500°C	6	1	-	-	-	-	33	59
Overheating, paper 800°C	9	8	1	4	-	1	50	25

TABLE 13 Letter-coding of key gases [50].

Letter	Fault type
A	Main fault gas with maximum relative concentration
B	Gas with a high content and relative concentration at the second level among the key gases under consideration $c_r^i \geq 1$
C	Gas with a relative concentration at the second and third level among the key gases under consideration $c_r^i < 1$
D	All other gases

4.2 | Methods based on gas ratios approach

Gas ratio methods are based on the correlation between the fault-related gases ratios and the type and/or severity of the fault. In these methods, a code based on gas ratios is used as a fault indicator. The first methods using ratios of gas concentrations were developed by Rogers and Doernenburg. These methods were considered promising because they eliminate the effect of the quantity of individual gases used in the key gas methods, with one gas being measured per unit of another. Following Doernenburg and Rogers, many traditional gas ratio methods have been proposed in the literature. This section reviews them.

The Doernenburg ratios method (DRM) was proposed in 1974 by Doernenburg [56]. This method uses four gas ratios, namely CH_4/H_2, C_2H_2/C_2H_4, C_2H_2/CH_4 and C_2H_6/C_2H_2, to diagnose corona, arcing and thermal decomposition. Table 15 shows the proposed fault diagnosis based on ranges of gas ratios. The DRM is recommended in IEEE Std C57.104 and is applied provided that the concentration of at least one of the key gases exceeds the permissible concentration values given in Table 16 by the following proportions; at least twice for H_2, CH_4, C_2H_4 and C_2H_2 and at least once for the other gases [56]. The main drawback of this method is that it does not allow the

TABLE 14 Fault diagnosis by characteristic gas ensembles method [50].

	Key gas				
Fault type	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2
Overheating, $T < 300$°C	C, D	B	A	C, D	D
Overheating, 300°C $< T <$ 700°C	D	A	C	B	D
Overheating, $T >$ 700°C	D	B	C	A	D
Partial discharges	A	C	D	D	D
Discharges of low energy	A	C	D	D	B
Discharges of high energy	B	C	D	D	A
Combination of faults with prevalence of an electrical fault	D	B	D	C	A
Combination of faults with prevalence of a thermal fault	C, D	A	B	D	C, D

TABLE 15 Interpretation scheme by DRM [55].

Fault type	$\frac{CH_4}{H_2}$	$\frac{C_2H_2}{C_2H_4}$	$\frac{C_2H_6}{C_2H_2}$	$\frac{C_2H_2}{CH_4}$
Thermal decomposition	>1.0	<0.75	<0.3	>0.4
Corona (low intensity partial discharges)	<1.0	/	<0.3	>0.4
Arcing (High intensity partial discharges)	0.1–1.0	>0.75	>0.3	<0.4

severity of the faults to be assessed. Nevertheless, it is widely used nowadays to assess the fault type of power transformers.

Following Doernenburg and based on the Halstead's thermodynamic model on the generation of hydrocarbon gases in insulation oil [57], Rogers proposed a ratio method allowing to assess the fault severity. Rogers Ratios Method (RRM) was first proposed in 1975 with four gas ratios, namely CH_4/H_2, C_2H_6/CH_4, C_2H_2/C_2H_6 and C_2H_2/C_2H_4 [58]. At the time of its introduction in 1975, in addition to the normal state, 11 kinds of faults were diagnosed. This method was inspired by the one introduced at the Central Electricity Generation Board (CEGB) in 1973 [59]. Therefore, Rogers' four ratios method is also known as the CEGB ratios method (RRM/CEGB). Table 17 shows the coding of gas concentration and Table 18 shows the proposed diagnoses.

In a first revision of RRM/CEGB method in 1978, the ratio of C_2H_6/CH_4 was removed. In this three-ratio version, the original 12 suggested diagnoses were replaced by only nine including the normal state [60]. This 1978 revision is included in IEC 60599-1978 [61] but not in IEEE Std C57.104. In the literature it is also known as the IEC standard method, RRM/IEC method, basic gas ratios method or IEC ratios method. Table 19 shows the proposed diagnoses and coding of gas concentration. The drawback of this method is the problem of interference between low- and high-energy discharges which can lead to misclassification.

TABLE 16 Permissible concentration values for DRM.

	Limit values (in ppm)	
Key gases	**Doernenburg [55]**	**IEEE C57.104 [22]**
H_2	200	100
CH_4	50	120
C_2H_6	15	65
C_2H_4	60	50
C_2H_2	15	35

TABLE 17 Coding of gas ratio (in ppm).

Ratio	Range	Code
$R_1 = C_2H_2/C_2H_4$	$R_1 < 0.5$	0
	$0.5 \leq R_1 < 3.0$	1
	$R_1 \geq 3.0$	2
$R_2 = CH_4/H_2$	$R_2 \leq 0.1$	5
	$0.1 < R_2 < 1.0$	0
	$1.0 \leq R_2 < 3.0$	1
	$R_2 \geq 3.0$	2
$R_3 = C_2H_4/C_2H_6$	$R_3 < 1.0$	0
	$1.0 \leq R_3 < 3.0$	1
	$R_3 \geq 3.0$	2
$R_4 = C_2H_6/CH_4$	$R_4 < 1.0$	0
	$R_4 \geq 1.0$	1

A second revision of RRM/CEGB method was proposed by Rogers in 1991 [40]. As in the 1978 revision, only three ratios are taken into account and the original 12 suggested diagnoses were replaced by six including the normal state.

Unlike the 1978 revision, the 1991 revision is included in IEEE Std C57.104–1991 and its 2008 and 2019 revisions. Table 20 shows the proposed diagnoses of RRM.

Another ratios method widely used in the literature is the IEC 60599 method. First proposed in IEC 60599–1999 [41], the IEC 60599 method has evolved from the RRM/IEC method through several modifications and adaptations. Like the RRM/IEC method, it uses the same three gas ratios as

TABLE 18 Interpretation scheme by RRM/CEGB method [57].

Fault type	R_1	R_2	R_3	R_4
Normal deterioration	0	0	0	0
Partial discharge	0	5	0	0
Slight overheating, $T < 150°C$	0	1/2	0	0
Slight overheating, $150°C \leq T < 200°C$	0	1/2	0	1
Slight overheating, $200°C \leq T < 300°C$	0	0	0	1
General conductor overheating	0	0	1	0
Circulating currents between core and tank	0	1	1	0
Circulating currents in winding	0	1	2	0
Flashover without power flow through	1	0	0	0
Arc with power flow through	1/2	0	1/2	0
Continuous sparking to floating potential	2	0	2	0
Partial discharge with tracking	1/2	5	0	0

TABLE 19 Interpretation scheme by RRM/IEC method [59].

Range	R_1	R_2	R_3
Coding			
<0.1	0	1	0
0.1–1.0	1	0	0
1.0–3.0	1	2	1
>3.0	2	2	2
Fault type	R_1	R_2	R_3
Interpretation scheme			
No fault	0	0	0
Low-energy partial discharge (PD1)	NS	1	0
High-energy partial discharge (PD2)	1	1	0
Low-energy discharge	1/2	0	1/2
High-energy discharge	1	0	2
Thermal fault, $T < 150°C$	0	0	1
Thermal fault, $150°C < T < 300°C$	0	2	0
Thermal fault, $300°C < T < 700°C$	0	2	1
Thermal fault, $T > 700°C$	0	2	2

diagnostic criteria but suggest different interpretations and ratio ranges. The nine suggested diagnoses of RRM/IEC method were replaced by six basic faults as shown in Table 21. The interpretation scheme of Table 21 can be used provided that at least one of the key gases exceeds the permissible concentration values given in the first row of Table 5.

Widely used in many countries like India, Brazil or Russia, the IEC 60599 method has inspired the methods used in their national standards. This method is included in the Indian standard IS 10593 [35]. In addition, a simplified version is proposed in order to obtain at least a rough distinction between three main faults rather than no diagnosis at all. Table 22 shows this simplified interpretation scheme. A modified version of IEC 60599 method using the same ratio ranges and interpretation scheme is proposed in the Russian Std CTO 34.01-23-003-2019 [43]. In the Russian Std, in addition to faults, the normal state is also diagnosed.

Like DRM, RRM/IEC method or IEC 60599 method, other methods based on dissolved gas ratios have been proposed in national Std and guidelines such as the ETRA ratios method of the Electrical Technology Research Association (ETRA) of Japan [62], the NBR 7274 method [63] of the Brazilian Association of Technical Standards, the ratios method of Ukrainian Std SOU-N EE 46.501 [64], the CIGRE ratios method of the International Council of Major Electrical Networks (CIGRE) [39], the ratios method of Russe Std RD 153-34.0-46.302-00 [44] or the ASTM method of American Society for Testing and Materials (ASTM) [31].

The NBR 7274 method of the Brazilian Association of Technical Standards is based on IEC 60599-1978 and is very similar at RRM/IEC method.

The CIGRE ratios method was suggested in CIGRE TF 15.01.01 considers five gas ratios, namely C_2H_2/C_2H_6, H_2/CH_4, C_2H_4/C_2H_6, C_2H_2/H_2, and CO_2/CO to diagnose transformer faults ranging from electrical faults to thermal faults to solid insulation faults as shown in Table 23. If all values of the different gas ratios are below the limits given in Table 23, then the transformer is in a normal state.

The CIGRE ratio method is mostly used in combination with the CIGRE key gas method. The interpretation scheme taking into account both methods is presented in Table 24 and the meaning of the letters is given in Table 25.

The ASTM ratio method is very similar to the Rogers' four ratios method. Indeed, it uses the same ratios as the latter. The

TABLE 20 Interpretation scheme by RRM [40].

Type de défaut	C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6
Normal	<0.1	0.1–1.0	<1.0
Low-energy density arcing – PD	<0.1	<0.1	<1.0
Arcing – High-energy discharge	0.1–3.0	0.1–1.0	>3.0
Low temperature thermal fault	<0.1	0.1–1.0	1.0–3.0
Thermal fault, $T < 700°C$	<0.1	>1.0	1.0–3.0
Thermal fault, $T > 700°C$	<0.1	>1.0	>3.0

TABLE 21 Interpretation scheme by IEC 60599 method [41].

Fault type	C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6
PD	Not significant	<0.1	<0.2
D_1	>1.0	0.1–0.5	>1.0
D_2	0.6–2.5	0.1–1.0	>2.0
T_1	Not significant	>1.0	<1.0
T_2	<0.1	>1.0	1.0–4.0
T_3	<0.2	>1.0	>4.0

TABLE 22 Simplified interpretation scheme of IEC 60599 method proposed in IS 10593 [35].

Fault type	C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6
Partial discharges	-	<0.2	-
Arcing	>0.2	-	-
Thermal fault	<0.2	-	-

TABLE 23 Fault diagnosis by CIGRE ratio method [38].

Ratio	Limit	Fault type
C_2H_2/C_2H_6	≥1.0	Arcing
H_2/CH_4	≥10.0	Partial discharges
C_2H_4/C_2H_6	≥1.0	Thermal fault
C_2H_2/H_2	≥2.0	Discharges in OLTC
CO_2/CO	≥10.0	Overheating, paper
	<3.0	Cellulosic degradation by electrical fault

TABLE 24 Interpretation procedure by both CIGRE ratios and key gases methods [38].

Ratios method	Key gases method	Interpretation
R_1	K_1	No action, transformer most probably healthy
R_2	K_2	Transformer most probably faulty, additional analyses needed
R_2	K_1	Possible incipient failure, additional analyses needed
R_1	K_2	Possibility of more than one failure, further investigations needed

TABLE 25 Letter-coding of CIGRE methods [38].

Letter	Interpretation
K_1	All key gases have concentrations lower than the concentration limits given in Table 11;
K_2	At least one of the key gases has a concentration greater than the concentration limits shown in Table 11;
R_1	All gas ratios have values lower than the limits given in Table 23;
R_2	At least one of gas ratio has value greater than the limits given in Table 23.

difference between the two methods is in the coding, the interpretations given for the combinations of codes and the number of faults diagnosed. Tables 26 and 27 show respectively, the coding and the proposed diagnoses of the ASTM ratios method [65].

The SOU-N EE 46.501:2006 method was proposed in 2007 in the standard regulating the implementation of dissolved gas analysis in the Ukrainian power engineering sector [64]. Table 28 shows the proposed diagnosed for the different ratio ranges. With this method, in addition to the diagnosis of the six basic IEC faults, it also allows the diagnosis of the normal state and creeping discharges (D_3) which are discharges that occur on the surface and in the solid insulation. The ratios method of Russian Std RD 153-34.0-46.302-00 was first proposed in 1989 and revised in the standard published in 2001. It takes into account the ratios of the RRM/IEC method as diagnostic criteria. Like the RRM/IEC method, nine diagnoses are proposed, but the ratio ranges are different. The ETRA ratios method uses three gas ratios calculated from the concentrations of C_2H_6, C_2H_4 and C_2H_2 to diagnose the 6 basic IEC faults. Tables 29 and 30 show, respectively, the coding and the proposed diagnoses of this method [62].

In addition to national standard methods, other ratios methods are proposed by scholars, such as the three ratios technique [66], the Muller, Schliesing and Soldner (MSS)

TABLE 26 Coding of gas ratio (in ppm).

Ratio	Range	Code
$R_1 = C_2H_2/C_2H_4$	$R_1 < 0.5$	0
	$0.5 \leq R_1 < 3.0$	1
	$R_1 \geq 3.0$	2
$R_2 = CH_4/H_2$	$0 < R_2 \leq 0.1$	1
	$0.1 < R_2 < 1.0$ or $R_2 = 0$	2
	$1.0 \leq R_2 < 3.0$	3
	$R_2 \geq 3.0$	4
$R_3 = C_2H_4/C_2H_6$	$R_3 < 1.0$	0
	$1.0 \leq R_3 < 3.0$	1
	$R_3 \geq 3.0$	2
$R_4 = C_2H_6/CH_4$	$R_4 < 1.0$	0
	$R_4 \geq 1.0$	1

TABLE 27 Interpretation scheme by ASTM ratios method [64].

Fault type	R_1	R_2	R_3	R_4
No fault	0	2	0	0
Partial discharge	0	1	0	0
Slight overheating, $T < 150°C$	0	3/4	0	0
Slight overheating, $150°C \leq T < 200°C$	0	3/4	0	1
Slight overheating, $200°C \leq T < 300°C$	0	4	0	1
Increase in all conductors	0	2	1	0
Circulating currents in winding	0	3	1	0
Circulating currents between core and tank	0	3	2	0
Flashover with very low-energy density	1	2	0	0
Arc with high-energy density	1/2	2	1	0
Arc with high-energy density	1	2	2	0
Continuous spark	2	2	2	0
Partial discharge with tracking	1/2	1	0	0

TABLE 28 Interpretation scheme by SOU-N EE 46.501:2006 method [64].

Fault type	C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6
No fault	Not significant	0.1–1.0	<0.2
PD	Not significant	<0.1	<0.2
D_1	>1.0	0.1–0.5	>1.0
D_2	>1.0	0.1–1.0	>2.0
D_3	<1.0	0.3–0.5	>5.0
T_{12}	Not significant	>1.0	<1.0
T_2	Not significant	>1.0	1.0–4.0
T_3	<0.2	>1.0	>4.0

TABLE 29 Coding of gas ratios of ETRA ratios method.

Ratio	Range	Code
$R_1 = C_2H_2/C_2H_4$	$R_1 \leq 0.01$	0
	$0.01 < R_1 < 0.2$	1
	$R_1 \geq 0.2$	2
$R_2 = C_2H_2/C_2H_6$	$R_2 \leq 0.01$	0
	$0.01 < R_2 < 1.0$	1
	$1.0 \leq R_2 < 10.0$	2
	$R_2 \geq 10.0$	3
$R_3 = C_2H_4/C_2H_6$	$R_3 < 1.0$	0
	$1.0 \leq R_3 < 4.0$	1
	$4.0 \leq R_3 < 1$	
	$R_3 \geq 10.0$	3

TABLE 30 Interpretation scheme by ETRA ratios method [62].

Fault type	R_1	R_2	R_3
Partial discharge	2	1	0/1/2
Low-energy discharge	2	2	0/1/2
High-energy discharge	2	2	3
High-energy discharge	2	3	/
Thermal fault, $T < 300°C$	0	0	0
Thermal fault, $300°C < T < 700°C$	0	0/1	1
Thermal fault, $T > 700°C$	0	0/1	2/3

method [67], the one-ratio methods [23], the C_3 hydrocarbon method [68], and the Hyosun Corporation ratios method [69].

Developed by Korean scientists from HYOSUNG Corporation in collaboration with Duval, the Hyosung Corporation ratios method was proposed in 2013 [69]. This method uses six gas ratios as shown in Table 31 to diagnose the six basic IEC faults. The principle of this method is to use combinations of gas ratios to distinguish between the faults. First, the pair of gas ratios (R_1, R_2) is used to distinguish between thermal and electrical faults. Once this is done, each group is treated separately from the other. For thermal faults, the pair of gas ratios (R_5, R_6) is used to identify the T_1 fault from other thermal faults. After distinguishing the T_1 fault, the gas ratio pairs (R_2, R_5) is used to distinguish the T_2 fault from the T_3 fault. For electrical faults, the gas ratio pairs (R_2, R_5) is used to distinguish between the PD, D_1 and D_2 faults. Figure 3 shows the flowchart of this method.

In 2018, Gouda et al. proposed the three ratios technique [66]. This ratio method uses three new gas ratios selected on the basis of their ability to distinguish faults according to their severity. Table 32 shows the ratio ranges and corresponding codes, and Table 33 shows the interpretation scheme. The interpretation scheme of Table 33 can be used provided that at least one of the key gases exceeds the permissible concentration values given in the first row of Table 5. If this condition is not met, the transformer is considered to be in a normal state.

TABLE 31 Gas used in the HYOSUN Corporation gas ratio method.

Ratio	R_1	R_2	R_3	R_4	R_5	R_6
Expression	$\frac{CH_4}{H_2}$	$\frac{C_2H_2}{C_2H_4}$	$\frac{C_2H_2}{CH_4}$	$\frac{C_2H_6}{C_2H_2}$	$\frac{C_2H_4}{C_2H_6}$	$\frac{C_2H_4}{CH_4}$

Named after its authors, Müller, Schliesing and Soldner, the MSS method was proposed in 1974. It uses, in addition to the seven main fault-related gases widely used in the literature, propene to calculate five gas ratios (C_2H_4/C_2H_6, H_2/C_2H_4, C_2H_4/C_2H_6, C_2H_4/C_3H_6, CO_2/CO) to be used as diagnostic criteria. Table 34 shows the coding and interpretation scheme proposed by the method. The simplified version of this method shown in Table 35 is used in Germany [70].

Like MSS method, the C_3 hydrocarbons method uses the concentrations of C_3 hydrocarbons (C_3H_6 and C_3H_8), to diagnose faults in power transformers. Used in Poland as a diagnostic method, the ratios C_3H_6/C_3H_8 and C_2H_4/C_3H_8 are used to confirm the temperature range of thermal faults as shown in Table 36 [71].

One ratio method like CO_2/CO ratio method uses the ratio of two main gases to determine the state of the power transformer. The CO_2/CO ratio method is a method used as an indicator of the thermal decomposition of solid insulation.

This method is based on the fact that in normal operation the rate of CO_2 production is usually 7–20 times higher than that of CO [71]. Discussed in IEC 60599 and IEEE C57.104 standards, Table 37 shows the corresponding faults for the different ranges of the ratio of this method.

Recent works by specialists in the CIGRE, IEC and IEEE working groups has updated the CO_2/CO ratio method by completing the interpretations for the different ranges.

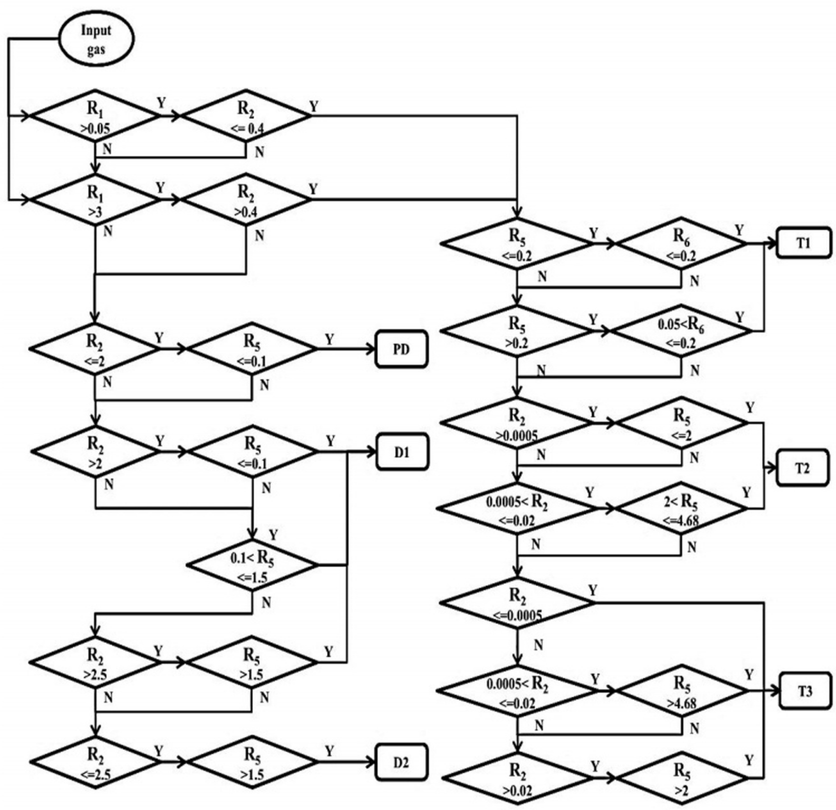

FIGURE 3 Flowchart of the HYOSUN Corporation gas ratio method [69].

TABLE 32 Coding of gas ratio (in ppm).

Ratio	Range	Code
$R_1 = \frac{C_2H_6+C_2H_4}{H_2+C_2H_2}$	$R_1 < 0.05$	0
	$0.05 \leq R_1 \leq 0.9$	1
	$R_1 > 0.9$	2
$R_2 = \frac{C_2H_2+CH_4}{C_2H_4}$	$R_2 < 1.0$	0
	$1.0 \leq R_2 \leq 3.5$	1
	$R_1 > 3.5$	2
$R_3 = \frac{C_2H_2}{C_2H_4}$	$R_3 < 0.05$	0
	$0.05 \leq R_3 \leq 0.5$	1
	$R_3 > 0.5$	2

TABLE 33 Interpretation scheme by TRT [66].

Fault type	R_1	R_2	R_3
Thermal fault, $T > 700°C$	1/2	0	0/1
Thermal fault, $300°C < T < 700°C$	1/2	1	0/1
Thermal fault, $150°C < T < 300°C$	1/2	2	0/1
Thermal fault, $T < 150°C$	1	/	0
Low-energy partial discharge	0	1/2	0/1
High-energy partial discharge	0	1/2	2
High-energy discharge	0/1	0/1	2
Low-energy discharge	1/2	2	2
Mix of electrical and thermal faults	2	0/1	2

Therefore, the new views on the interpretation of carbon oxides and CO_2/CO ratio are as follows [71]:

- CO > 1000 ppm and/or $CO_2/CO < 3$, without significant amounts of other fault gases, do not indicate a carbonisation fault in the paper, but are due to oxidation of the mineral oil under conditions that correspond to a low oxygen content in the oil;
- CO > 1000 ppm and $CO_2/CO < 3$ with the presence of significant amounts of other fault-related gases and furans are considered to confirm the involvement of the paper in the occurrence of a fault, with possible carbonisation;
- CO_2 >10,000 ppm, $CO_2/CO > 20$ and high furan values (>5 ppm) show a slight overheating of temperature below 160°C with slow degradation of the paper until low values of the degree of polymerisation of the paper are reached.

Another one ratio method discussed in IEC 60599 is the one of O_2/N_2. At equilibrium with air, the concentrations of oxygen and nitrogen are in such proportions that the O_2/N_2 ratio is about 0.5 [22, 23]. The decrease in this ratio during transformer operation reflects the oxidation of the oil due to its overheating [71]. The O_2/N_2 ratio method uses this ratio to confirm thermal faults. The last one ratio method addressed in IEC 60599 is the one of C_2H_2/H_2. In power transformers with tap-changer, contamination of the main tank oil may occur. Thus, values between 2 and 3 of the C_2H_2/H_2 ratio are considered indicative of contamination of the transformer's main tank oil by oil or gas from the tap-changer [22, 23].

TABLE 34 Interpretation scheme by MSS method [67].

Range	$R_1 = C_2H_2/C_2H_6$	$R_2 = H_2/C_2H_4$	$R_3 = C_2H_4/C_2H_6$	$R_4 = C_2H_4/C_3H_6$	$R_5 = CO_2/CO$
Coding					
<0.3	0	0	0	0	1
0.3 to <1.0	1	0	0	1	1
1.0 to <3.0	1	1	1	2	1
3.0 to <10.0	2	2	1	3	0
≥10.0	2	3	1	3	2

Fault type	R_1	R_2	R_3	R_4	R_5
Interpretation scheme					
Normal ageing	0	0	0	0	0
High-energy discharge	2	1	1	2/3	1
Low-energy discharge	2	2	1	2/3	1
High-energy partial discharge	1	3	0	Not significant	0
Low-energy partial discharge	0	3	0	Not significant	0
Local overheating, $T < 300°C$	0	0	0	1	2
Local overheating, $300°C < T < 1000°C$	0	0	1	2	2
Local overheating, $T > 1000°C$	1	0	1	2/3	2
Thermal fault and discharge	1	1	1	2	2
Thermal fault and partial discharge	0	3	1	2	2

TABLE 35 Simplified version of MSS method [70].

Fault type	R_4
Local overheating, $T < 300°C$	0.3 to <1.0
Local overheating, $300°C < T < 1000°C$	1.0–3.0
Local overheating, $T > 1000°C$	>3.0

TABLE 36 Interpretation scheme by C3 hydrocarbons method [68].

	Temperature range (°C)		
Ratio	150–300	300–700	>700
C_3H_6/C_3H_8	<2.0	2.0–6.0	>6.0
C_2H_4/C_3H_8	<3.0	3.0–15.0	>15.0

TABLE 37 Interpretation scheme by CO_2/CO ratio method [22, 23].

Ratio	Range	Fault type
$X = CO_2/CO$	$X \leq 3$	Thermal fault with high deterioration of the cellulose
	$3 \leq X \leq 5$	Thermal fault with medium deterioration of the cellulose
	$5 \leq X \leq 7$	Thermal fault with low deterioration of the cellulose
	$7 \leq X \leq 11$	Normal
	$X \geq 11$	Severe and rapid electrical discharges

On the other hand, other researchers have looked at the existing ratio methods to propose improved versions. These include Souahlia with the Doernenburg method, Dhote with the MRR/CEI method and Taha with the MRR/CEI and MRR/CEGB methods. The modified version of the DRM was proposed in 2013 by Souahlia et al. [72]. With this modified version, the severity of the fault can be diagnosed. Table 38 shows the faults diagnosed by this modified DRM.

Improved versions of MRR/IEC method were proposed in the literature. This is the case in 2012 with the work of Dhote et al. [73] and in 2016 with the work of Taha et al. [74] who proposed modified versions of the method in which, the gas ratio ranges are not changed, but new fault code combinations are added to improve the diagnostic accuracy of the method. In ref. [75], Taha et al. propose a revised version of this method in which the ratio ranges are changed and the new values are determined using the particle swarm optimisation algorithm and fuzzy logic. Tables 39 and 40 show the modified versions of the RRM/IEC method proposed in refs. [73, 75] respectively. The Figure 4 shows the flowchart of modified RRM/IEC method proposed in ref. [74].

Two modified versions of RRM/CEGB method were recently proposed by Taha et al. in 2016 [74] and 2021 [75]. In ref. [74], the gas ratio ranges are not changed, but new fault code combinations are added to improve the diagnostic accuracy of the method. Whereas in ref. [75], the ratio ranges are

TABLE 38 Interpretation scheme by modified DRM proposed by Souahlia et al. [72].

Fault type	C_2H_2/C_2H_4	CH_4/H_2	C_2H_2/CH_4	C_2H_6/C_2H_2
PD	<0.75	<0.10	<0.10	>1.00
D_1	>1.00	0.10–1.00	0.10–0.30	<0.10
D_2	≥0.75	0.10–1.00	0.10–0.30	≤1.00
T_1	<0.75	>1.00	<0.10	>1.00
T_2	<0.75	>1.00	0.10–0.30	>1.00
T_3	<0.75	>1.00	>0.30	>1.00

TABLE 39 Interpretation scheme by modified RRM/IEC method proposed by Dhote et al. [73].

Fault type	R_1	R_2	R_3
Normal	0	0	0
Low-energy partial discharge	0	0	2
Thermal fault, $150°C < T < 300°C$	0/1	1	1
Thermal fault, $T < 150°C$	0	1	2
Flashover, intermittent sparking	1	0	0
Thermal fault, $T > 700°C$	1	1	2
Circulating currents between core and tank	1	2	0/2
Circulating currents in winding	1	2	1
High-energy partial discharge, corona	2	0/1	0
High-energy discharge, arcing	2	0/1	1
Low-energy discharge, continuous sparking	2	0/1	2
Severe arcing, overheating of oil ($T > 1000°C$)	2	2	0/1/2

changed and determined using the particle swarm optimisation algorithm and fuzzy logic. Tables 41 and 42 show, respectively, the new coding and the proposed diagnoses of the modified version of the RRM/CEGB method proposed in ref. [75]. Figure 5 shows the flowchart of the one proposed in ref. [74].

In ref. [74], in addition to modified versions of the RRM/CEGB and RRM/IEC methods, the authors proposed a combined technique based on the results of two previous ones, as shown in Figure 6 in this combined technique Diag1 is the output of modified MRR/IEC method and Diag2 the output of modified MRR/CEGB method.

Due to their ease of implementation and understanding, ratio methods are the most commonly used traditional methods in the literature. However, these methods have several drawbacks [76]:

- No decision in certain cases that do not fall within the specified codes;
- Inconclusive assessment of fault severity;
- Uncertainty about the validity of gas report ranges;
- The diagnostic process for these methods is a one-step process

TABLE 40 Interpretation scheme by modified RRM/IEC method proposed by Taha et al. [75].

Range	R_1	R_2	R_3
Coding			
≤0.12	0	1	0
0.12–0.18	0	0	0
0.18–0.3	0	2	0
0.3–1.0	1	2	0
1.0–1.3	1	2	1
1.3–3.42	2	2	1
>3.42	2	2	2
Fault type	R_1	R_2	R_3
Interpretation scheme			
Partial discharge	0	1	0/1
	0	1	2
	0	0	0
	1	0/1	0
	1	0	1
	2	0	0
Low-energy discharge	1	1	1/2
	2	1	0/1/2
	2	0	1/2
High-energy discharge	1	0	2
	1	2	0/1/2
	2	2	0/1/2
Thermal fault, $T < 300°C$	0	2	0
Thermal fault, $300°C < T < 700°C$	0	2	1
Thermal fault, $T > 700°C$	0	0/2	2

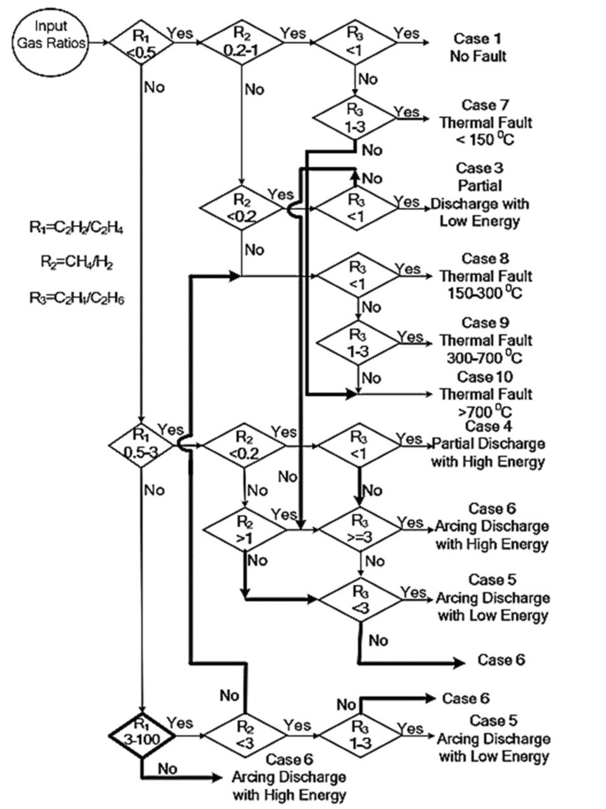

FIGURE 4 Flowchart of modified RRM/IEC method proposed by Taha et al. [74].

TABLE 41 Coding of gas ratio (in ppm).

Ratio	Range	Code
$R_1 = C_2H_2/C_2H_4$	$R_1 \leq 0.45$	0
	$0.45 < R_1 \leq 1.37$	1
	$R_1 > 3.0$	2
$R_2 = CH_4/H_2$	$R_2 \leq 0.18$	5
	/	0
	/	1
	$R_2 > 0.18$	2
$R_3 = C_2H_4/C_2H_6$	$R_3 \leq 1.0$	0
	$1.0 < R_3 \leq 3.5$	1
	$R_3 > 3.5$	2
$R_4 = C_2H_6/CH_4$	$R_4 \leq 0.22$	0
	$R_4 > 0.22$	1

4.3 | Graphical methods

Graphical methods or percentage methods use graphical representations to diagnose faults in power transformers. They are based on the projection in a two- or three-dimensional plane of a point representing the power transformer condition. Each side of the graph represents the relative proportions of concentrations or combinations of concentrations of key gases. Many graphical methods have been proposed in the literature, such as Shanks' graphical method [59], ETRA's squares [77], Church's logarithmic nomograph [45], Duval's triangles [22], Gouda's triangle [78], Duval's pentagons [79], Denkyoken method [80], Mansour pentagon [81], or Gouda heptagon [82].

The logarithmic nomogram method is a one of most popular graphic method. Developed in 1975 by Church for the US bureau of reclamation, the logarithmic nomogram method aims to provide both a graphical representation of the data and a means of interpreting it. The nomograph consists of vertical logarithmic scales representing the concentrations of the different gases. The measured gas concentrations are plotted in the nomograph and the respective points of adjacent nomographs are connected by straight lines. The slopes of these lines are the diagnostic criteria for determining the type of fault [45]. A visual comparison of the slopes of the line segments with the keys provided is all that is needed to identify the type of fault. Figure 7 shows the nomograph proposed by Church for the interpretation of dissolved gas analysis.

TABLE 42 Interpretation scheme by modified RRM/CEGB method proposed by Taha et al. [75].

Fault type	R_1	R_2	R_3	R_4
Partial discharge	0	5	0	0/1
	0	5	1	0/1
	1	5	0	0/1
	0	5	2	0
	0	2	0	0
	2	5	0	0
Low-energy discharge	0	5	2	1
	1	5	1	1
	2	5	0/1	1
	2	5	2	0/1
	2	2	1	0
High-energy discharge	2	2	2	1
	1	3	2	0/1
	1	2	1	0/1
	1	2	2	0/1
	2	2	0	0/1
	2	2	1	1
	2	2	2	0
	1	2	0	1
Thermal fault, $T < 300°C$	0	2	0	1
Thermal fault, $300°C < T < 700°C$	0	2	1	0/1
Thermal fault, $T > 700°C$	0	2	2	0/1

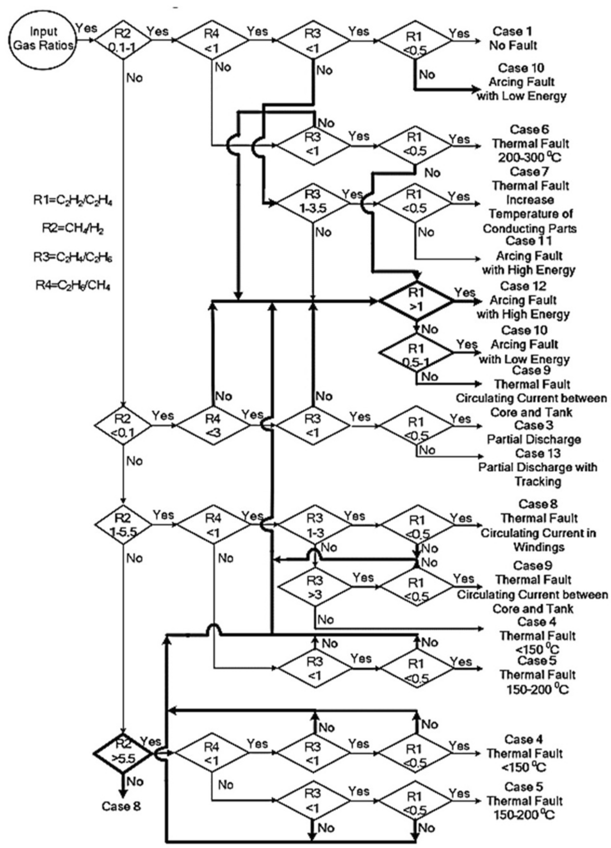

FIGURE 5 Flowchart of modified RRM/CEGB method proposed by Taha et al. [74].

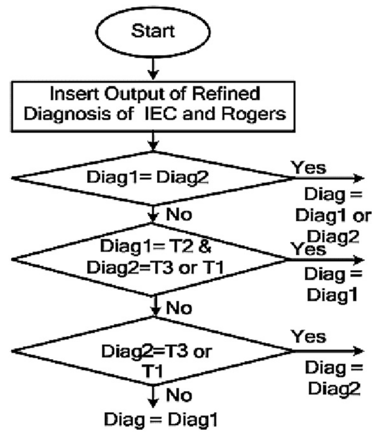

FIGURE 6 Flowchart of modified RRM/CEGB method proposed by Taha et al. [74].

The ETRA squares method is a two-axis graphical method proposed in the Japanese national standard, where the axes are represented by the ratios of the concentrations of C_2H_6, C_2H_4 and C_2H_2 gases. Two squares are proposed in this method (type A and type B) and their surfaces are subdivided into five fault regions labelled PD, T_1, T_2, T_3 and (DT or T_3) for type A and seven fault regions labelled PD, D_1, D_2, T_1, T_2, T_3 and (DT or T_3) for type B as shown in Figure 8. The intersection point obtained from the perpendicular plots of the gas ratio values of each axis indicates the corresponding fault type.

The Duval triangle method is probably the most popular of graphical methods. It is a graphical method with three axes, where the axes represent the percentages of the following key gases: CH_4, C_2H_4 and C_2H_2. These percentages are calculated using Equation (2):

$$\begin{cases} \%CH_4 = 100CH_4/(CH_4 + C_2H_4 + C_2H_2) \\ \%C_2H_4 = 100C_2H_4/(CH_4 + C_2H_4 + C_2H_2) \\ \%C_2H_2 = 100C_2H_2/(CH_4 + C_2H_4 + C_2H_2) \end{cases} \quad (2)$$

Based on Duval's experience on Hydro-Quebec transformers, the Duval triangle method was first proposed in 1974 [83] and revised in 1980 and 1993 [84]. In the original version, the whole triangular area was subdivided into six fault zones labelled "a" (high energy arc discharge), "b" (low energy arc discharge), "c" (partial discharges), "d" (hot spots of temperature T < 200°C), "e" (hot spots of temperature 200°C < T < 400°C) and "f" (hot spots of temperature T > 400°C) as shown in Figure 9a. In the revised version, the whole triangular area has been subdivided into seven fault regions labelled PD, D_1, D_2, T_1, T_2, T_3 and DT as shown in Figure 9b. This triangle is also known as Triangle 1 of Duval.

The (x, y) coordinates of the point of intersection of the three axes are calculated from Equation (3):

$$\begin{cases} x = 100 - \%C_2H_2 - \%CH_4 \cos\left(\frac{\pi}{6}\right)\cot\left(\frac{\pi}{3}\right) \\ y = \%CH_4 \cos\left(\frac{\pi}{6}\right) \end{cases} \quad (3)$$

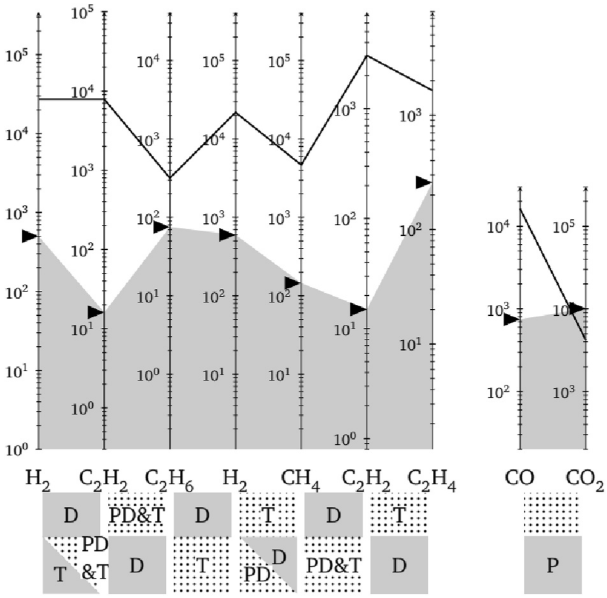

FIGURE 7 Church's nomograph [45].

However, Triangle 1 does not take into account H_2 and C_2H_6 gases in the fault diagnosis process, which limits its ability to accurately detect partial discharges and thermal faults. In order to overcome this limitation, Duval introduces in 2008 two triangles: Triangle 4 constructed from the concentrations of H_2, CH_4 and C_2H_6 gases and Triangle 5 constructed from the concentrations of CH_4, C_2H_4 and C_2H_6 gases [85]. The procedure for using these two triangles is as follows: If triangle 1 returns a T_1 or T_2 thermal fault or a PD fault, then triangle 4 should be used for clarity. Triangle 5 is only used if triangle 1 has identified the fault as T_2 or T_3. Figure 10 shows Duval triangles 4 and 5.

The Duval triangle method is only applied if there is a suspicion of a fault following an increase in the concentration of at least one key gas exceeds the permissible limits given in Table 43.

A modified version of Duval's triangle 1 is proposed in 2017 by Siniša [86]. This modified version allows the diagnosis of new fault combinations in addition to the 6 basic IEC faults as shown in Figure 11.

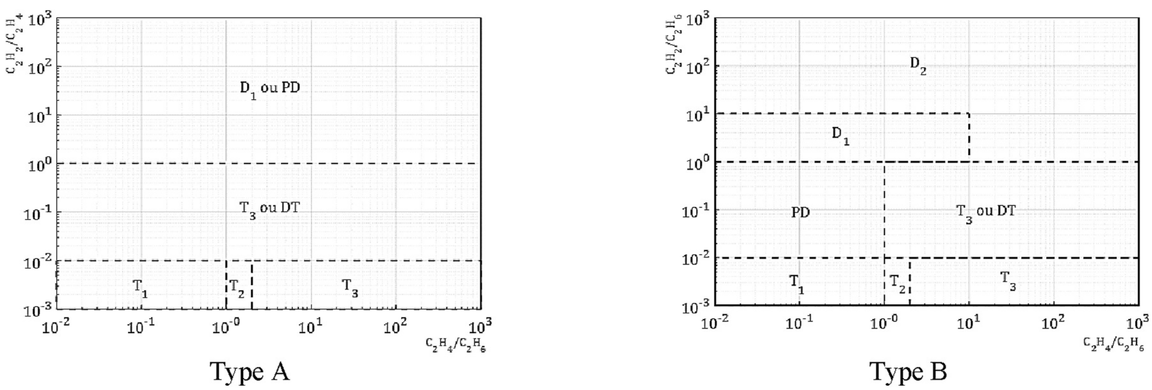

FIGURE 8 Two squares of ETRA square method [77].

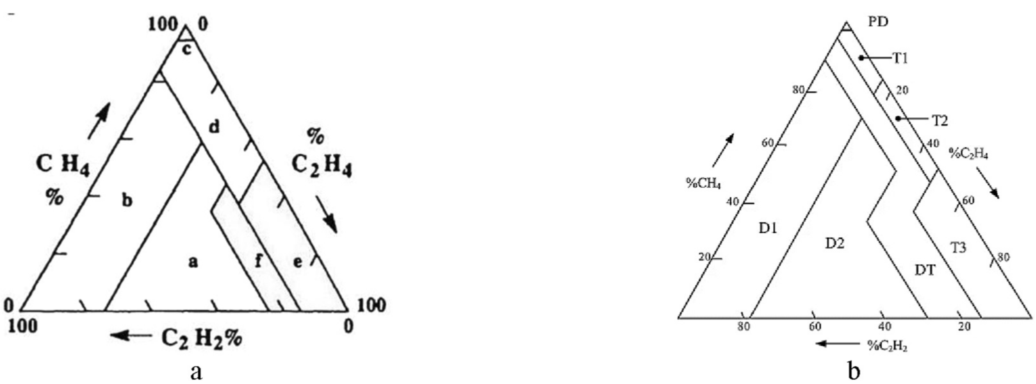

FIGURE 9 (a) Original [83] and (b) revised Duval triangle [22].

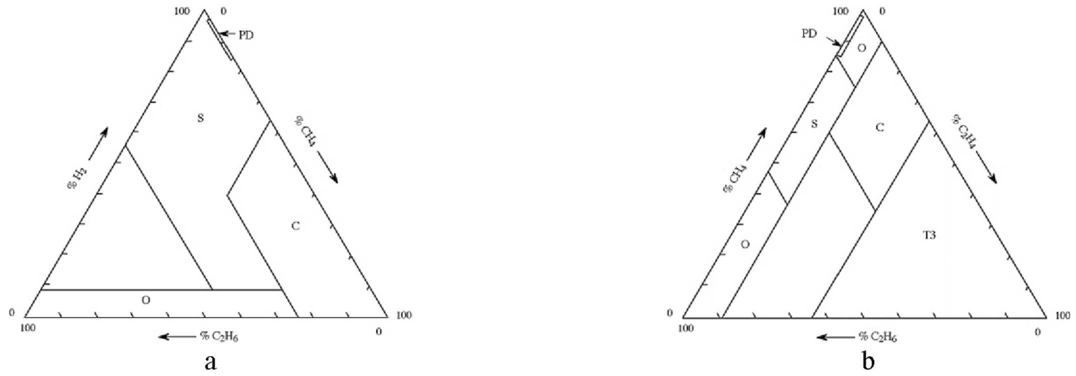

FIGURE 10 Duval triangles (a) 4 and (b) 5 [85].

TABLE 43 Permissible limits of dissolved gases of the Duval triangle method [22].

Key gas	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	CO	CO_2
Limit values (in ppm)	100	75	75	75	3	700	700

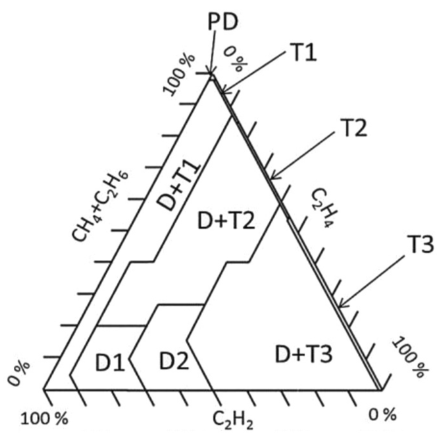

FIGURE 11 Modified version of Duval triangle 1 is proposed in [86].

Similar triangle methods were proposed in the literature such as the Gouda triangle, the GATRON triangle or the low-energy degradation triangle. The first of above methods is the GATRON triangle developed in 2013 by GATRON GmbH in Germany [87]. A method widely used in several European countries for monitoring power transformers, the three sides of the triangle are respectively the percentages of the gases H_2, C_2H_2 and CH_4^+ where CH_4^+ is the sum of the concentrations of the gases CH_4, C_2H_6, C_2H_4, C_3H_6 and C_3H_8. The percentages of the key gases are calculated using Equation (4).

The whole GATRON triangle is subdivided into seven fault zones labelled PD, D_1, D_2, T_1, T_2, T_3 and OLTC Leakages as shown in Figure 12a.

In 2017, the low energy degradation triangle method (LEDTM) is proposed by Moodley and Gaunt [88]. It is based on three low-energy dissolved gases, namely H_2, CH_4 and CO, to detect in the early stages the transition from normal to unhealthy state. With this method, the normal state and the six basic IEC faults are diagnosed using a triangular shape constructed from the concentrations of the above low-energy dissolved gases as shown in Figure 12b.

$$\begin{cases} \%H_2 = 100H_2/(H_2 + C_2H_2 + CH_4{}^+) \\ \%C_2H_2 = 100C_2H_2/(H_2 + C_2H_2 + CH_4{}^+) \\ \%CH_4{}^+ = 100CH_4{}^+/(H_2 + C_2H_2 + CH_4{}^+) \end{cases} \tag{4}$$

The Gouda triangle method is a DGA-based graphical method proposed in 2018 by Gouda et al. [78]. Similar to DTM, it also diagnoses electrical faults, thermal faults and the combination of both. However, unlike DTM, it uses the concentrations of the gases H_2, CH_4, C_2H_6, C_2H_4 and C_2H_2 and the sides of the triangle represent the percentages of three ratios R_1, R_2 and R_3 calculated from Equation (5).

The whole triangular area of the Gouda's triangle is subdivided into seven fault zones labelled PD, D_1, D_2, T_1, T_2, T_3 and DT as shown in Figure 12c. Like DTM, GTM is only applied if there is a suspicion of a fault following an increase in the concentration of at least one key gas exceeds the permissible limits given in the first row of Table 5.

$$\begin{cases} \%R_1 = 100\mathrm{R}_1/(R_1 + R_2 + R_3) \\ \%R_2 = 100\mathrm{R}_2/(R_1 + R_2 + R_3) \\ \%R_3 = 100\mathrm{R}_3/(R_1 + R_2 + R_3) \end{cases}$$

with (5)

$$\begin{cases} R_1 = CH_4/(CH_4 + C_2H_6 + C_2H_4 + C_2H_2) \\ R_2 = C_2H_2/(H_2 + CH_4 + C_2H_6 + C_2H_4) \\ R_1 = C_2H_4/(H_2 + CH_4 + C_2H_6 + C_2H_2) \end{cases}$$

The (x, y) coordinates of the point of intersection of the three axes are calculated from Equation (6):

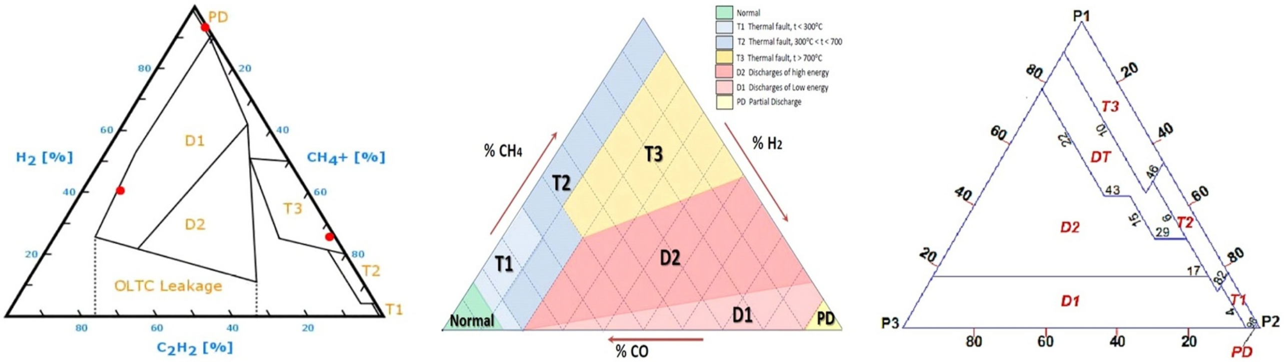

FIGURE 12 (a) GATRON triangle [87] (b) Low-energy degradation triangle [88] and (c) Gouda triangle [78].

$$
\begin{cases}
x = 100 - \%R_2 - \%R_3 \cos\left(\frac{\pi}{6}\right)\cot\left(\frac{\pi}{3}\right) \\
y = \%R_3 \cos\left(\frac{\pi}{6}\right)
\end{cases}
\tag{6}
$$

Another triangle method was proposed in 2020 by Dukarm et al. [89]. This graphical method known as the DGA 4-simplex method is a higher-dimensional version of the DTM. It is a combined graphical method that uses the results returned by 10 triangles for the diagnosis of faults in power transformers. The triangles used in the diagnostic procedure are constructed from the concentrations of 3 of the 5 main key gases as shown in Figure 13. The special feature of this method is that not only does it take all the gases into account in the interpretation, but it also returns several diagnoses suggested by different points of view (the different triangles). Triangles A, D, and I correspond to Duval triangles 1, 4, and 5, respectively, but the order of the gases is reversed for triangles 4 and 5.

To take into account all the five main fault-related gases and to overcome the drawbacks of Duval triangles, Duval was proposed in 2014 two graphical methods known as Duval pentagons (type 1 and 2) [79]. Based on the concentrations of five key gases (H_2, CH_4, C_2H_6, C_2H_4 and C_2H_2), each pentagon is subdivided into seven zones corresponding to the seven identifiable faults as shown in Figure 14.

In the Duval pentagon type 1, in addition to the six basic IEC faults, the stray gas area (S), which corresponds to the occurrence of gas during normal transformer operation is added. In the Duval pentagon type 2, the areas for thermal faults are redefined to provide more information on the involvement of the paper in the occurrence of a thermal fault. This pentagon is then used when the type 1 pentagon returns a thermal fault, such as T_1, T_2 or T_3.

The fault zone is identified by the centroid of the pentagon obtained from the relative percentages of five key gases. The (C_x, C_y) coordinates of these centroid are calculated from the Equation (7). The parameter y_i can be found by replacing the cosine with the sine in the x_i expressions.

$$
\begin{cases}
C_x = \dfrac{1}{6}\dfrac{\sum_{i=0}^{4}(x_i + x_{i+1})(x_i y_{i+1} - x_{i+1} y_i)}{\frac{1}{2}\sum_{i=0}^{4}(x_i y_{i+1} - x_{i+1} y_i)} \\[2ex]
C_y = \dfrac{1}{6}\dfrac{\sum_{i=0}^{4}(y_i + y_{i+1})(x_i y_{i+1} - x_{i+1} y_i)}{\frac{1}{2}\sum_{i=0}^{4}(x_i y_{i+1} - x_{i+1} y_i)}
\end{cases}
\tag{7}
$$

With

$$
\begin{cases}
x_0 = \%\mathrm{H_2} \cos\left(\frac{\pi}{2}\right) \\
x_1 = \%\mathrm{C_2H_6} \cos\left(\frac{\pi}{2} + \frac{2\pi}{5}\right) \\
x_2 = \%\mathrm{CH_4} \cos\left(\frac{\pi}{2} + \frac{4\pi}{5}\right) \\
x_3 = \%\mathrm{C_2H_4} \cos\left(\frac{\pi}{2} + \frac{6\pi}{5}\right) \\
x_4 = \%\mathrm{C_2H_2} \cos\left(\frac{\pi}{2} + \frac{8\pi}{5}\right)
\end{cases}
\tag{8}
$$

A combination of the two Duval pentagons was proposed in 2020 by Cheim et al. [90]. The aim of this combination is to reduce all the features of the two original pentagons to a single geometry and to provide more precision on the involvement of the insulation system in the occurrence of the fault. The combined pentagon results in a number of 10 fault zones as shown in Figure 15a where the 6-thermal fault areas are defined in Table 44.

One year later the Duval pentagons, a novel pentagon shape method was proposed by Mansour for the interpretation of dissolved gas concentrations [81]. As in the Duval

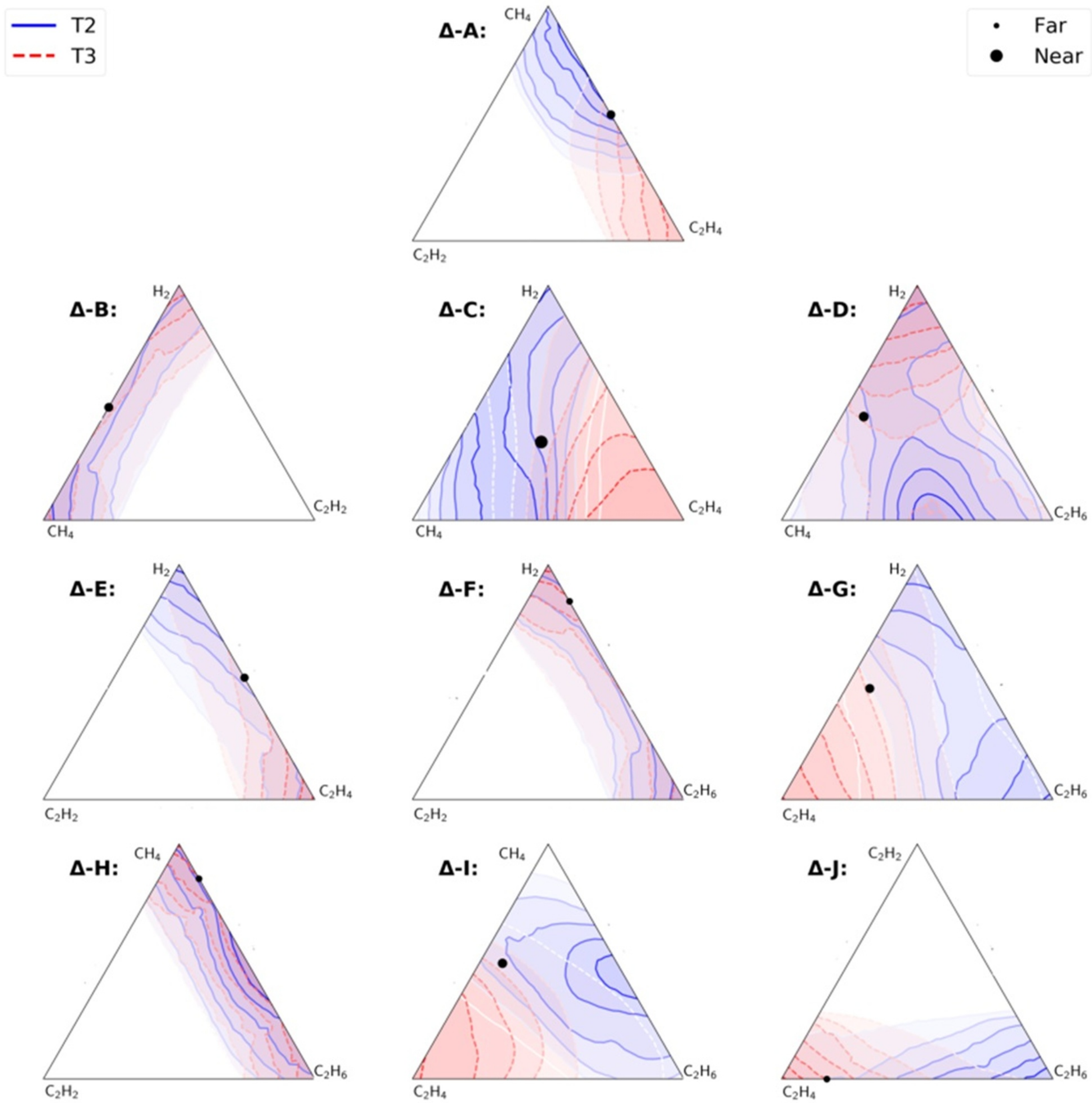

FIGURE 13 The ten triangular faces of the DGA 4-simplex method [89].

pentagons, the percentages of the five dissolved gases H_2, CH_4, C_2H_6, C_2H_4 et C_2H_2 represent the axes. The whole pentagon area was subdivided into six labelled fault zones corresponding to the six basic IEC faults as shown in Figure 15b.

The Gouda heptagon method is a graphical method for power transformer fault diagnosis proposed in 2018 by Gouda et al. [82]. Based on the concentrations of the gases H_2, CH_4, C_2H_4, C_2H_6, C_2H_2, CO and CO_2, each side of the heptagon represents the relative percentages of the weighted key gases. The weighting factors of the key gases proposed by the authors are given in Table 45. As shown in Figure 16, in addition to the six basic IEC faults and the combination of electrical and thermal faults, the Gouda heptagon allows the diagnosis of three levels of cellulose degradation indicated as HCCD for high concentration of cellulose degradation, MCCD for medium concentration of cellulose degradation and LCCD for low concentration of cellulose degradation.

Other graphical methods based on comparison with labelled reference diagrams, rather than projection into the graphical form, have also been proposed in the literature such as Denkyoken method or radar chart method. Denkyoken method was developed in Japan by a special committee on "Conservation and Control of Oil Insulated Components by Gas-in-Oil Diagnosis". First proposed in 1980, it is used to diagnose faults in oil-insulated electrical equipment in general and power transformers in particular [80, 91]. The principle of this method is to construct the fault pattern from the

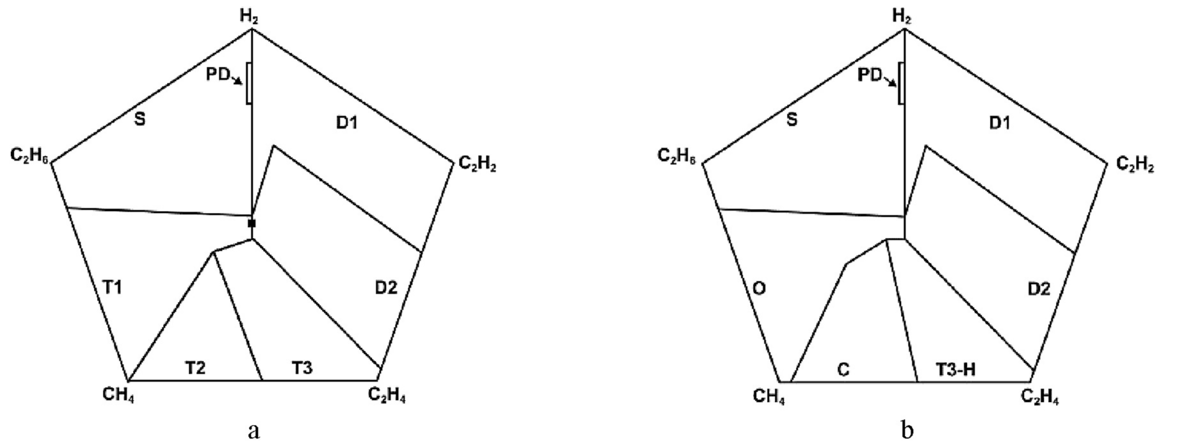

FIGURE 14 Duval pentagons (a) Type 1 and (b) 2 [79].

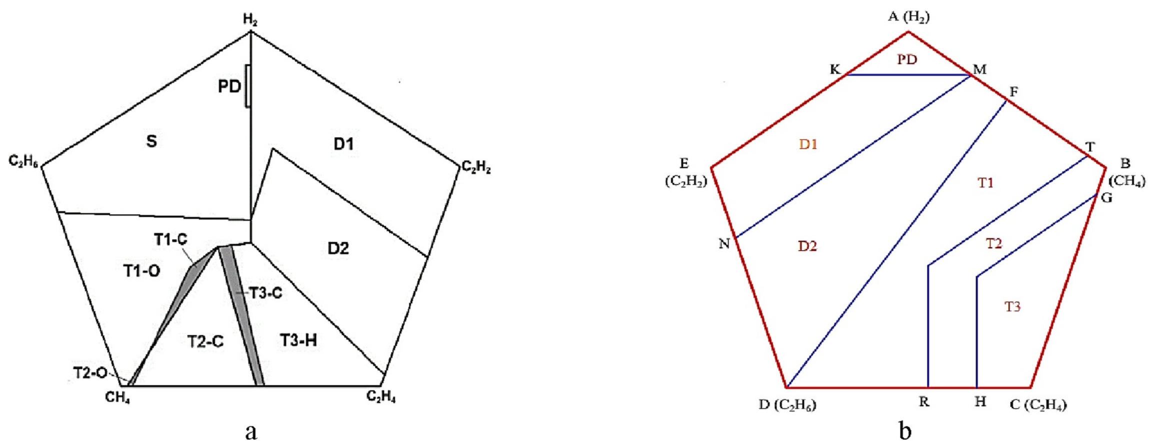

FIGURE 15 Combined Duval pentagons of Cheim et al. [90], (b) Mansour's pentagon [81].

TABLE 44 Meaning of thermal fault zones of combined pentagon proposed Cheim et al. [90].

Fault area	Fault type
T_1-O	Thermal fault, $T < 300°C$ without paper carbonisation
T_1-C	Thermal fault, $T < 300°C$ with paper carbonisation
T_2-O	Thermal fault, $300°C < T < 700°C$ without paper carbonisation
T_2-C	Thermal fault, $300°C < T < 700°C$ with paper carbonisation
T_3-C	Thermal fault, $T > 700°C$ with paper carbonisation
T_3-H	Thermal fault, $T > 700°C$ only in oil

TABLE 45 Weighting factors of the key gases in GHM [82].

Key gas	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	CO	CO_2
Weighting factor	3.5	2.9167	5.3846	7	116.6667	1	0.14

concentrations of the gases H_2, CH_4, C_2H_6, C_2H_4 and C_2H_2 and to compare the result obtained with the 13 labelled diagrams called nomograms proposed by the committee. Applied if at least one of the gas concentrations exceeds its permissible limit value, the fault patterns are constructed by following the steps [80, 87]:

- For a given sample of dissolved gases, identify and select the one with the highest absolute concentration (major gas);
- Determine the respective ratios of the concentrations of each gas to the major gas;
- Draw the fault pattern by placing the gases on the x-axis in the following order: H_2, CH_4, C_2H_6, C_2H_4 and C_2H_2, and the calculated ratios for each gas on the y-axis. Connect the points with lines.

The identification of the fault is done by comparing the fault pattern with the nomograms and the one with the best match determines the fault. Figure 17 shows the representation of the 13 reference nomograms and Table 46 the corresponding faults.

Many other researchers have studied this method and proposed other nomograms. This is the case of Shutenko and Kulyk who proposed other nomograms for the diagnosis of T_1 and T_2 thermal faults [92, 93], D_1 and D_2 faults [94, 95], PD faults [96], faults with ethane as major gas [97] and faults with acetylene as major gas [98].

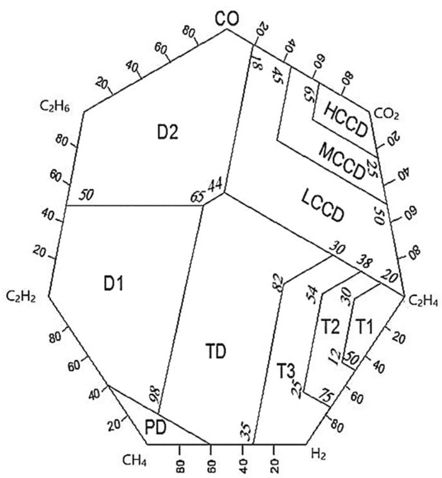

FIGURE 16 Gouda's heptagon [82].

Another graphical method based on direct comparison between fault patterns and reference labelled diagrams was proposed by specialists of the Urals Federal University in Russia under the coordination of Davydenko. Known as the radar chart method, it uses the concentrations of the gases H_2, CH_4, C_2H_4, C_2H_6, C_2H_2, CO and CO_2. The fault pattern is an 8-axis diagram where seven of the axes represent the concentrations of the key gases and the eighth axis their sum calculated from Equation (9).

$$S = H_2 + CH_4 + C_2H_6 + C_2H_4 + C_2H_2 + m(CO + CO_2) \tag{9}$$

Where m is the scaling factor generally taken to be 0.01.

The resulting image is then compared with 12 reference diagrams proposed by the authors, ranging from electrical to thermal faults.

Other graphical methods have been proposed in the literature for interpreting dissolved gas concentrations. In ref. [99], a two-shapes graphical method that uses two graphical shapes in its approach to fault diagnosis in power transformers was proposed.

Developed in 2021 by Emara et al., the two shapes used are a square constructed from the percentages of key gases H_2, CH_4, C_2H_6 and C_2H_4 and a pentagon constructed from the percentages of key gases H_2, CH_4, C_2H_6, C_2H_4 and C_2H_2 as shown in Figure 18. The fault type is defined according to the location of the end point obtained with the square or pentagonal shape. The choice of the shape to be used depends on the relative proportion of the key gas C_2H_2 as follows: if % $C_2H_2 \leq 1$ then square shape is used else pentagon shape is used.

In ref. [100], two graphical methods based on five shapes were proposed. Developed by Korean scientists from HYOSUNG Corporation in collaboration with M. Duval, the two Hyosung Corporation graphical methods are proposed in 2013. The first method is a rhombus constructed from the relative proportions of the key gases H_2, CH_4, C_2H_4 and C_2H_2. With this method, the six basic IEC faults corresponding to the six fault zones of the rhombus are diagnosed as shown in Figure 19. The fault zone is determined from the centre of the square formed by the intersection points of the perpendicular plots of the values of the relative proportions of each gas. The second method is a combined method that integrates the diagnostics returned by four diagnostic triangles into one final result. Unlike the Duval or Gouda triangles, the triangles used in this method are constructed from the relative proportions of only two key gases. Figure 20 shows the four triangles constructed from the following combinations: H_2 and CH_4 (Trg-1), H_2 and C_2H_2 (Trg-2), C_2H_4 and C_2H_2 (Trg-3), C_2H_4 and CH_4 (Trg-4). Figure 21 shows the flowchart of the method.

Graphical methods have the advantage of always returning a decision. They provide a solution to the non-decision limit encountered with ratio methods. However, there is a risk of misclassification near the boundaries between adjacent fault regions [37]. In addition, for the vast majority of these methods, the diagnostic process is a one-step process.

4.4 | Combined methods

Key gas methods, gas ratio methods and graphical methods each have benefits and drawbacks. Methods based on the key gas approach can distinguish between normal and abnormal conditions or are indicative of a particular type of fault, but provide little information on the nature and severity of the fault [54]. Gas ratio methods are the most widely used traditional methods in the literature due to their simplicity of implementation and understanding. In addition, they eliminate the effect of the quantity of individual gases used in the key gas methods. However, these methods can lead to an inconclusive assessment of fault severity, a lack of decision for some cases that fall outside the specified codes, or in the extreme case, misidentification [76, 101]. Graphical methods give good results and provide a solution to the non-decision problem encountered with gas ratio methods. However, there is a risk of misclassification of faults near boundaries between adjacent regions [37]. The principle of combined methods is to use the strengths of each approach to propose new, more effective methods. This has been done by many researchers, such as Ghoneim et al. [102], Ward et al. [103] or Wani et al. [104].

The method proposed in 2011 by Xiaohui Li et al. [105] is based on three approaches. Known as Xiaohui Li's method, it uses the percentages of gases H_2, CH_4, C_2H_4 and C_2H_2 calculated from Equation (10), six gas ratios obtained from the concentrations of the seven key gases as shown in Table 47 and the concentration of gas H_2. The percentages and gas ratios are used to establish four rules that will use as diagnostic criteria for PD, D_1, D_2, T_1/T_2 and T_3 faults. Table 48 and Figure 22 show the rules and flowchart of the method respectively. A modified version of this method was proposed in 2014 by Zhao et al. [106]. In this version, five rules are proposed by the authors for the diagnosis of the six basic IEC faults.

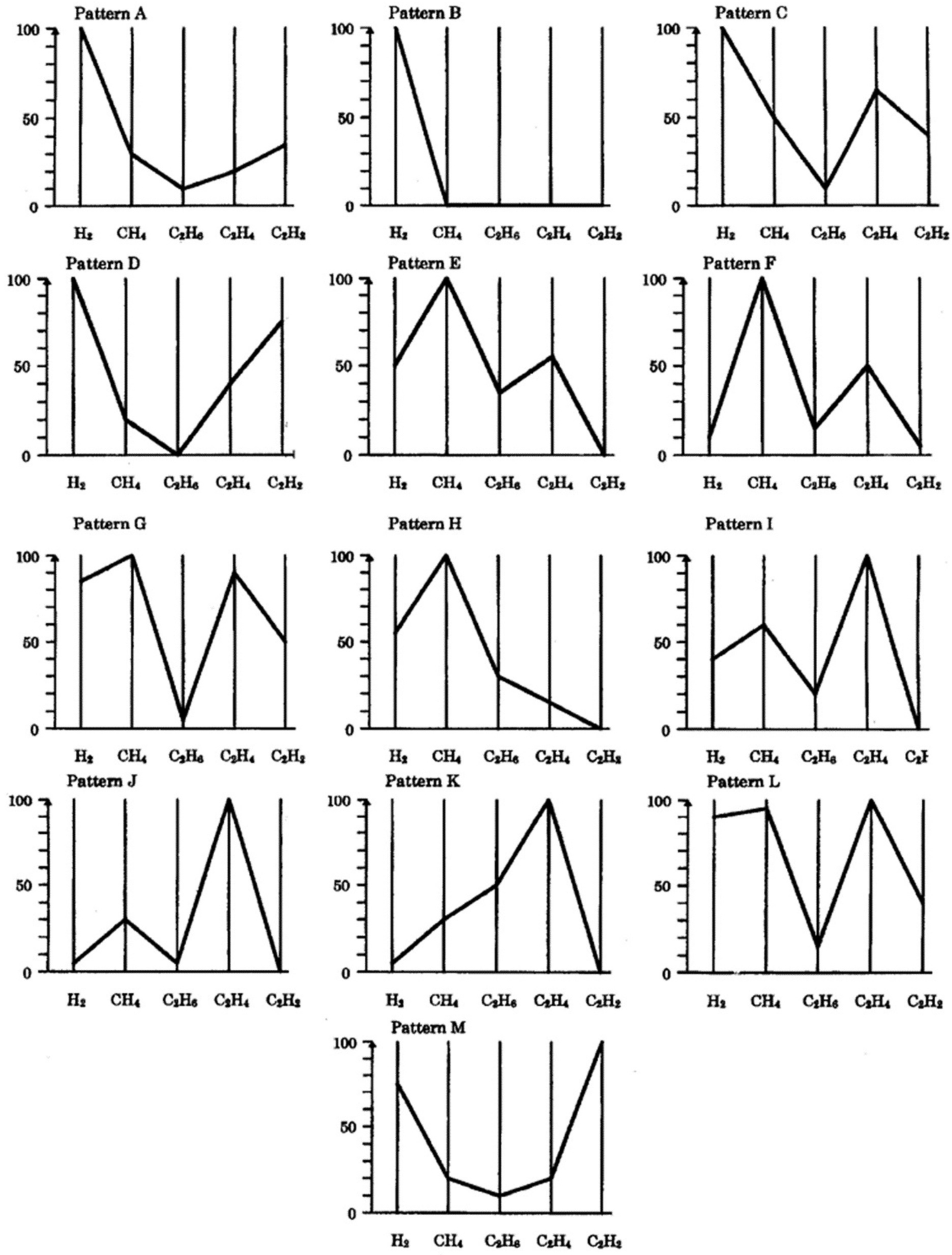

FIGURE 17 Thirteen patterns representation [91].

TABLE 46 Description of the patterns and corresponding faults of Denkyoken method [91].

Pattern	Major gas	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	Fault type
A	H_2	100	30	10	20	30	Partial discharge or arcing
B	H_2	100	0	0	0	0	Partial discharge or arcing
C	H_2	100	50	10	65	40	Partial discharge or arcing
D	H_2	100	20	0	40	75	Partial discharge or arcing
E	CH_4	50	100	35	55	0	Overheating by bad contact
F	CH_4	10	100	15	50	5	Overheating by bad contact
G	CH_4	85	100	5	90	50	Overheating by bad contact. Sometimes a partial discharge or high energy discharge can be produced by overheating
H	CH_4	55	100	30	15	0	Overheating by bad contact
I	C_2H_4	40	60	20	100	0	Overheating by bad contact
J	C_2H_4	5	30	5	100	0	Overheating by bad contact
K	C_2H_4	5	30	50	100	0	Overheating by bad contact
L	C_2H_4	90	95	15	100	40	Overheating by bad contact
M	C_2H_2	75	20	10	20	100	Arcing

$$\begin{cases} \%H_2 = \dfrac{100H_2}{H_2 + CO + CO_2 + C_2H_6} \\ \%CH_4 = \dfrac{100CH_4}{CH_4 + C_2H_4 + C_2H_2} \\ \%C_2H_4 = \dfrac{100C_2H_4}{CH_4 + C_2H_4 + C_2H_2} \\ \%C_2H_2 = \dfrac{100C_2H_2}{CH_4 + C_2H_4 + C_2H_2} \end{cases} \quad (10)$$

The clustering method proposed in 2016 by Ghoneim et al. [102] is based on the gas ratio approach and the graphical approach. This is a two-step method. In the first step, for a given sample, the corresponding subset is determined using a set of rules based on combinations of the relative proportions of the different fault-related gases. The subset determined gives an idea of the potential faults of the sample. In the second step, gas ratios are used to discriminate between the potential faults and the "true" fault. Table 49 shows the rules used in the first step to identify probable faults and Table 50 shows the seven gas ratios used in the second step. The rules used in the second step to identify the "true" fault among the potential faults are given in Table 51. Figure 23 shows the flow chart of the method which illustrates the diagnostic process step by step.

In 2021, Ward et al. proposed a combined technique that combines the advantages of three existing traditional DGA-based methods to build a more accurate diagnostic model [103]. This combined technique is based on the integration among the results of the Duval triangle method, the modified RRM/CEGB method [75] and the modified RRM/IEC method [75]. The flowchart of the method in Figure 24 shows how the inputs (diagnostic results from existing methods) are processed to return the final result. In this flowchart, dig1, dig2

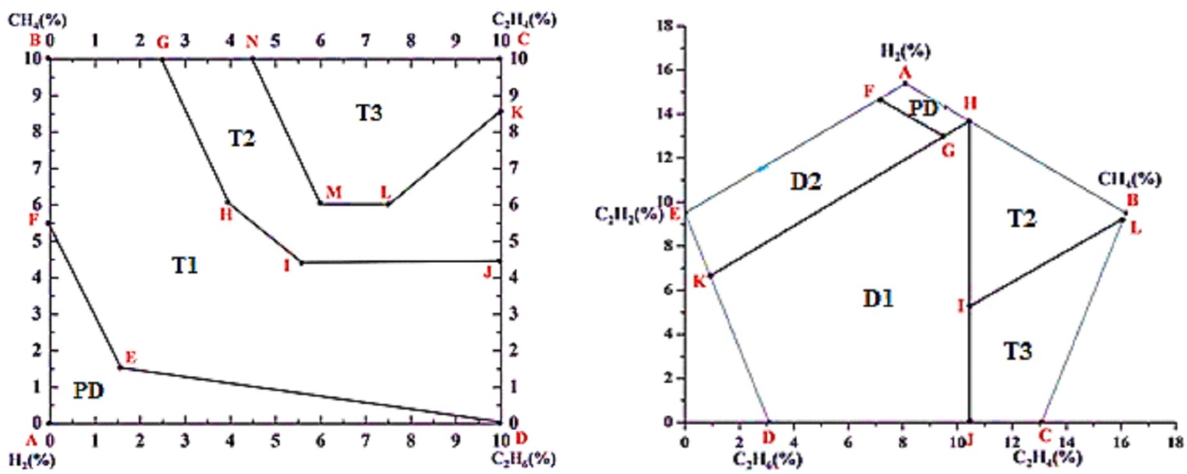

FIGURE 18 Two-shapes graphical method [99].

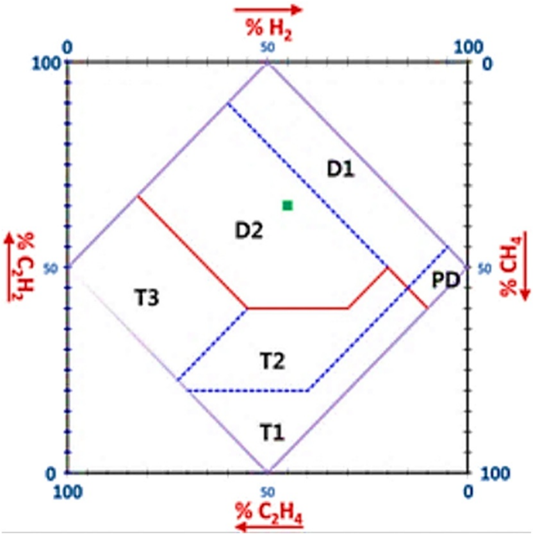

FIGURE 19 Method I of Hyosung Corporation [100].

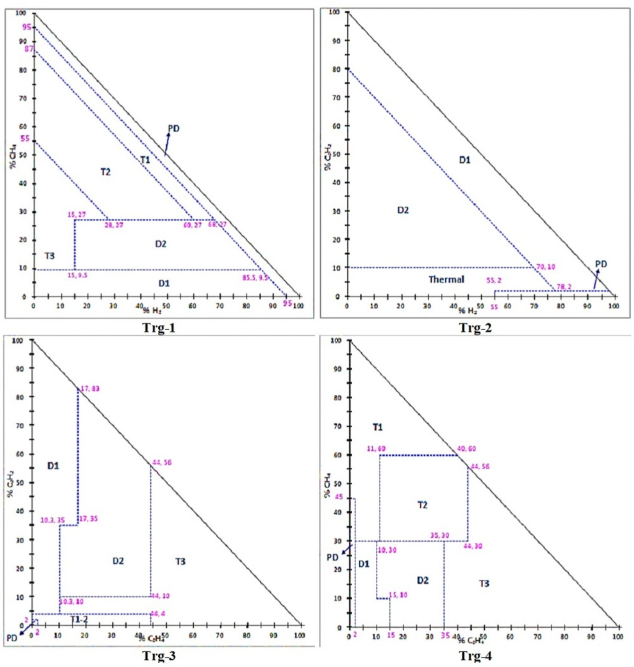

FIGURE 20 Triangles of Method II of Hyosung Corporation [100].

and dig3 are respectively the diagnosis results by Duval triangle, modified RRM/CEGB and modified RRM/IEC methods.

In 2017, a composite DGA method was proposed by Wani et al. [104]. This composite method is based on the fusion of the Duval triangle and the IEC ratio methods. With this method, the authors try to solve the problems of normal state identification and fault classification near the boundaries between adjacent fault zones encountered in the Duval triangle. For this purpose, DTM is used to detect dominant faults and IEC ratios method to detect "no" and boundary fault. Figure 25 shows the flowchart of method and Table 52 the merging of DTM and IEC ratios method for boundary faults.

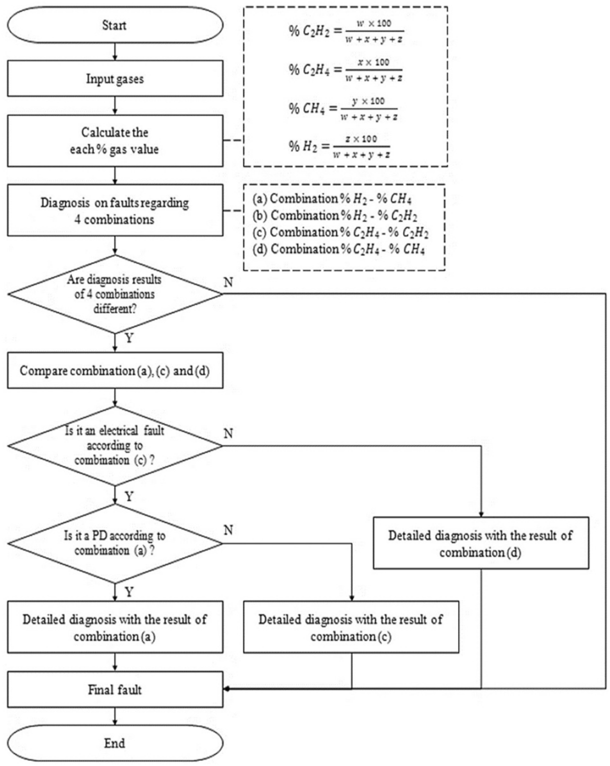

FIGURE 21 Flowchart of Method II of Hyosung Corporation [100].

TABLE 47 Gas ratios of Xiaohui li's method [105].

Ratio	R_1	R_2	R_3	R_4	R_5	R_6
Expression	$\frac{C_2H_2}{C_2H_4}$	$\frac{C_2H_2}{CH_4}$	$\frac{C_2H_4}{C_2H_6}$	$\frac{C_2H_2}{H_2}$	$\frac{C_2H_4}{CH_4}$	$\frac{CH_4}{H_2}$

TABLE 48 The rules of the Xiaohui Li method [105].

Code	Rule	Fault type
RG_1	(%CH_4 > 96 & %H_2 > 90) or (%CH_4 > 96 & H_2 > 2500 ppm.)	PD
RG_2	(%C_2H_2 > 13 & R_1 > 0.4)	D_1/D_2
RG_3	(%C_2H_2 > 13 & %C_2H_4 < 23.3) or (R_2 > 15)	D_1
RG_4	(R_3 > 3.5 & R_4 > 0.015) or (R_5 > 0.8 & R_6 > 2.6)	T_3

In 2021, a subset analysis method was proposed by Nanfak et al. [107]. Like Ghoneim's clustering method, this is a two-step method in which the state of a sample is determined by first identifying the subset to which it belongs and then using the appropriate diagnostic sub-model. The subsets are formed by grouping together samples with the same combination of maximum and minimum concentration(s) of the different fault-related gases. The fault prediction of a new sample is performed using the sub-model corresponding to the subset to which it belongs. Figure 26 shows the schematic view of the approach used to implement the method and gas ratios used to discriminate between faults in the same subset are shown in Table 53.

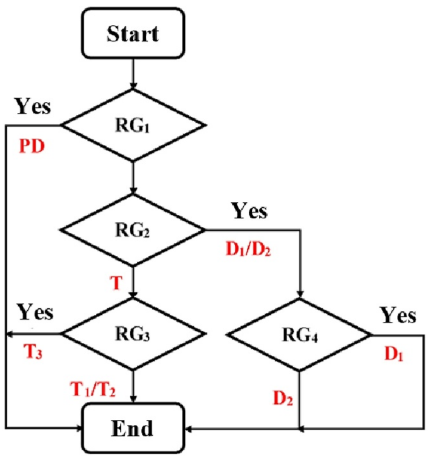

FIGURE 22 The Flowchart of the Xiaohui Li's method [105].

TABLE 49 Gas ratios of clustering method [102].

Ratio	R_1	R_2	R_3	R_4	R_5	R_6	R_7
Expression	$\frac{C_2H_2}{H_2}$	$\frac{C_2H_2}{CH_4}$	$\frac{C_2H_2}{C_2H_6}$	$\frac{C_2H_4}{H_2}$	$\frac{C_2H_4}{CH_4}$	$R_4 + R_5$	$\frac{C_2H_4}{C_2H_6}$

TABLE 50 Percentage limits of key gases for each fault type [102].

Fault type	$\%H_2$	$\%CH_4$	$\%C_2H_6$	$\%C_2H_4$	$\%C_2H_2$
PD	30–98	≤18	≤66	≤13	≤2.5
D_1	10–96	≤14.5	≤42	≤15	≤40
D_2	≤61	≤20	≤70	≤35	≤80
T_1	≤50	≤80	≤100	≤40	≤4
T_2	≤25	≤83	4–90	10–70	≤2
T_3	≤35	≤50	≤20	40–100	≤12

TABLE 51 Gas ratios of clustering method [102].

Fault type	PD	D_1	D_2	T_1	T_2	T_3
Ratio	$R_2 \leq 0.2$	$R_1 \leq 2$	$R_2 \geq 0.1$	$R_6 \leq 5$	$R_7 \leq 4$	
	$R_4 \leq 0.16$	$R_3 \geq 0.7$	$R_3 \geq 0.14$	$R_7 \leq 0.8$		
		$R_4 \leq 0.7$	$R_4 \leq 1.8$			

Although the majority of combined methods date from the 2010s and beyond, this approach was first used in the 1980s by the Belgian laboratory of the electrical supply industry [108]. This method known as the Laborelec method considers the ratio CH_4/H_2, the concentrations of H_2, C_2H_2 and CO and the total of the hydrocarbons C_1 and C_2 as diagnosis criteria. With this method, 10 suggested diagnoses including normal state are proposed. Table 54 shows the interpretation scheme of this method.

4.5 | Future of traditional methods

Table 55 shows the chronological summary of the publication of traditional DGA-based methods in the literature. Figure 27 shows the number of traditional methods proposed in the literature over the years. The increase in the number of traditional methods proposed in the literature over the years may be justified by the progress made in the field of DGA, particularly in the understanding of the gas formation process and the relationships between the gases produced and the various faults.

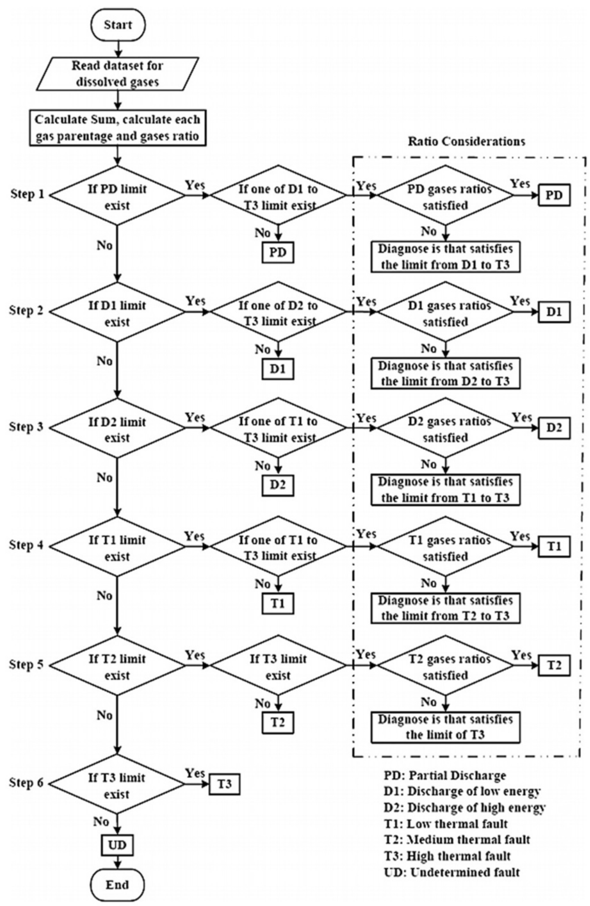

FIGURE 23 Flowchart of clustering method [102].

The strong non-linearity that exists between the gases produced and the faults is the main reason for the limitations of existing traditional methods, such as incomplete ratio ranges for gas ratio methods or misclassification of faults near the boundaries between adjacent regions for graphical methods. These limitations are exacerbated by the fact that these methods use a one-step diagnostic approach. This does not allow them to take into account all the specific features of the dataset used to build their diagnostic models.

In fact, the size of the dataset used has a significant impact on the data mining and fault signature identification stages when implementing traditional DGA-methods. The use of a small dataset facilitates data mining and the identification of different fault signatures. However, the disadvantage of such a dataset is that it is poor in terms of fault signatures. In practice, this leads to incomplete diagnostic methods, with no decision for ratio methods or misclassification for graphical methods. Unlike a small dataset, a large dataset is richer in terms of fault signatures. However, a large dataset makes it difficult the data mining and the identification of the different fault signatures. In practice, this leads to incorrect diagnoses.

Despite the increasing use of artificial intelligence in the interpretation of DGA data, recent works on traditional diagnostic methods have provided some encouraging leads. This was the case in 2016 with the work of Ghoneim et al. [102], who proposed a traditional two-step diagnostic method. The results of this method are good and very interesting. However, this method is limited by the fact that a misdiagnosis in the first stage leads to a misdiagnosis in the second stage. The work of Emara et al. [99] in 2021 goes in the same direction. Unlike Ghoneim's previous method, the first stage decision does not concern the transformer condition, but the graphical submodel to be used. The limitation of this method is that the other key gases are not taken into account in the decision-making process of the first stage. In the same year, the authors of ref. [107] propose a two-step diagnostic method, similar to Ghoneim's clustering method and Emara's two-shape graphical method.

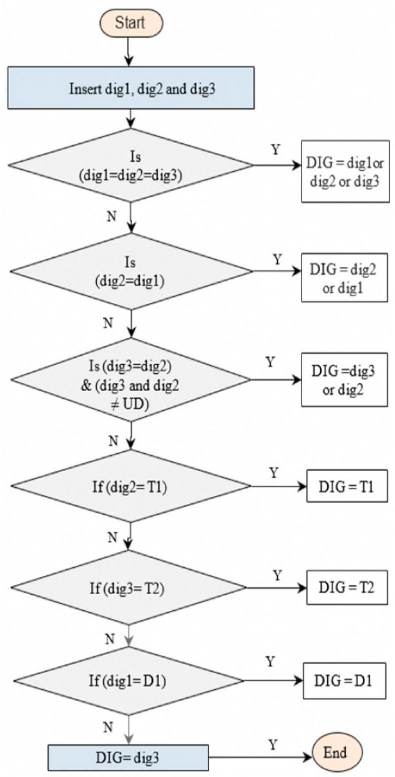

FIGURE 24 The Flowchart of the combined technique of Ward et al. [103].

In this method, the transformer condition is determined by first identifying the subset to which the sample belongs and then using the appropriate diagnostic sub-model. The idea of a two-step diagnosis, which is common to these traditional methods, has certain advantages. Indeed, the creation of labelled subsets in the first stage allows a "microscopic" study of the main labelled dataset. For each subset, a diagnostic sub-model is built, reducing the number of samples to be examined simultaneously by the human expert. As a result, increasingly large datasets can be used to implement traditional methods. The subsets obtained by dividing the main database can be formed either from the expert's knowledge or from unsupervised machine learning.

On the basis of the knowledge of the expert, the following observations can be used:

- The presence or absence of one or more gases indicates a type or group of faults: the presence of a gas provides information to the expert. The same is true for the absence of a gas. For example, the absence of C_2H_2 excludes a thermal fault with temperatures $T > 700°C$. The relative percentages

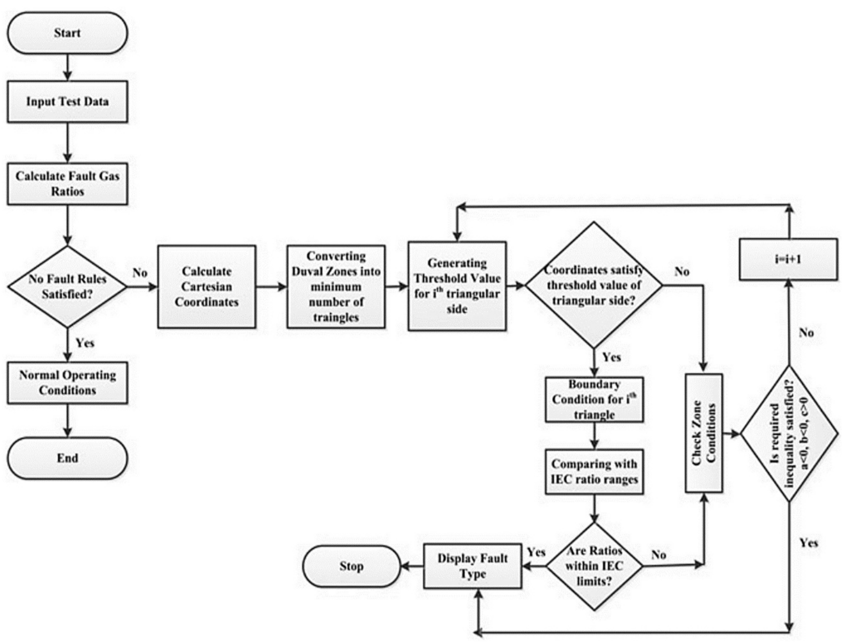

FIGURE 25 Flowchart of composite DGA method of Wani et al. [104].

of the different gases provide information about a type or group of faults: This observation is the origin of the key gas methods. The relative percentage of a gas or group of gases in relation to all gases provides information to the expert. The predominance of this gas or group of gases is associated with a fault or group of faults. For example, the predominance of H_2 relates to partial discharges, while the predominance of H_2 and C_2H_2 relates to arc discharges.

- The gas of maximum or minimum concentration, or a combination of the two, provides information about a type or group of faults: This observation can be seen as the sum of the first two. The gas with the highest concentration gives information to the expert. Similarly, the gas with the lowest concentration also provides information. The combination of the two provides the expert with information about a fault or group of faults. For example, a maximum concentration of hydrogen and a minimum concentration of acetylene are indicative of electrical faults.
- A ranking of fault-related gas concentrations, in ascending or descending order, provides information on a type or group of faults: This observation is more general than the third. In fact, maximum and minimum concentrations as well as intermediate concentrations are taken into account in the descending order of gas concentrations.

TABLE 52 Merging od DTM and IEC ratio method for boundary faults [104].

Boundaries	C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6
Between D_1 and DT	>0.1	0.1–1	>1
Between D_2 and DT	0.1–3	0.1–1	>3
Between D_1 and D_2	0.1–3 or >3 for D_1	/	1–3 for D_1
	0.1–3 for D_2		1–3 or >3 for D_2
Between T_1 and DT	<0.1	>1	<1
Between T_2 and DT	<0.1	>1	1–3
Between T_3 and DT	<0.1	>1	>3
Between T_1 and PD	<0.1 for T_1	0.1–1 or >1 for T_1	1–3 or >3 for T_1
	<0.1 or 0.1–3 for PD	<0.1 for PD	<1 for PD
Between T_1 and T_2	/	/	<1 for T_1 and (1–3) for T_2
Between T_2 and T_3	/	/	(1–3) for T_2 and >3 for T_3
Between DT, D_1 and D_2	0.1–3 or >3 for D_1	/	1–3 for D_1
	0.1–3 for D_2		1–3 or > 3 for D_2
Between DT, T_1 and T_2	/	/	<T_2

Another approach to subset formation has been explored by other researchers, such as Islam et al. [37] or Nanfak et al. [109]. In these methods, subsets are created using *k*-mean clustering algorithm and evolutionary *k*-mean clustering algorithm respectively. The study of subsets by human experts leads not to traditional methods, but to hybrid methods that simultaneously combine the advantages of artificial intelligence with human expertise to improve power transformer fault diagnosis.

5 | PERSPECTIVES

Even though DGA is a reliable technique for identifying incipient faults occurring in power transformers. However, traditional interpretation techniques still remain a complex process due to the large number of variables involved. The issue of its accuracy, which depends on the extraction method, gas handling, sensing system and the oil type and quality, is still concerning. Indeed, variability in accuracy can induce mistaken diagnoses [24]. Keeping in mind that the DGA technique is not an exact science but an art subject to variability [22], the first step towards improving traditional techniques should be understanding the mechanisms related to chemical reactions contributing to the generation of fault-related gases in transformer oils and also taking into account the whole DGA monitor accuracy.

Hereafter, some pitfalls that need to be taken into account [110]:

- The fault-related gases produced are not always the result of an incipient fault. They can result from contamination due

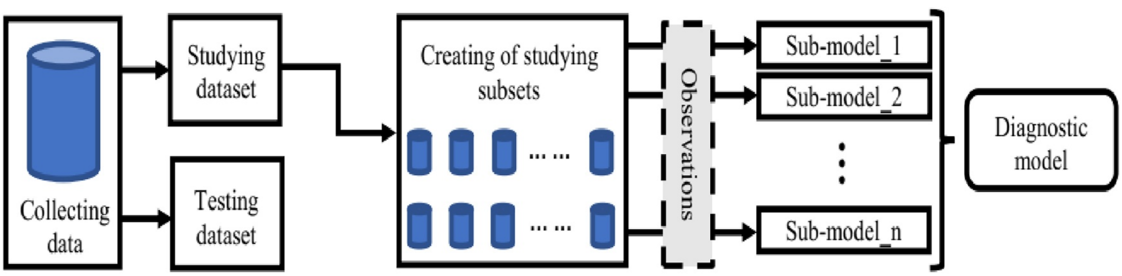

FIGURE 26 Schematic view of the approach used to implement the method proposed by Nanfak et al. [107].

TABLE 53 Gas ratios used in sub-model [107].

Ratio	Expression
R_1	$(CH_4 + C_2H_6)/THHG$
R_2	$(CH_4 + C_2H_4)/THHG$
R_3	$C_2H_6/(CH_4 + C_2H_4)$
R_4	$(CH_4 + H_2)/THHG$
R_5	$(C_2H_4 + C_2H_2)/THHG$
R_6	C_2H_2/C_2H_4

Note: $THHG = H_2 + CH_4 + C_2H_6 + C_2H_4 + C_2H_2$.
Abbreviation: THHG, Total hydro hydrocarbon gas.

to a leak between the tap changers and the main tank, from welding which produces C_2H_2 and other gases, from outgassing of paints and gaskets (usually CO and CO_2), decomposition of additives such as passivators can produce gases as well H_2 and CO_2 or from galvanic reactions between steel, water and O_2 which produce H_2;

- Highly refined oils used as insulating oil produce large quantities of H_2 without this always being the result of a fault situation;
- Low-voltage transformers have higher CO and CO_2 values due to non-vacuum treatment, oxidation and thermal heating of the insulating oil;

TABLE 54 Interpretation scheme of Laborelec method [108].

H_2	C_1&C_2	CH_4/H_2	C_2H_2	CO	Fault type	Intensity of fault
<200	<300			<400	Normal	/
201–300	<300	<0.15			Partial discharges	Medium
		0.16–1.0	<20		Sparking	
		0.16–1.0	>21		Sparking and g.t.	
<200	301–400	>0.61		<400	Thermal oil	
		>0.61		>401	Thermal (oil and paper)	
		>0.60	>21	<400	Thermal (oil and g.t.)	
		>0.60	>21	>401	Thermal (oil and paper and g.t.)	
			>21		Sparking and g.t.	
			>20		Thermal oil	
				>401	Thermal (paper)	
301–600	<400	<0.15			Partial discharges	Important
		0.16–1.0	<50		Sparking	
		0.16–1.0	>51		Sparking and g.t.	
<300	401–800	>0.61		<500	Thermal oil	
		>0.61		>501	Thermal (oil and paper)	
		>0.60	>51	<500	Thermal (oil and g.t.)	
		>0.60	>51	>501	Thermal (oil and paper and g.t.)	
301–600	401–800		>51		Arcing oil or g.t.	
			<50	<500	Thermal oil	
			<50	>501	Thermal (oil and paper)	
>601	<800	<0.15			Partial discharges	Very important
		0.16–1.0	<50		Sparking	
		0.16–1.0	>51		Sparking and g.t.	
<600	>801	>0.61		<700	Thermal oil	
		>0.61		>701	Thermal (oil and paper)	
		>0.60	>51	<700	Thermal (oil and g.t.)	
		>0.60	>51	>701	Thermal (oil and paper and g.t.)	
>601	>801		>101		Arcing oil or g.t.	
			<100	<700	Thermal oil	
			<100	>701	Thermal (oil and paper)	

TABLE 55 Chronological summary of the publication of traditional DGA-based methods in the literature.

Method	Number of states diagnosed	Year of first publication	Authors	Reference
Potthoff's scheme	/	1969	K. Potthoff	
Trilinear plot method	/	1970	/	
Shanks graphical method	/	1970s	Shanks	
Doernenburg ratios method	3	1974	Doernenburg and Strittmatter	[56]
Müller, Schliesing and Soldner ratio method	10	1974	Müller, Schliesing and Soldner	[67]
IEEE key gas method	4	1974	D. Pugh/IEEE C57.104	[22]
Duval 1 triangle method	7	1974, 2019	M. Duval	[82]
Fallou key gas method	9	1975	CIGRE	[55]
MRR/CEBG method	12	1975	R. R. Rogers	[58]
Church's logarithmic nomograph method	6	1975	Church et al.	[45]
CSUS method	7	1976	CSUS	[46]
LCIE method	5	1976	Electrical research association	[49]
MRR/IEC method	9	1978	R. R. Rogers	[60]
TDCG method	4	1978	IEEE C57.104	[22]
Muller key gas method	6	1980	Muller et al.	[51]
Denkyoken method	13	1980	Japan committee	[80]
NBR 7274 method	9	1982	NBR 7274	[63]
Laborelec method	9	1986	Belgian laboratory of the electrical supply industry	[108]
Russian Std RD 153-34.0-46.302-00 method	9	1989, 2001	RD 153-34.0-46.302-00	[44]
Rogers ratios method	6	1991	R. R. Rogers	[40]
CO_2/CO method	5	1991	IEC 60599/IEEE C57.104	[22, 23]
CIGRE key gas method	4	1999	CIGRE	[39]
IEC 60599 method	6	1999	IEC 60599	[41]
CIGRE ratio method	6	1999	CIGRE	[39]
ETRA square method	6	1999	ETRA	[77]
RRM/ASTM method	13	2002	ASTM	[31]
Ukrainian Std SOU-N EE 46.501 method	8	2007	SOU-N EE 46.501	[64]
Duval 4 and 5 triangles method	5	2008	M. Duval	[85]
ETRA ratio method	6	2009	ETRA	[62]
Xiaohui Li's method	5	2011	Xiaohui et al.	[105]
Modified MRR/IEC method	12	2012	Dhote et al.	[73]
C3 hydrocarbons method	3	2012	CIGRE	[68]
Modified Doernenburg ratios method	6	2013	Souahlia et al.	[72]
Hyosun Corporation gas ratios method	6	2013	Korean scientists from HYOSUNG Corporation	[69]
GATRON TRIANGLE	6	2013	GATRON GmbH	[87]
Hyosun Corporation graphic method 1	6	2013	Korean scientists from HYOSUNG Corporation	[100]
Hyosun Corporation graphic method 2	6	2013	Korean scientists from HYOSUNG Corporation	[100]

(Continues)

TABLE 55 (Continued)

Method	Number of states diagnosed	Year of first publication	Authors	Reference
Duval pentagon method	10	2014	Duval and Lamare	[79]
Modified Xiaohui Li's method	6	2014	Zhao et al.	[106]
Mansour pentagon method	6	2015	Mansour	[81]
Modified MRR/CEBG method	12	2016	Taha et al.	[74]
Modified MRR/IEC method	9	2016	Taha et al.	[74]
Combined technique of modified MRR/IEC and modified MRR/CEBG methods	12	2016	Taha et al.	[74]
Clustering method	6	2016	Ghoneim and Taha	[102]
Modified Duval 1 triangle method	9	2017	Sinisa et al.	[86]
Low-energy degradation method	7	2017	Moodley et Gaunt	[86]
Composite DGA method	6	2017	Wani et al.	[104]
Characteristic gas ensemble method	8	2018	Davidenko and Ovchinnikov	[50]
Simplified version of IEC 60599 method	3	2018	IS 10593	[35]
Three ratios technique	9	2018	Gouda et al.	[66]
Gouda triangle method	7	2018	Gouda et al.	[78]
Gouda heptagon method	10	2018	Gouda et al.	[82]
Other versions of Denkyoken method		2018	Oleg and Ivan	[96]
Radar charts method	10	2018	Urals Federal university in Russia	[87]
Russian Std CTO 34.01-23-003-2019 method	7	2019	STO 34.01-23-003	[43]
Other versions of Denkyoken method		2019, 2020	Shutenko and Kulyk	[92–95, 97, 98]
Modified MRR/CEBG method	6	2020	Taha et al.	[75]
Modified MRR/IEC method	6	2020	Taha et al.	[75]
Combined DPM	10	2020	Cheim et al.	[90]
DGA 4-simplex method	6	2020	Dukam et al.	[89]
Two-shapes graphical method	6	2021	Emara et al.	[99]
Combined technique	6	2021	Ward et al.	[103]
Subset analysis method	6	2021	Nanfak et al.	[107]
Simplified version MSS method	3		CIGRE	[70]

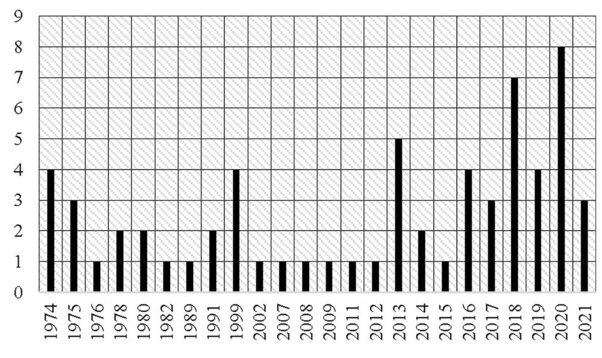

FIGURE 27 Evolution of the number of traditional methods proposed over the years.

- The difficulties encountered by researchers in distinguishing between an incipient fault and the normal ageing of the insulation system mean that incipient faults are not really covered;
- The type of fluid used as insulating oil in the power transformer may have an impact on DGA-based diagnostic methods. Indeed, the gassing tendency of an insulating oil depends on its chemical composition [111, 112];
- Under laboratory conditions, the theoretical premises that oil ageing by-products contribute to the gassing of an insulating fluid was experimentally confirmed [111, 112]. The obtained results provide experimental evidence that ageing by-products can affect the diagnostics predicted by some DGA-based methods [113, 114];

- The quality and quantity of cellulose paper affects the gases dissolved in the oil when electrical and thermal defects occur [115];
- Oxygen, which is a "diradical" specie, may contribute to the gassing of oil. Without knowing how much gases, radicals and colloidal suspensions arise in oil samples submitted to the incipient electrical and/or thermal stress, the amount of gases generated by an insulating oil sample cannot be reliably determined. In this context, it is understood that additional investigations involving repeatability and reproducibility are required before more general conclusions can be drawn;
- The accuracy of the DGA monitor system as a whole has a significant impact on the accuracy of DGA-based diagnostic methods [116].

6 | CONCLUSION

Dissolved gas analysis is a preventive maintenance tool for power transformers. It has proven its effectiveness in early detection and classification of power transformer faults. A number of methods based on DGA are proposed in the literature to assess the condition of power transformers. These methods can be divided into two main categories: traditional methods and intelligent methods. Simple, easy to understand and to implement, traditional methods are widely adopted by power transformer maintenance professionals and national standards, such as IEEE, IEC, CIGRE, NBR, ETRA or CTO. These methods are reviewed in this article. This review has been organised into key gas methods, gas ratio methods, graphical methods, and combined methods. For each category, the methods proposed to date were presented, highlighting their strengths and weaknesses. In addition to this review, the two-stage diagnostic approach with the advantage of better data mining by the human expert proposing the traditional DGA-based method is also presented. Finally, some pitfalls need to be taken into account when implementing methods for interpreting DGA data are presented.

AUTHOR CONTRIBUTIONS

Arnaud Nanfak: Conceptualization; data curation; formal analysis; methodology; writing – original draft. **Eke Samuel**: Methodology; supervision; validation. **Issouf Fofana**: Methodology; supervision; validation; writing – original draft; writing – review & editing. **Fethi Meghnefi**: Supervision; validation. **Martial Gildas Ngaleu**: Methodology; supervision; validation. **Charles Hubert Kom**: Supervision; validation.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data sharing not applicable – no new data used or generated, or the article describes entirely theoretical research.

ORCID

Arnaud Nanfak https://orcid.org/0000-0002-6432-3365

Martial Gildas Ngaleu https://orcid.org/0000-0003-2374-9527

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