Hindawi
International Journal of Energy Research
Volume 2023, Article ID 9960743, 14 pages
https://doi.org/10.1155/2023/9960743

WILEY | Hindawi

Research Article

Comparative Performance Study of Dissolved Gas Analysis (DGA) Methods for Identification of Faults in Power Transformer

Abdul Wajid,[1,2] Atiq Ur Rehman,[1] Sheeraz Iqbal,[3] Mukesh Pushkarna,[4] Syed Mudassir Hussain,[5] Hossam Kotb,[6] Mohammed Alharbi,[7] and Ievgen Zaitsev[8]

[1]*Department of Electrical Engineering, Balochistan University of Information Technology, Engineering and Management Sciences (BUITEMS), Quetta 87300, Pakistan*
[2]*Department of Electrical Engineering, Balochistan University of Engineering and Technology, Khuzdar, Uthal Campus, Lasbela, Pakistan*
[3]*Department of Electrical Engineering, University of Azad Jammu and Kashmir, Muzaffarabad, Pakistan*
[4]*Department of Electrical Engineering, GLA University, Mathura 281406, India*
[5]*School of Physics, Engineering and Computer Science, University of Hertfordshire, Hatfield AL10 9AB, UK*
[6]*Department of Electrical Power and Machines, Faculty of Engineering, Alexandria University, Alexandria 21544, Egypt*
[7]*Department of Electrical Engineering, College of Engineering, King Saud University, Riyadh 11421, Saudi Arabia*
[8]*Department of Theoretical Electrical Engineering and Diagnostics of Electrical Equipment, Institute of Electrodynamics, National Academy of Sciences of Ukraine, Peremogy, 56, Kyiv-57 03680, Ukraine*

Correspondence should be addressed to Ievgen Zaitsev; zaitsev@i.ua

Received 9 March 2023; Revised 13 June 2023; Accepted 7 September 2023; Published 25 September 2023

Academic Editor: Adrian Loy Chun Minh

The power transformer is an essential component of the electrical network that can be used to step up and step down voltage. Dissolved gas analysis (DGA) is the most reliable method for the identification of incipient faults in power transformers. Various DGA methods are used to observe the generated key gases after oil decomposition. The main gases included are hydrogen (H_2), ethylene (C_2H_4), acetylene (C_2H_2), methane (CH_4), and ethane (C_2H_6). There is a lack of research that can compare the performance of various DGA methods in identification of faults in power transformer. In addition, it is also not clear which DGA method is optimal for identification of faults in power transformer. In this paper, the comparative performance study of seven DGA methods such as Roger's ratio, key gas, IEC ratio, the Doernenburg ratio, the Duval triangle, three-ratio method, and the relative percentage of four gases is carried out in order to identify the optimal technique for fault identification in transformer. The data of various power transformers installed in "RAWAT" NTDC grid station, Islamabad, and "UCH-II" power station, Balochistan, are considered for the comparative analysis. This analysis shows that the three-ratio method provides better performance than other DGA methods in accurately identifying the faults in power transformers. The three-ratio method has 90% accuracy in identifying the faults in power transformer.

1. Introduction

Power transformer is the key component of an electrical network system that can be used to step up and step down voltage. The health condition of power transformer mainly depends on the insulation oil during normal operation [1]. The intensive care and analysis of insulation condition of power transformers are essential to make certain the consistent operation. Therefore, it is essential to identify the transformer faults at the earliest to ensure the proper operation of an electrical power system. When used in a transformer, the oil serves as both a heat transfer agent and a dielectric medium. Due to accelerated stress, combustible gases such as hydrogen (H_2), methane (CH_4), acetylene (C_2H_2), ethane (C_2H_6), and ethylene (C_2H_4) and noncombustible gases carbon monoxide (CO) and carbon dioxide (CO_2) are generated in transformer. The sum of all combustible gases with a rise in individual or ratio gas-generated rates indicates a transformer fault and can also indicate the fault level [2].

For the evaluation of transformer health state, various offline and online analytical methods have been presented for decades. Amongst these, dissolved gas analysis (DGA) is the most advanced and technically acknowledged online analytical method for identification of faults in power transformer. DGA can be utilized to evaluate type and amount of dissolved gases in transformer's oil, which can help in studying failure procedure of transformer and ultimately prevent transformer from the worst damage. The typical method of identifying faults in transformers using DGA involves (i) manually extracting a sample of transformer oil (with a syringe) and (ii) testing and analysing of sample in laboratory [3, 4]. Using DGA methods on an oil sample, dissolved gases may be measured.

At present, few publications attempted to compare DGA methods for identification of faults in transformer. But none of the publications comprehensively compared the performance of all seven DGA methods. For example, References [5–8] have not considered the three-ratio and relative percentage of four gas methods for comparative study. References [9, 10] compared the performance of IEC code and Roger's ratio method. Reference [11] considered the Doernenburg and Roger's ratio method for comparison, and Reference [12] lacks the comparison of key gas and relative percentage of four gas methods. Thus, there is a research gap regrading the evaluation of performance of different DGA methods in identifying the faults in power transformer. In this work, the comparative performance study of seven DGA techniques is carried out, which has significant benefits for identification of several internal faults of power transformer such as normal ageing, thermal breakdown, partial discharge, arcing, and combination of thermal and electrical faults.

In this paper, the seven DGA methods such as Roger's ratio, key gas, IEC ratio, the Doernenburg ratio, the Duval triangle, three-ratio method, and the relative percentage of four gas methods have been selected for better fault identification of power transformer. The data of 22 critical power transformers installed in "RAWAT" NTDC grid station in Islamabad and "UCH-II" power station in Baluchistan is considered for the comparative analysis. The analysis shows that the three-ratio method provides better performance than other DGA methods in accurately identifying the faults in power transformers. The three-ratio method has 90% accuracy in identifying the faults in power transformer.

The paper is arranged in the following manner: Section 2 illustrates the detailed procedure of dissolved gas analysis (DGA). Section 3 provides the dissolved gas data of transformers installed in "RAWAT" NTDC grid station in Islamabad and "UCH-II" power station in Balochistan. Section 4 describes the various fault identification methods based on DGA. The detailed comparative performance study of different DGA techniques for identification of faults is described in Section 5. Finally, the paper is concluded in Section 6.

Table 1: Dissolved gas data of transformers.

S. no.	C_2H_2	C_2H_4	C_2H_6	CH_4	H_2	CO	CO_2
T-1	1	68	30	70	55	150	1500
T-2	1	20	10	70	20	280	1400
T-3	21	380	91	200	160	612	1100
T-4	0	60	40	200	80	1650	4000
T-5	0	70	15	10	40	1200	2700
T-6	0	60	20	100	35	140	900
T-7	22	291	94	134	156	1400	1800
T-8	0	350	60	270	100	250	1500
T-9	1	360	80	240	115	1300	5000
T-10	0	270	75	250	100	310	1600
T-11	200	370	630	1200	1300	790	2800
T-12	0	140	60	80	80	600	3000
T-13	65	100	130	240	200	612	2250
T-14	125	50	38	95	700	500	4550
T-15	1	20	80	120	45	1100	5100
T-16	0	400	70	300	180	500	1100
T-17	1	50	40	8	40	2700	3500
T-18	67	282	95	140	152	610	11000
T-19	15	55	70	70	800	500	5100
T-20	0	90	10	40	20	70	900
T-21	0	230	70	120	60	1080	5580
T-22	0	60	80	15	10	700	4600

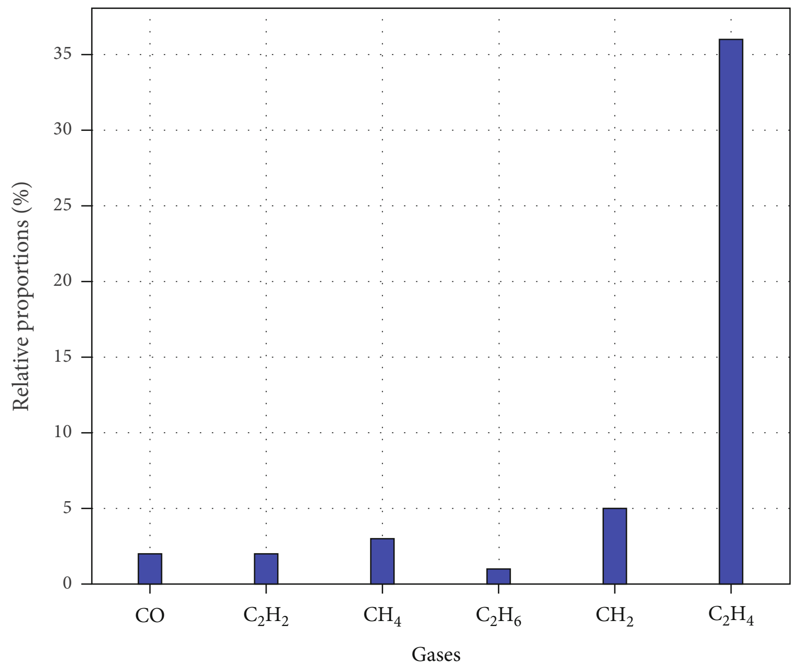
2. Dissolved Gas Analysis (DGA) Procedure

The DGA technique works effectively in laboratories since it necessitates high-precision measuring devices. It can be stated in four steps [3].

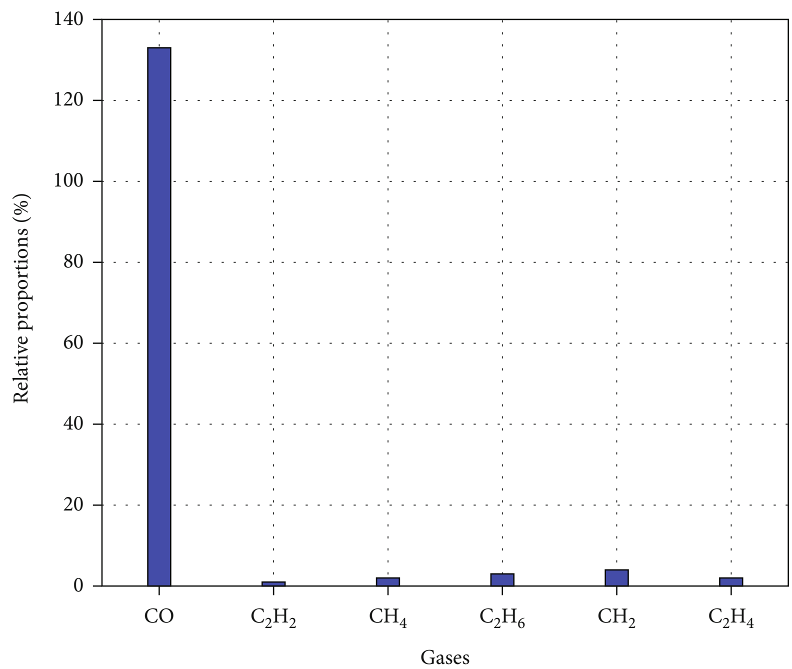
2.1. Oil Taken from the Unit. In any case, confirmation of a dielectric will pass by taking a test; safety measures are required for it to be an agent of the dielectric contained within the transformer [5]. The method of collecting the test sample differs depending on the location, mode, term, recurrence, climate, and weather. All these factors will have an impact on the consistent quality of the outcomes. As a result, we must be aware of the effects on the sample taken.

Take a test as soon as possible after the transformer has been turned off to get a regular test resulting from the blending works caused by the dielectric development. On the other hand, this test will continue to warm, leaving it less exposed to the possibility of surrounding sticky condensation.

2.2. Extraction of Gases from Oil. The nominal key gases are extracted using a degassing technique, which frequently employs a Toepler pump system. While long-term experience has shown that this extraction is efficient and yields good results for subsequent analysis, this vacuum pump typically contains high levels of mercury, posing a risk to the operating personnel as well as the environment [6]. Alternative processes such as "headspace extraction," in which the number of dissolved gases is determined by dissolving the

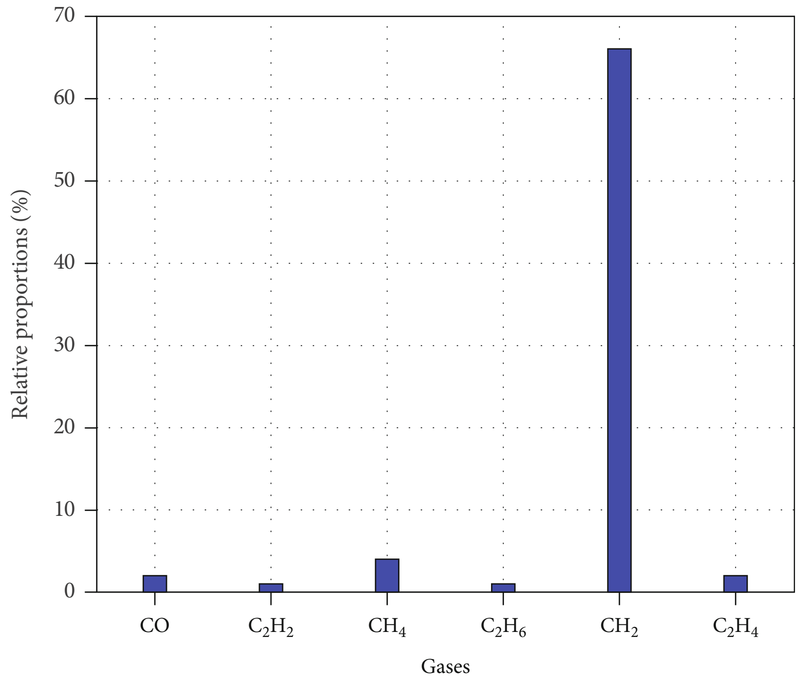


(a)

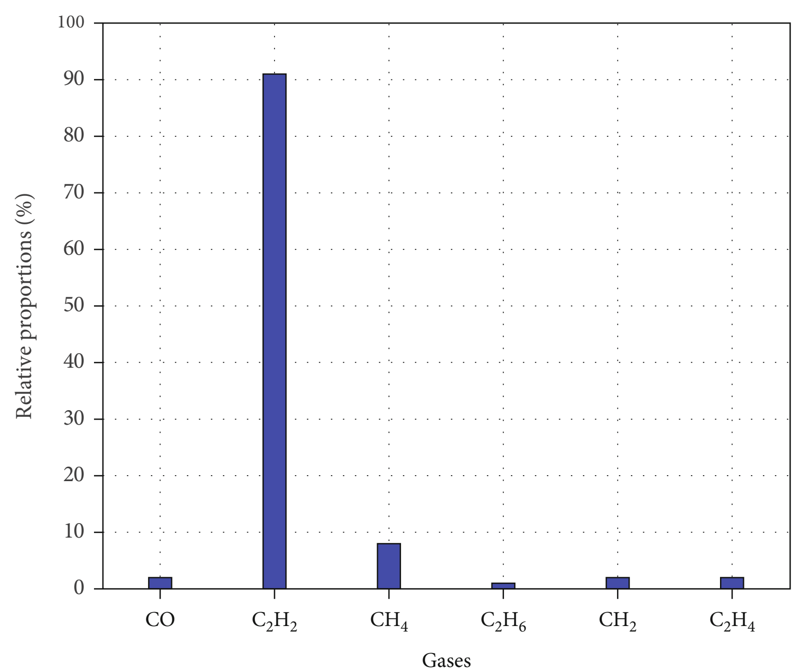


(b)

Figure 1: Continued.



(c)



(d)

Figure 1: (a) "Arcing in oil" fault identified in transformer "T-3" with 36% of C_2H_4 gas. (b) "Overheat of cellulose" fault identified in transformer "T-7" with 133% of CO gas. (c) "Overheat in oil" fault identified in transformer "T-13" with 66% of H_2 gas. (d) "Corona" fault identified in transformer "T-18" with 91% of C_2H_2.

gases in the liquid into a designated gas in the Phiole headspace, produce somewhat different findings and are more imprecise, as stated in the standard IEC 60567.

2.3. Analysis of Extracted Gases. With the use of the nominal gas chromatography strategy, the extricated gas blend is segregated into different chemical constituents after extraction. Each compound is identified and the concentrations of each are calculated [7].

2.4. Interpretation of Gas Data. It is time to translate the results after the unique gases in the oil test have been discovered and examined. What must be resolved to assess the transformer's condition is whether the displayed sum of dissolved gases is abnormal or not. In the event of irregular gas production, attempting to pinpoint the start of the gas production is a challenge [8].

3. Collected Data of Dissolved Gases of Transformers

To compare the performance of various DGA methods, the various transformers installed in "RAWAT" in Islamabad and "UCH" power station in Balochistan, Pakistan, are considered. The considered transformers have different ratings such as 450 MVA, 250 MVA, 20 MVA, 1600 kVA, and 1000 kVA. These transformers are tested in the laboratory, and the generated gas data of various transformers are obtained and are summarized in Table 1.

4. DGA Fault Identification Methods

The various DGA methods used for fault identification in power transformers are IEC ratio, key gas, the Doernenburg ratio, Roger's ratio, the Duval triangle, three-ratio method, and relative percentage of four gases. The detailed analysis of these methods is as follows:

4.1. Key Gas Method. The key gas method specifies key gases for every fault type and utilizes percentage of that gases to identify fault. Hydrogen (H_2), ethylene (C_2H_4), ethane (C_2H_6), methane (CH_4), acetylene (C_2H_2), carbon monoxide (CO), and oxygen (O_2) are main gases generated by breakdown of oil and paper insulation. Excluding oxygen (O_2) and carbon monoxide (CO), all other gases are generated by oil's decomposition. Degradation of paper insulation generates carbon dioxide (CO_2), carbon monoxide (CO), and oxygen (O_2). The type and amount of gas are governed by the type of transformer fault, their severity, and energy of incident. The key gas method identifies four different faults in transformer [13–15].

The DGA data of transformers (T-3, T-7, T-13, and T-18) taken from Table 1 are presented here as a sample for easy understanding. The key gas method is implemented into these transformers to assess different faults. The fault "arcing in oil" is identified in transformer "T-3" due to 36% generation of key gas ethylene (C_2H_4) as shown in Figure 1(a). The "overheat of cellulose" fault is observed in transformer "T-7" due to 133% generation of key gas carbon monoxide (CO) as depicted in Figure 1(b). Similarly, in transformer "T-13, the "corona" fault is identified due to 60% generation of key gas hydrogen (H_2) as shown in Figure 1(c). The "arcing" fault is observed in transformer "T-18" due to 91% generation of key gas acetylene (C_2H_2) which is shown in Figure 1(d).

This method is unable to provide numerical correlations between gas types and fault types [5]. This technique needs a lot of practice for accurate diagnosis of faults in transformer.

4.2. Roger's Ratio Method. This technique was proposed in 1973, revised in 1975, and developed in 1977, based on Halstead's thermodynamic model [2]. The technique was developed into IEC standard after considering industry experiences, laboratory experiments, and theoretical study. CH_4/H_2, C_2H_6/CH_4, C_2H_4/C_2H_6, and C_2H_2/C_2H_4 are the four gas ratios studied by Roger's ratio method. This is a simple method for identification of faults in transformer relying on ratio ranges. Identification of faults is achieved using basic code mechanism relying on ratio ranges as shown in Tables 2 and 3 [9].

Table 2: Gas and Roger's ratio codes [2].

Gas ratios	Ratio code	Range	Code
CH_4/H_2	i	≤0.1	5
		>0.1, <1.0	0
		≥1.0 < 3.0	1
		≤3.0	2
C_2H_6/CH_4	j	<1.0	0
		≥1.0	1
C_2H_4/C_2H_6	k	<1.0	0
		≥1.0 < 3.0	1
		≥3.0	2
C_2H_2/C_2H_4	l	<0.5	0
		≥0.5 < 3.0	1
		≥3.0	2

The DGA data of transformer "T-18" is taken from Table 1 and evaluated using Roger's ratio code scheme to identify faults in the transformer. After using Roger's ratio code scheme, CH_4/H_2 ratio range is $i > 1$, and its code = 1. C_2H_6/CH_4 ratio range is $j \geqq 1$ and its code = 1. C_2H_4/C_2H_6 ratio range is $k < i$ and its code = 0. C_2H_2/C_2H_4 ratio range is $1 \leqq 0$ and its code = 0. Thus, ultimately, "thermal fault $T_o < 150°C$ $T_{emp} < 200°C$" fault condition is identified which can be seen in Table 4, and all ratio ranges and their codes are shown in Table 3.

This method did not consider values of dissolved gases lower than normal concentration which may lead to many misread cases [5].

4.3. IEC Ratio Method. The International Electrotechnical Commission (IEC) adopted Roger's ratio method with the exception that ratio C_2H_6/CH_4 is removed because it merely indicates narrow range of temperature decomposition [9]. The left over three gas ratios are sufficient for the identification of faults in transformer. These faults have various ranges of codes as compared to Roger's ratio method as depicted in Table 4. This method can detect nine different kinds of transformer faults as depicted in Table 5 [10].

The DGA data of transformer "T-14" is taken from Table 1 and is assessed using IEC ratio method for identification of faults in it. By applying this method to the given data, high-energy discharge fault is identified. Each gas ratio range and corresponding code are as follows: C_2H_2/C_2H_4 gas ratio range is ≥1.0 ≤ 3.0 and its code = 1. CH_4/H_2 gas ratio range is ≥0.1 ≤ 1.0 and its code = 0. C_2H_4/C_2H_6 gas ratio

Table 3: Fault classification using Roger's ratio codes [2].

Ratio codes				Identification of faults
i	*j*	*k*	*l*	
0	0	0	0	Normal
5	0	0	0	Partial discharge
1/2	0	0	0	Thermal fault T_o, $T_{emp} < 150^\circ C$
1/2	1	0	0	Thermal fault T_a, $150^\circ C < T_{emp} < 200^\circ C$
0	1	0	0	Thermal fault T_b, $200^\circ C < T_{emp} < 300^\circ C$
0	0	1	0	Overheating in conductors
1	0	1	0	Circulating currents in winding
1	0	2	0	Circulating currents in tank and core, overheated joints
0	0	0	1	Flashover without power follow-through
0	0	1/2	1/2	Arcing (high energy)
0	0	2	2	Continuous sparking to floating potential
5	0	0	1/2	Partial discharge with tracking (CO), involving solid insulation

Table 4: Overheating in conductor fault identified based on Roger's ratio code.

Ratio code	Gas ratio	Concentration (ppm)		Code
i	CH_4/H_2	140/152	0.9	0
j	C_2H_6/CH_4	95/140	0.6	0
k	C_2H_4/C_2H_6	282/95	2.9	1
l	C_2H_2/C_2H_4	67/282	0.2	0
Overheating in conductors				

Table 5: Gas and IEC ratio codes [9].

Ratio code	Range	Code
C_2H_2/C_2H_4 (*l*)	<0.1	0
	≥0.1 ≤ 1.0	1
	≥1.0 ≤ 3.0	1
	>3.0	2
CH_4/H_2 (*i*)	<0.1	1
	≥0.1 ≤ 1.0	0
	≥1.0 ≤ 3.0	2
	>3.0	2
C_2H_4/C_2H_6 (*k*)	<0.1	0
	≥0.1 ≤ 1.0	0
	≥1.0 ≤ 3.0	1
	>3.0	2

range is $k \geq 1.0 \leq 3.0$ and its code = 1. Hence, finally, "high-energy discharge" fault condition is identified which can be seen in Table 6, and all gas ratio ranges and codes are presented in Table 7.

In any case, it is unable to classify electrical and thermal faults of transformer into exact subtypes. Power transformer faults are normally categorized as partial discharges, discharges of low and high energy, and thermal faults in which severity relies on fault temperature.

Table 6: High-energy discharge fault identification based on IEC ratio code.

Gas ratio	Concentration (ppm)		Codes
C_2H_2/C_2H_4 (*l*)	125/50	2.5	1
CH_4/H_2 (*i*)	95/700	0.1	0
C_2H_4/C_2H_6 (*k*)	50/38	1.3	1
High-energy discharge fault			

Table 7: Fault classification based on IEC ratio codes [9].

Ratio codes			Fault identifications
l	*i*	*k*	
0	0	0	Normal
0	1	0	Partial discharge (low energy)
1	1	0	Partial discharge (high energy)
1	0	1	High-energy discharge
1	0	2	Low-energy discharge
0	0	1	Thermal fault T_o, $T_{emp} < 150^\circ C$
0	2	0	Thermal fault T_a, $150^\circ C < T_{emp} < 300^\circ C$
0	2	1	Thermal fault T_b, $300^\circ C < T_{emp} < 700^\circ C$
0	2	2	Thermal fault T_c, $T_{emp} > 700^\circ C$

4.4. Doernenburg Ratio Method. In 1970, Doernenburg was able to find arcing, thermal faults, and corona discharge by evaluating gas concentration ratios such as CH_4/H_2, C_2H_2/C_2H_4, C_2H_2/CH_4, and C_2H_6/C_2H_2, as shown in Table 6 [15]. This method is based on the concepts of thermal deterioration. The ratio process is valid in this method if the gas concentrations (ppm) for hydrogen (H_2), methane (CH_4), acetylene (C_2H_2), and ethylene (C_2H_4) surpass twice the value of the fixed limit for each gas and exceed thrice the value of the fixed limit for CO and C_2H_6 as shown in

Table 8: Fault identification for the Doernenburg ratio method [11].

Fault diagnosis	CH_4/H_2 (R_a)	C_2H_2/C_2H_4 (R_b)	C_2H_2/CH4 (R_c)	C_2H_6/C_2H_2 (R_d)
Corona (low-intensity PD)	<0.1 < 0.01	Not significant	<0.3 < 0.1	>0.4 > 0.2
Thermal decomposition	>1.0 > 0.1	<0.75 < 1.0	<0.3 < 0.1	>0.4 > 0.2
Arcing (high-intensity PD)	>0.1 > 0.01	>0.75 > 1.0	>0.3 > 0.1	<0.4 < 0.2

Table 9: Gas generation rate of T-11 for the Doernenburg ratio method [15].

Key gases	Concentration (ppm)
Acetylene (C_2H_2)	200
Ethylene (C_2H_4)	370
Ethane (C_2H_6)	630
Methane (CH_4)	1200
Hydrogen (H_2)	1300
Carbon monoxide (CO)	790

Table 8 [11]. Each consecutive ratio is then compared with values to determine the validity of the four ratios. Finally, if the entire four subsequent ratios for specific fault mode lie within predetermined values presented in Table 9, then identification of fault is confirmed.

For better understanding of the Doernenburg ratio method, the concentration values taken from Table 1 have been increased for transformer "T-11," and this method was used for identification of fault in it.

Each gas ratio range and corresponding code are as follows:

(i) CH_4/H_2 gas ratio range is $R_a < 0.1 < 0.01$

(ii) C_2H_2/C_2H_4 gas ratio range is $R_b < 0.75 < 1.0$

(iii) C_2H_2/CH_4 gas ratio range is $R_c < 0.3 < 0.1$

(iv) C_2H_6/C_2H_2 gas ratio range is $R_d > 0.4 > 0.2$

Hence, finally, corona (low-intensity PD) fault condition is identified which can be seen in Table 10.

If all succeeding ratios for a specific fault type fall within the values given in Table 9, the suggested diagnosis is valid. Else, the Doernenburg ratio method can lead to considerable proportion of no decision in many scenarios [15].

4.5. Duval Triangle Method. "Michal Duval" introduced the Duval triangle in 1979. In this method, methane (CH_4), ethylene (C_2H_4), and acetylene (C_2H_2) gases are used for identification of fault in power transformers. These gases are generated due to high electrical and thermal stresses occurred in power transformer. For each of these gases, methane (CH_4), ethylene (C_2H_4), and acetylene (C_2H_2), its individual percentage share in the total concentration is determined in accordance with the mathematical expressions using (1) to (3) [16–18]. The sum of gas percentages must be equal to 100% [16–18]. The Duval triangle consists of seven different faults as shown in Table 10.

Table 10: Identified fault in "T-11" based on the Doernenburg ratio method.

Gas ratio	Concentration (ppm)	
CH_4/H_2 (R_a)	1200/1300	0.9
C_2H_2/C_2H_4 (R_b)	200/370	0.5
C_2H_2/CH_4 (R_c)	200/1200	0.1
C_2H_6/C_2H_2 (R_d)	630/200	3.1
Corona (low-intensity PD)		

Consider the proportions of three gases and draw parallel lines on the corresponding sides of the triangle. The dot visible inside the triangle indicates the fault zone. The main gas concentrations (ppm) taken are $\%CH_4 = 68$, $\%C_2H_4 = 21$, and $\%C_2H_2 = 11$.

Considering CH_4 (point A), C_2H_4 (point B), and C_2H_2 (point C), construct parallel line to JK, KI, and IJ, respectively. These lines intersect at one point which is the fault indicator region.

$$\%C_2H_2 = \frac{100 \times C_2H_2}{C_2H_2 + C_2H_4 + CH_4} \quad (1)$$

$$\%C_2H_4 = \frac{100 \times C_2H_4}{C_2H_2 + C_2H_4 + CH_4} \quad (2)$$

$$\%CH_4 = \frac{100 \times CH_4}{C_2H_2 + C_2H_4 + CH_4} \quad (3)$$

Figure 2 depicts the Duval triangle output for concentration of gases given in Table 11, which indicates that key gas concentrations $\%C_2H_2 = 11$, $\%CH_4 = 68$, and $\%C_2H_4 = 21$. Thus, it identifies fault "mix of electrical and thermal faults." The main drawback of this method is that it ignores hydrogen (H_2) and ethane (C_2H_6) concentrations in fault identification [13].

4.6. Relative Percentage of Four Gas Methods. This technique symmetrically places relative percentage of various gases (H_2, C_2H_4, C_2H_2, and CH_4) to classify zones according to the six types of faults in a transformer. The H_2, C_2H_4, C_2H_2, and CH_4 are associated with low-energy electrical faults, high-energy thermal faults, high-energy electrical faults, and low-energy thermal faults, respectively. The relative percentage of four gases is calculated using mathematical expressions (4)–(7). The sum of gas percentage should be equal to 100% [2, 13, 14, 19, 20]. The gas concentration values of transformer "T-17 "are taken from Table 1, and this technique is applied to identify faults in it. The process of this technique is depicted in Figure 3. Initially, the relative

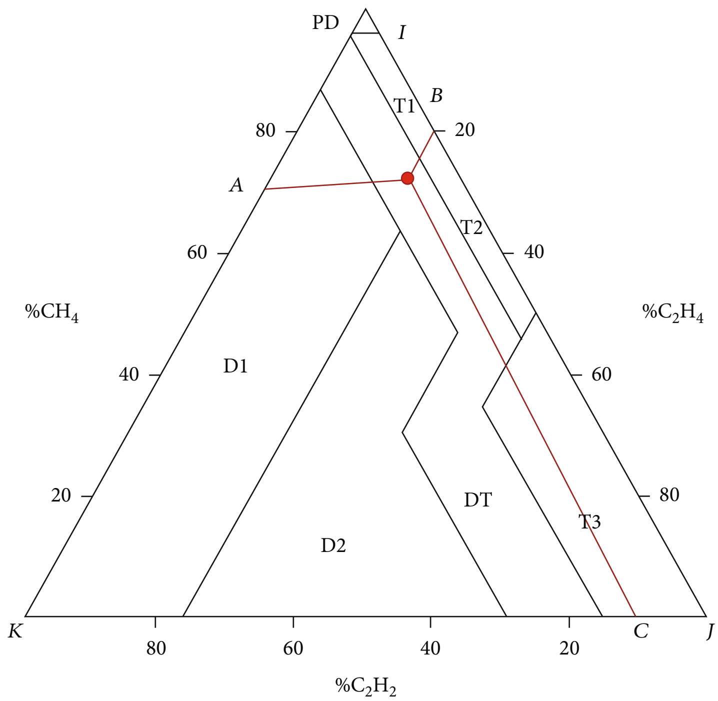


Figure 2: Identified faults in "T-5" using the Duval triangle method.

Table 11: Legends of the Duval triangle method [16].

PD	Partial discharge
T_1	Thermal fault 150°C < T_{emp} < 300°C
T_2	Thermal fault 300°C < T_{emp} < 700°C
T_3	Thermal fault T_{emp} > 700°C
D_1	Low-energy discharge (sparking)
D_2	High-energy discharge (arcing)
D_T	Mix of electrical and thermal fault

percentage of various gases is evaluated. The parallel lines are drawn for these percentage values. The mid point where intersection occurs represent the fault identification. For example, the mid point is T_b, "thermal fault" as depicted in Figure 3. The relative percentages of four gases are 52% H_2, 12% C_2H_4, 4% C_2H_2, and 38% CH_4.

$$\%CH_4 = \frac{CH_4 \times 100}{CH_4 + C_2H_2 + C_2H_4 + H_2} \quad (4)$$

$$\%C_2H_2 = \frac{C_2H_2 \times 100}{CH_4 + C_2H_2 + C_2H_4 + H_2} \quad (5)$$

$$\%C_2H_4 = \frac{C_2H_4 \times 100}{CH_4 + C_2H_2 + C_2H_4 + H_2} \quad (6)$$

$$\%H_2 = \frac{CH_4 \times 100}{CH_4 + C_2H_2 + C_2H_4 + H_2} \quad (7)$$

4.7. Three-Ratio Method. This method is based on analysis of five gases produced due to inner faults in oil-immersed power transformers. The gases are comprised of hydrogen (H_2), ethane (C_2H_6), methane (CH_4), acetylene (C_2H_2), and ethylene (C_2H_4) which are divided into three gas ratios that can be used to identify faults in power transformers as shown in Table 12. Normal ageing, thermal breakdown, partial discharge, arcing, and combination of thermal and electrical faults, which are presented in Table 13, are identified by this method [12]. On the other hand, based on temperature of fault type, each fault has a different severity level [21–23]. This method proposes three gas ratio combinations as shown in

$$R_a = \frac{C_2H_6 + C_2H_4}{H_2 + C_2H_2}, \quad R_b = \frac{C_2H_2 + CH_4}{C_2H_4}, \quad R_c = \frac{C_2H_2}{C_2H_4} \quad (8)$$

The DGA data from Table 1 of transformer "T-17" is taken, and the three-ratio method is implemented in order to assess the faults in transformer [21]. By applying data to this method, the thermal fault of 300 < T_{emp} < 700°C is identified. Each gas ratio range is as follows:

(i) R_a gas ratio range is $0.05 \le R_a \le 0.9$

(ii) R_b gas ratio range is $1 \le R_b \le 3.5$

(iii) R_c gas ratio range is $0.05 \le R_c < 0.5$

Hence, finally, "thermal faults of 300 < T_{emp} < 700°C" fault condition is identified which can be seen in Table 14.

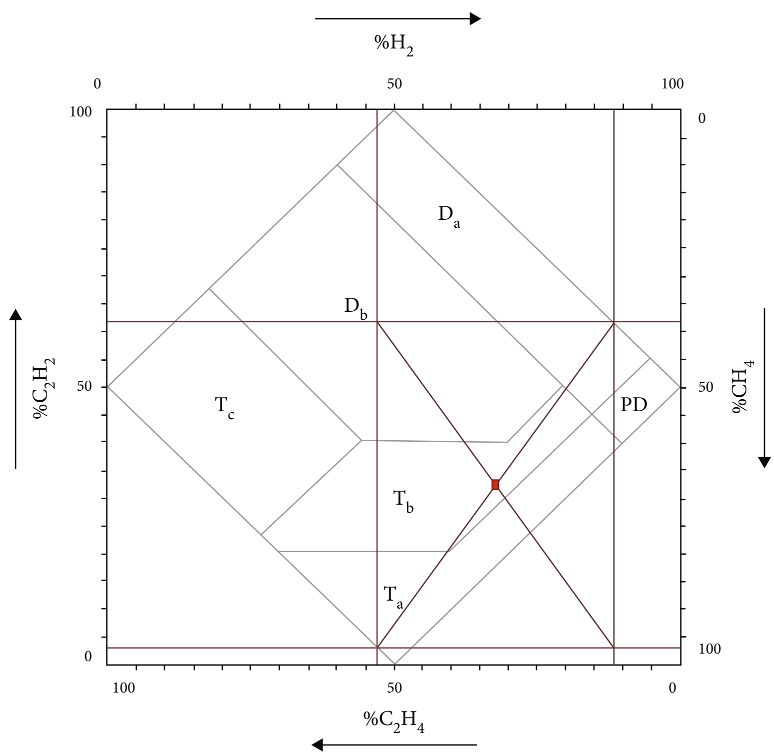


Figure 3: Identified fault in “T-17” using relative percentage of four gases.

Table 12: Specification of code rule based on three-ratio method [12].

R_a	R_b	R_c
$R_a < 0.05$	$R_b < 1$	$R_c < 0.05$
$0.05 \le R_a \le 0.9$	$1 \le R_b \le 3.5$	$0.05 \le R_c < 0.5$
$R_a > 0.9$	$R_b > 3.5$	$R_c \ge 0.5$

5. Comparison of Various DGA Methods

To compare the performance of various DGA methods, the different transformers installed in “RAWAT” in Islamabad and “UCH “power station in Balochistan, Pakistan, are considered. The considered transformers have different ratings such as 450 MVA, 250 MVA, 1600 kVA, and 1000 kVA. These transformers are tested in the laboratory, and the generated gas data of various transformers are obtained and are summarized in Table 1.

(i) The DGA data of transformers “T-3, T-7, T-13, and T-18” are taken from Table 1, and key gas method is applied to them. The faults “overheat of oil,” “overheat of cellulose,” “corona,” and “arcing” are detected, respectively, in the above-mentioned transformers by using key gas method as displayed in Figures 1(a)–1(d). But this method is unable to provide numerical correlations between gas types and fault types, since accurate diagnosis requires a lot of practice

(ii) The DGA data of transformer “T-18” from Table 1 is taken, and Roger’s code scheme is applied to it. The overheating in conductor fault is identified as shown in Table 4. This method did not consider values of dissolved gases lower than normal concentration which may lead many misread cases

(iii) For better understanding of the Doernenburg ratio method, the concentration values have been increased for transformer “T-11” DGA data given in Table 1 and applied to this method. The corona (low-intensity PD) fault is identified which is shown in Table 10. However, when gas concentrations surpass the limit, faults are identified. As a result of inadequate ratio ranges and method’s irrelevance, the Doernenburg ratio method can result in considerable proportion of no decision in many scenarios

(iv) The IEC ratio code scheme is employed to DGA data of transformer “T-14” taken from Table 1. The high-energy discharge fault is identified in transformer based on IEC ratio code scheme as shown in Table 6. In any case, it is unable to classify electrical and thermal faults of transformer into exact subtypes. The Rogers ratio and Doernenburg ratio method identified fault as “arc with power follow-through” and “arcing” concurrently; however, IEC ratio method fails to identify fault and indicates “not identified” as shown in Table 15

(v) Acetylene $(\%C_2H_2) = 11$, methane $(\%CH_4) = 68$, and ethylene $(\%C_2H_4) = 21$ are the calculation of

Table 13: Identification of fault coding used on three-ratio method [12].

Gases ratio code R_a	R_b	R_c	Fault type
$0.05 \le R_a \le 0.9$	NS	$R_c < 0.05$	Thermal faults T_o, $T_{emp} < 150^\circ C$
$R_a > 0.9$	$R_b > 3.5$	$R_c < 0.05$	Thermal faults T_a, $150 < T_{emp} < 300^\circ C$
$R_a > 0.9$	$R_b > 3.5$	$0.05 \le R_c < 0.5$	
$0.05 \le R_a \le 0.9$	$R_b > 3.5$	$0.05 \le R_c < 0.5$	
$0.05 \le R_a \le 0.9$	$R_b > 3.5$	$R_c < 0.05$	
$R_a > 0.9$	$1 \le R_b \le 3.5$	$R_c < 0.05$	Thermal faults T_b, $300 < T_{emp} < 700^\circ C$
$R_a > 0.9$	$1 \le R_b \le 3.5$	$0.05 \le R_c < 0.5$	
$0.05 \le R_a \le 0.9$	$1 \le R_b \le 3.5$	$0.05 \le R_c < 0.5$	
$0.05 \le R_a \le 0.9$	$1 \le R_b \le 3.5$	$R_c < 0.05$	
$R_a > 0.9$	$R_b \le 1$	$R_c < 0.05$	Thermal faults T_c, $T_{emp} > 700^\circ C$
$R_a > 0.9$	$R_b \le 1$	$0.05 \le R_c < 0.5$	
$0.05 \le R_a \le 0.9$	$R_b \le 1$	$0.05 \le R_c < 0.5$	
$0.05 \le R_a \le 0.9$	$R_b \le 1$	$R_c < 0.05$	
$0.05 \le R_a \le 0.9$	$R_b > 3.5$	$R_c \ge 0.5$	Low-energy discharge
$R_a > 0.9$	$R_b > 3.5$	$R_c \ge 0.5$	
$0.05 \le R_a \le 0.9$	$R_b \le 3.5$	$R_c \ge 0.5$	High-energy discharge
$R_a \le 0.05$	$R_b \le 3.5$	$R_c \ge 0.5$	
$R_a \le 0.05$	$R_b > 1$	$R_c < 0.05$	Low-energy corona partial discharge
$R_a \le 0.05$	$R_b > 1$	$0.05 \le R_c < 0.5$	
$R_a \le 0.05$	$R_b > 1$	$R_c \ge 0.5$	High-energy corona partial discharge
$R_a > 0.9$	$R_b \le 3.5$	$R_c \ge 0.5$	Mix of electrical and thermal fault

Table 14: Identification of fault in "T-17" using coding of three-ratio method [22, 23].

Gas ratio		Concentration (ppm)	
R_a	$\frac{C_2H_6+C_2H_4}{H_2+C_2H_2}$	12.800 + 4.701/17.737 + 1.037	0.932193
R_b	$\frac{C_2H_2+CH_4}{C_2H_4}$	1.037 + 14.606/4.701	3.32759
R_c	$\frac{C_2H_2}{C_2H_4}$	1.037/4.701	0.220591
Thermal faults of $300 < T_{emp} < 700^\circ C$			

the transformer "T-16" taken from Table 1 and the "thermal fault T_b, $300^\circ C < T_{emp} < 700^\circ C$" is identified utilizing the Duval triangle method as depicted in Figure 2. The main drawback of this method is that it ignores hydrogen (H_2) and ethane (C_2H_6) concentrations in fault identification, despite their significance in identifying specific types of faults

(vi) The relative percentage of four gas methods did not identified faults in transformers "T-5, T-7, T-15, and T-16," but other all methods identified faults in these transformers

(vii) Three-ratio method identified faults in all transformers except "T-5" and "T-7"

(viii) In this comparative performance study, various DGA methods take into account the facts of the entire fault identification methods and ultimately identify real incipient faults of power transformers. Hence, by comparative study of all these seven fault identification DGA methods, identification of all type faults is possible such as partial discharge (PD) of with and without arcing, thermal faults with various ranges (300°C-700°C), arc-associated power follow, discharge of high energy, arcing, and mix of thermal and electrical faults.

The performance accuracy of each technique has been assessed as shown in Table 16. The accuracy is considered only for the total number of cases (T_c). The percentage of accuracy is calculated using [13]

$$A_t = \frac{T_r}{T_c} \times 100 \quad (9)$$

Table 15: Fault identification results of each DGA methods.

S. no.	Roger's ratio method	IEC ratio method	Doernenburg ratio method	Duval triangle method	Three-ratio method	Relative percentage of four gas methods	Key gas method
T-1	T2	T2	Thermal decomposition	T1	T1	NR	NR
T-2	NI	T2	Thermal decomposition	T1	T1	T2	NR
T-3	T2	T3	PD	T2	T3	T3	NI
T-4	T2	T2	NI	NI	T2	T1	PD
T-5	NI	NI	NI	NR	NI	NI	Overheat of oil
T-6	T3	T3	NI	NR	T3	T2	NR
T-7	NI	NI	T1	NR	T3	NI	Overheat of cellulose
T-8	T2	T3	NI	NI	NI	T3	Arc
T-9	T4	T3	NI	T2	T3	T3	PD
T-10	T1	T3	NI	NR	T3	NI	PD
T-11	D1	NI	Thermal decomposition	DT	D1	T2	NI
T-12	T3	T2	NI	NI	T2	NR	NR
T-13	NI	NI	Thermal decomposition	D1	D2	T1	Overheat of oil
T-14	NI	PD	Arc	D2	D1	D2	Overheat of cellulose
T-15	T1	NI	T1	NR	D2	NI	Overheat of oil
T-16	T3	T3	NI	NR	T1	NI	Arc
T-17	NI	NI	T1	NR	T1	PD	Overheat of oil
T-18	T3	PD	Arc	T2	T3	T2	NI
T-19	NI	F6	T1	DT	D2	NR	F3
T-20	T3	T3	NI	NR	NR	T3	NR
T-21	T3	T2	NI	NR	T3	T2	Overheat of cellulose
T-22	T1	NI	NI	NI	T1	T2	Overheat of oil

Table 16: Performance accuracy comparison of each DGA method.

Total cases T_c	Roger's ratio method	IEC ratio method	Doernenburg ratio method	Duval triangle method	Three-ratio method	Relative percentage of four gas methods	Key gas method
Number of total predictions T_p	22	22	22	22	22	22	22
Total right predictions T_r	15	16	11	18	20	17	19
Total wrong predictions T_w	7	6	11	4	2	5	3
Total accuracy A_t	68%	72%	50%	81%	90%	77%	86%

where A_t is for the total number of accuracy, T_r is the total number of right predictions, and T_c represents the total number of cases.

In this research, considering the concentration of key gases such as hydrogen (H_2), ethylene (C_2H_4), acetylene (C_2H_2), ethane (C_2H_6), methane (CH_4), carbon dioxide (CO_2), and carbon monoxide (CO), the faults recognized by seven DGA techniques provide diverse conditions for similar sample unit given in Table 1. Figure 4 indicates the percentage prediction of all seven DGA methods. It is depicted that the IEC and Roger's ratio methods have an accuracy of 72% and 68%, respectively. The performance accuracy of the Doernenburg ratio method in identifying faults in power transformer is 50%. The key gas and the Duval triangle techniques have succeeded in identifying faults in power transformer for less than 90% accuracy. This

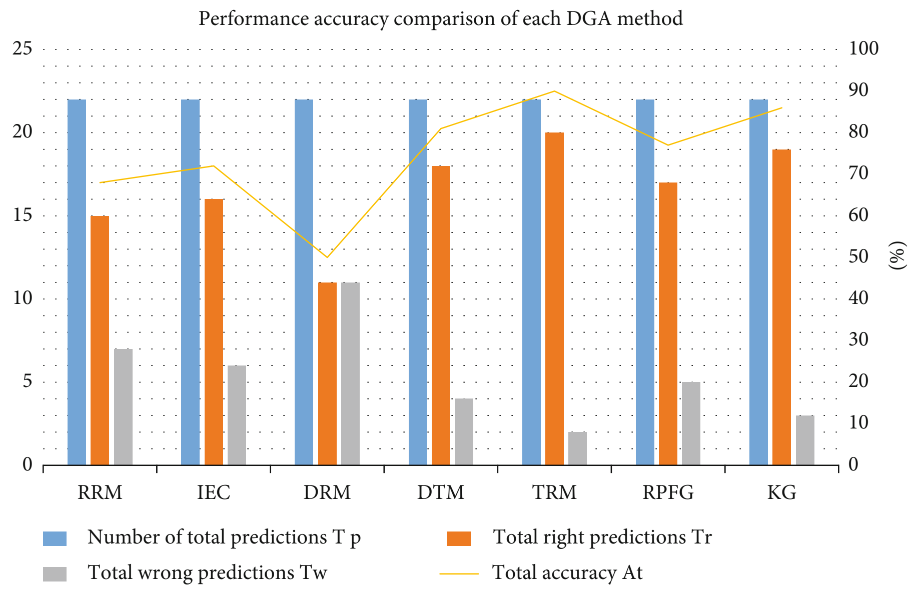


Figure 4: Performance accuracy comparison of each DGA method.

is equivalent to 17 cases out of a total of 22, followed by relative percentage of four gases with an accuracy of 77%. Cellulose degradation is identified individually because none of these methods include the interpretation of carbon monoxide and carbon dioxide. Three-ratio method has succeeded in identifying faults of power transformer approximately 90%. Thus, we can say from the above discussion that the three-ratio method is the most accurate (90% accuracy) method in identifying the faults in power transformers installed in "RAWAT" NTDC grid station in Islamabad and "UCH-II" power station in Balochistan, Pakistan.

6. Conclusions

Power transformer is an essential element of an electrical energy system. There are certain faults occurred in power transformer due to electrical and thermal stress. An accurate and timely evaluation of a transformer's condition is necessary for its efficient and secure functioning. The dissolved gas analysis (DGA) method is well regarded as a viable technique for assessing transformer's fault conditions. The transformer oil is an important information carrier that gives perception on all transformer's faults and enables for the timely application of the most appropriate repair measures. However, a successful gas-in-oil analysis is required, and its success is contingent on DGA method's proper execution.

The DGA method has been popular for almost 40 years due to its effectiveness and appropriate methods for diagnosing faults in transformers. As a result, power companies have teamed up with the oil diagnostic industry to utilize enhanced measuring mechanism for gas-in-oil assessment, as well as develop statistical interpretation methods for fault diagnosis. In this research work, the main focus is on the detailed comparative performance study of various DGA techniques (Roger's ratio, key gas, IEC ratio, Doernenburg ratio, Duval triangle, three-ratio method, and relative percentage of four gases) for evaluation of different faults in power transformer. The comparative points are as follows:

(i) Partial discharge faults are low-intensity faults that arise at minimal temperature, but they can be accompanied with arcing discharges that produce high quantities of methane, hydrogen, and acetylene in some situations

(ii) Thermal faults exceeding 500°C produce huge volumes of ethylene, methane, hydrogen, and acetylene

(iii) For temperatures above 1000°C, the volume of gases generated rapidly increases

(iv) Arcing discharge faults have a substantially faster energy dissipation rate, resulting in the highest hydrogen and acetylene concentrations

(v) The performance accuracy of IEC and Roger's ratio technique in identifying faults in power transformer is 72% and 68%, respectively

(vi) The Doernenburg ratio method demerits over the IEC and Roger's ratio methods, and it does not provide the faults' detail

(vii) The key gas and the Duval triangle mechanisms have succeeded in identifying the faults in power transformer with accuracy of 86% and 81%, respectively

(viii) The relative percentage of four gases identified faults in 17 cases out of a total of 22 transformers, which indicates an accuracy of 77%

(ix) The cellulose degradation is identified individually because none of these methods include the interpretation of carbon monoxide (CO) and carbon dioxide (CO_2)

(x) The three-ratio method has 90% accuracy in identifying the faults in power transformer

(xi) Thus, we can conclude that three-ratio method is optimal and the most accurate technique in identifying the faults in power transformer

This research work has compared the performance of various DGA techniques for fault identification in transformers. The limitations of DGA techniques are taking longer time in fault identification, high cost of gases, and low concentration of gases that might result in failure of fault identification. In the future, this work can be extended to incorporate machine learning and AI algorithms for identification of faults in transformer. Furthermore, soy seed-based oils and natural ester can be utilized for transformer's status monitoring.

Data Availability

Data are available on request.

Conflicts of Interest

The authors declare no conflict of interest.

Authors' Contributions

The authors confirm the final authorship for this manuscript. All the authors have equally contributed to this manuscript.

Acknowledgments

This work was supported by the Researchers Supporting Project Number RSP2023R467, King Saud University, Riyadh, Saudi Arabia.

References

[1] Z. Wu, B. Lin, J. Fan, J. Zhao, Q. Zhang, and L. Li, "Effect of dielectric relaxation of epoxy resin on dielectric loss of medium-frequency transformer," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 29, no. 5, pp. 1651–1658, 2022.

[2] M. D. Equbal, M. M. Nezami, H. Hashem et al., "IOT based classification of transformer faults using emerging techniques of E-nose and ANFIS," *Frontiers in Energy Research*, vol. 10, 2022.

[3] S. Xiao, Z. Wang, G. Wu et al., "The impact analysis of operational overvoltage on traction transformers for high-speed trains based on the improved capacitor network methodology," *IEEE Transactions on Transportation Electrification*, vol. 7, 2023.

[4] B. Zhang, S. Wang, L. Chen, X. Li, and N. Tang, "Influence of oxygen on solid carbon formation during arcing of eco-friendly SF6-alternative gases," *Journal of Physics D: Applied Physics*, vol. 56, no. 36, article 365502, 2023.

[5] H. C. Sun, Y. C. Huang, and C. M. Huang, "A review of dissolved gas analysis in power transformers," *Energy Procedia*, vol. 9, pp. 20–26, 2012.

[6] N. A. Muhamad, B. T. Phung, and T. R. Blackburn, "Comparative study and analysis of DGA methods for mineral oil using fuzzy logic," in *2007 International Power Engineering Conference (IPEC 2007)*, pp. 1301–1306, Singapore, 2007.

[7] O. Shutenko and O. Kulyk, "Comparative analysis of the defect type recognition reliability in high-voltage power transformers using different methods of DGA results interpretation," in *2020 IEEE Problems of Automated Electrodrive. Theory and Practice (PAEP)*, pp. 1–6, Kremenchuk, Ukraine, 2020.

[8] N. Huang, Q. Chen, G. Cai, D. Xu, L. Zhang, and W. Zhao, "Fault diagnosis of bearing in wind turbine gearbox under actual operating conditions driven by limited data with noise labels," *IEEE Transactions on Instrumentation and Measurement*, vol. 70, pp. 1–10, 2021.

[9] I. B. Taha, S. S. Ghoneim, and H. G. Zaini, "Improvement of Rogers four ratios and IEC code methods for transformer fault diagnosis based on dissolved gas analysis," in *Proceedings of North American Power Symposium (NAPS)*, pp. 1–5, Charlotte, NC, USA, 2015.

[10] S. Lu, Y. Ban, X. Zhang et al., "Adaptive control of time delay teleoperation system with uncertain dynamics," *Frontiers in Neurorobotics*, vol. 16, article 928863, 2022.

[11] I. B. Taha, H. G. Zaini, and S. S. Ghoneim, "Comparative study between dorneneburg and rogers methods for transformer fault diagnosis based on dissolved gas analysis using Matlab Simulink Tools," in *2015 IEEE Conference on Energy Conversion (CENCON)*, pp. 363–367, Johor Bahru, Malaysia, 2015.

[12] S. Lu, J. Guo, S. Liu et al., "An improved algorithm of drift compensation for olfactory sensors," *Applied Sciences*, vol. 12, no. 19, p. 9529, 2022.

[13] S. Ghoneim and K. A. Shoush, "Diagnostic tool for transformer fault detection based on dissolved gas analysis," *Advances in Electrical Engineering Systems*, vol. 3, pp. 152–156, 2014.

[14] J. Li, Y. Deng, W. Sun et al., "Resource orchestration of cloud-edge–based smart grid fault detection," *ACM Transactions on Sensor Networks (TOSN)*, vol. 18, no. 3, pp. 1–26, 2022.

[15] N. A. Bakar, A. Abu-Siada, H. Cui, and S. Li, "Improvement of DGA interpretation using scoring index method," in *Proceedings of in 1st International Conference on Electrical Materials and Power Equipment (ICEMPE)*, pp. 502–506, Xi'an, China, 2017.

[16] G. S. Sarma, R. Reddy, P. M. Nirgude, and V. Naidu, "A review on real time fault detection and intelligent health monitoring techniques of transformer," *International Journal of Engineering Research and Applications*, vol. 11, pp. 40–47, 2021.

[17] T. Piotrowski, P. Rozga, R. Kozak, and Z. Szymanski, "Using the analysis of the gases dissolved in oil in diagnosis of transformer bushings with paper-oil insulation—a case study," *Energies*, vol. 13, no. 24, p. 6713, 2020.

[18] W. Hu, T. Wang, and F. Chu, "A novel Ramanujan digital twin for motor periodic fault monitoring and detection," *IEEE Transactions on Industrial Informatics*, vol. 23, pp. 1–9, 2023.

[19] H. Syafruddin and H. P. Nugroho, "Dissolved gas analysis (DGA) for diagnosis of fault in oil-immersed power transformers: a case study," in *Proceedings of 4rd International Conference on Electrical, Telecommunication and Computer Engineering (ELTICOM)*, pp. 57–62, Medan, Indonesia, 2020.

[20] P. Luo, B. Wang, H. Wang, F. Ma, H. Ma, and L. Wang, "An ultrasmall bolt defect detection method for transmission line inspection," *IEEE Transactions on Instrumentation and Measurement*, vol. 72, pp. 1-2, 2023.

[21] O. E. Gouda, S. M. Saleh, and S. H. El-Hoshy, "Power transformer incipient faults diagnosis based on dissolved gas analysis," *ELKOMNIKA Indonesian Journal of Electrical Engineering*, vol. 16, pp. 10–16, 2015.

[22] M. M. Islam, G. Lee, and S. N. Hettiwatte, "A nearest neighbour clustering approach for incipient fault diagnosis of power transformers," *Electrical Engineering*, vol. 99, no. 3, pp. 1109–1119, 2017.

[23] Y. Han, S. Chen, C. Gong, X. Zhao, F. Zhang, and Y. Li, "Accurate SM disturbance observer-based demagnetization fault diagnosis with parameter mismatch impacts eliminated for IPM motors," *IEEE Transactions on Power Electronics*, vol. 38, no. 5, pp. 5706–5710, 2023.