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Reliable Estimation for Health Index of Transformer Oil Based on Novel Combined Predictive Maintenance Techniques

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ABSTRACT Transformer oil insulation condition may be deteriorated due to electrical and thermal faults, which may lead to transformer failure and system outage. In this regard, the first part of this paper presents comprehensive maintenance for power transformers aiming to diagnose transformer faults more accurately. Specifically, it aims to identify incipient faults in power transformers using what is known as dissolved gas analysis (DGA) with a new proposed integrated method. This proposed method for DGA is implemented based on the integration among the results of five different DGA techniques; 1) conditional probability, 2) clustering, 3) Duval triangle, 4) Roger's four ratios refined, and 5) artificial neural network. Accordingly, this proposed integrated DGA method could improve the overall accuracy by 93.6% compared to the existing DGA techniques. In addition, the second part used for predictive maintenance is based on determining the health index for five new transformers and an aged power transformer (66/11 kV, 40 MVA) filled with NYTRO 10XN oil by evaluating the breakdown voltage, DGA, moisture content, and acidity for the oil. In the breakdown voltage test, two practical types of transformer oil; NYTRO 10XN and HyVolt III alongside their mixtures are estimated and compared. In addition, aged oil samples extracted from a real case study in-service transformer during operation with different aged durations; 9, 10, 11, 12, and 13 years, are tested for breakdown voltage, and then compared with fresh oil samples. For DGA, a temperature rise test is performed on the five new transformers with a comparison between dissolved gases before and after the temperature rise. In addition, winding resistance is measured after the temperature rise. Also, acidity and moisture are measured for oils extracted from the new five transformers and from the 13-year in-service transformer for studying their health index. The health index of the transformer insulation system is examined using only DGA and DGA plus breakdown voltage (BDV), moisture, and acidity. The results show that by using DGA plus BDV, moisture, and acidity, the health index provides reliable estimation results compared to using only DGA.

INDEX TERMS Transformer oil, dissolved gas analysis, fault diagnosis, breakdown voltage, temperature rise, health index, predictive maintenance.

I. INTRODUCTION

Power transformers are an essential apparatus in the electrical power network. It is an expensive item in electrical networks. The failure of a power transformer leads to substantial costs either due to system outage or due to increased maintenance costs [1]. Oil is used in power transformers as an insulating medium and a heat transfer medium. The transformer oil insulation condition shall be deteriorated by electrical and thermal possible faults. These possible faults can be classified into

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electrical and thermal types. Electrical fault types include partial discharge (PD) as well as low and high energy discharge (D1 and D2), while thermal fault types include low, medium, and high thermal faults (T1, T2, and T3) [2], [3]. Hence, the continuous monitoring of oil insulation condition plays an important role in increasing the power system reliability and reducing the risk of power transformer failure. Electrical and chemical test techniques are used as diagnostic techniques for detecting the oil insulation condition. Dissolved Gas Analysis (DGA) is one of the most common chemical methods used for detecting the insulation fault type [4]–[6]. During the normal transformer operation, some low concentrations of gases are released such as Hydrogen (H_2), Methane (CH_4), Acetylene (C_2H_2), Ethylene (C_2H_4), Ethane (C_2H_6), Carbon monoxide (CO), and Carbon Dioxide (CO_2). While during fault conditions, these gases are produced with high concentrations, and hence DGA techniques depend on detecting the released concentrations in case of thermal and electrical stresses [7], [8].

Many conventional techniques were developed and used for the interpretation of transformer incipient faults based on DGA such as key gas ratio [9], Rogers' ratio [9], [10], IEC gas ratio [10], Dornenburg ratio technique [9], and Duval techniques [11], [12]. The conventional approaches do not often yield accurate analysis while missing important incipient faults, thereby leading to the 'no decision' issue [7]. Most of the existing DGA techniques have limited diagnostic accuracy and may fail to interpret the oil faults in transformers [13]. More studies have been presented to improve the traditional interpretation techniques using artificial intelligence (AI) and computational techniques [14]–[16]. However, most AI techniques are complicated and difficult for practical engineers to apply. Hence, this research topic is still open for improving the diagnostic accuracy of transformer faults. Recently, new approaches have been presented including a combination and integration between the diagnosis results of multiple techniques. Four techniques have been presented with an accuracy of 69.96%, 84.96%, 83.27%, and 85.3% based on using 532 samples [17]. Two graphical shapes were presented to improve the diagnosis accuracy of the transformer fault types using the DGA approach [18]. In addition, an approach was presented based on the limits of new gas concentration percentages to improve the faults diagnostic accuracy [19]. In [20], a model of convolutional neural network (CNN) was studied to accurately predict the types of faults under different levels of noise in measurements. In addition, another proposed DGA technique based on extreme machine learning was presented as in [21]. Also, a new maintenance decision-making model was proposed for power transformer based on economy and reliability assessment [22]. According to support vector machine (SVM), a novel technique was proposed to improve the diagnostic accuracy of transformer fault types [16]. DGA lacks two main issues. Firstly, its accuracy needs to be increased for reliable fault diagnosis. Secondly, it cannot provide sufficient information about the condition of the transformer oil itself. On the other side, different approaches of diagnosis and monitoring were used, based on a wide variety of thermal, mechanical, electrical, and optical effects. These approaches provided information on aging, allowing the state assessment, and recommended measures to improve the quality of the insulation and lifetime assessment [23], [24]. One of these approaches is the health index, whose evaluation is based on different factors [23], [25]. These factors include dielectric strength measurement, DGA, turns ratio, leakage reactance, winding resistance, and degree of polymerization for paper insulation.

For breakdown voltage test, it is an indicator for dielectric severity in power transformers [26]. In [27], dielectric characteristics of transformer mineral oil with different compositions of corn oil were studied. In addition, the effect of the natural fibres on the dielectric strength of natural ester as a liquid insulating material was presented in [28]. In addition, a comparative study of the positive and negative DC breakdown voltages of different transformer oils was presented in [29]. The aging characteristics of mineral oil were studied in [30]. Further, a temperature rise test was used as an indicator of thermal severity in power transformers [31]. According to the literature review, most existing DGA techniques have poor diagnostic accuracy for certain fault types, which in turn can fail to interpret the diverse transformer oil faults. Based on this notice, a combined DGA method could distinct the conflict among the various transformer oil faults, yielding higher accuracy rates. Another gap in the literature is that the health condition index of power transformer oil is estimated by individual approaches, which can lead to unreliable estimation results, thereby it is covered in this work.

To cover the abovementioned gap in the literature, this paper presents comprehensive predictive maintenance for power transformers based on a new DGA technique alongside additional health index evaluation that is simultaneously based on the breakdown voltage test, acidity and moisture measurements, as well as DGA results before and after temperature rise test. First, the new DGA technique is presented and developed using 360 samples of known actual faults collected from the Egyptian Electricity network and from literature. The accuracy of the proposed technique is compared with its construction techniques as well as the recently published techniques. Next, a health index calculation is presented, based on the test results of the transformer insulation system (breakdown strength, dissolved gas analysis, moisture, and acidity) for new and aged transformers. Transformer case study of rating (66/11 kV) of NYTRO 10XN oil type is collected from ELMACO Company, Egypt. For calculation of the health index of transformer insulation system, breakdown voltage tests for two practical types of transformer oil; NYTRO 10XN and HyVolt III alongside their mixtures are estimated and compared. The oil mixture is investigated to study the effect of mixing that could happen inside the transformer in the absence of one of these oils. Finally, a temperature rise test is performed on five new transformers of the same rating with a comparison between dissolved gases before and after the temperature rise. In addition, winding resistance is measured after the temperature rise. Also, acidity and moisture are measured for oils extracted from the new five transformers and from a 13-year in-service transformer for studying their health index. The health index of the transformer insulation system is examined using only DGA and DGA plus breakdown voltage (BDV), moisture, and acidity.

II. PROPOSED DGA BASED FAULT DIAGNOSTIC TECHNIQUE

The existing interpretation techniques have not provided properly accepted results for detecting transformer faults. Hence, it is an open research area for new proposed DGA techniques to overcome the problems of existing ones. The limiting accuracy of conventional DGA techniques is still a major problem for diagnosing transformer faults due to interference between electrical and thermal faults. A newly proposed technique for fault diagnosis is prepared and presented. This proposed technique is developed based on the integration among the results of conventional and non-conventional techniques. These techniques are five techniques; conditional probability [32], clustering [33], Duval [11], Roger's four ratios refined [34], and artificial neural network (ANN) [35] techniques. A total of 360 samples of known actual faults are used in developing the proposed technique, and also are used as a dataset for testing the technique accuracy. A total 120 samples have been recently collected from the Central Laboratory of the Egyptian Ministry of Electricity and 240 samples are extracted from literature [33]. Table 1 summarizes the distribution of all these samples for various fault types.

The selected samples have a convergence between the number of samples for each fault type avoiding a noticeable discrepancy between number of samples for each fault used in the literature [17]. The used datasets have been analyzed based on the IEEE Std. C57.104-2008 [9]. Fig. 1 presents the range of gas concentration percentage (GCP) for each fault type. GCP is the parentage of each gas divided by the sum of the five main gases (H_2, CH_4, C_2H_2, C_2H_4, and C_2H_6) as shown in the following equations:

$$GCP_{H_2} = \frac{H_2}{H_2 + CH_4 + C_2H_4 + C_2H_6 + C_2H_2}\% \quad (1)$$

$$GCP_{CH_4} = \frac{CH_4}{H_2 + CH_4 + C_2H_4 + C_2H_6 + C_2H_2}\% \quad (2)$$

$$GCP_{C_2H_6} = \frac{C_2H_6}{H_2 + CH_4 + C_2H_4 + C_2H_6 + C_2H_2}\% \quad (3)$$

$$GCP_{C_2H_4} = \frac{C_2H_4}{H_2 + CH_4 + C_2H_4 + C_2H_6 + C_2H_2}\% \quad (4)$$

$$GCP_{C_2H_2} = \frac{C_2H_2}{H_2 + CH_4 + C_2H_4 + C_2H_6 + C_2H_2}\% \quad (5)$$

Fig. 1(a) shows that H_2 is the most generated gas due to the PD fault type. Hence, H_2 is the main key gas in partial discharge. Fig. 1(b) shows that Hydrogen (H_2) is the dominant key gas in the case of low energy discharge (D1). Acetylene (C_2H_2) is the dominant gas in case of high energy discharge (D2), see Fig. 1(c). The Ethan (C_2H_6) is the dominant gas in low thermal fault, see Fig. 1(d). The methane (CH_4) and ethane (C_2H_6) are the dominant gases in the case of medium thermal fault (T2), see Fig. 1(e). Ethylene (C_2H_4) is the dominant gas in case of high thermal fault (T3), see Fig. 1(f). These results are summarized in Table 2, indicating that the resulting key gas for each fault type matches the standard IEEE Std. C57.104-2008 [9]. Hence, the accuracy and reliability of the used datasets were confirmed.

A. THE STRUCTURE AND PROCEDURES OF THE PROPOSED TECHNIQUE

The new technique for the fault diagnosis is prepared based on the integration among different conventional and non-conventional techniques. The best techniques, that exhibited good accuracy, are adopted in this work. These techniques are five techniques; conditional probability, clustering, Duval, Roger's four ratios refined, and ANN as shown in Table 3.

Techniques (1, 2, 3, 4, and 5) are based on the five main gases (H_2, CH_4, C_2H_6, C_2H_4, and C_2H_2), represented in various ways. Techniques (1 and 2) are based on the percentages of main five gases with respect to their summation [32], [33] as shown in equations from (1) to (5). The technique (3) is based on the percentages of the three gases ratio (R_1, R_2, and R_3) as shown in equations from (6) to (8).

$$R_1 = \frac{CH_4}{CH_4 + C_2H_4 + C_2H_2}\% \quad (6)$$

$$R_2 = \frac{C_2H_4}{CH_4 + C_2H_4 + C_2H_2}\% \quad (7)$$

$$R_3 = \frac{C_2H_2}{CH_4 + C_2H_4 + C_2H_2}\% \quad (8)$$

TABLE 1. Number of samples for each fault type.

No. of samples	PD	D1	D2	T1	T2	T3	All
Literature [33]	27	42	55	70	18	28	240
Lab	33	2	1	30	25	29	120
Total	60	44	56	100	43	57	360

TABLE 2. The range of gas concentration percentage for each fault type according to the 360 datasets.

	PD	D1	D2	T1	T2	T3
H_2	30-98	8 – 95	0-61	0 – 58	0 - 57	5.5-58
CH_4	0.3-54	0.8-76	0-40	3 – 71	2 - 82	0–51
C_2H_6	0-65	0-41	0-68	0.5–91	5 – 79	0-32
C_2H_4	0-25	0-58	0-63	0 – 37	2 - 68	19-100
C_2H_2	0-2.1	1-61	3-73	0 – 3	0 – 2	0-7

The four ratios (R_4, R_5, R_6, and R_7), shown in equations from (9) to (12), are used for fault diagnosis in Technique (4) [34]. While the technique (5) in [35] is composed of multiple ANNs; the first ANN uses the percentages of the three gases ratio (R_1, R_2, and R_3) as inputs, the second ANN uses the

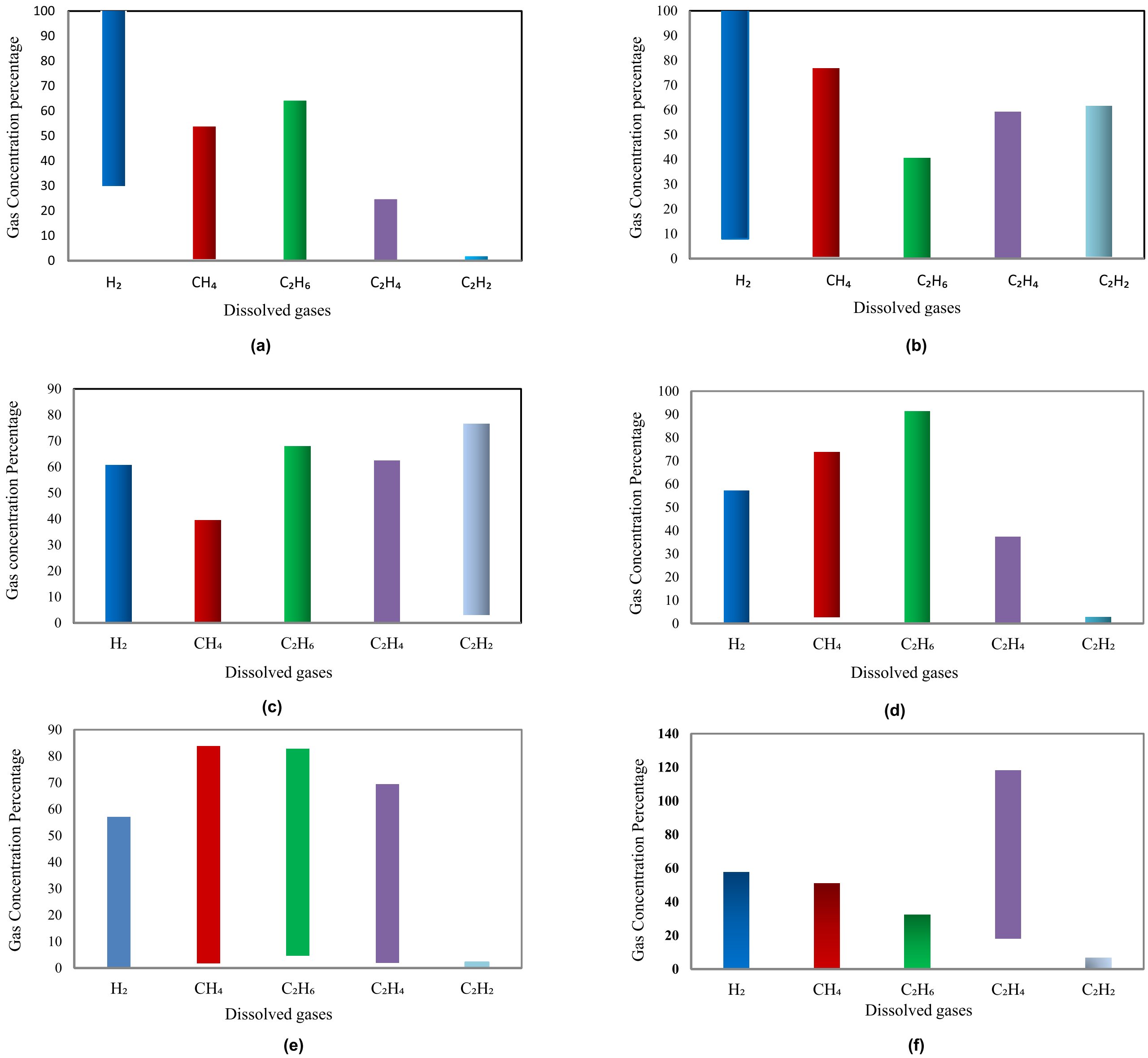

FIGURE 1. Distribution of the gases' concentration percentage according to the transformer fault types. (a) PD fault, (b) D1 fault, (c) D2 fault, (d) T1 fault, (e) T2 fault, and (f) T3 fault.

four ratios (R_4, R_5, R_6, and R_7) as inputs, and the third ANN uses the inputs of IEC technique that are given by the ratios (R_4, R_6, and R_7).

$$R_4 = \frac{CH_4}{H_2} \tag{9}$$

$$R_5 = \frac{C_2H_6}{CH_4} \tag{10}$$

$$R_6 = \frac{C_2H_4}{C_2H_6} \tag{11}$$

$$R_7 = \frac{C_2H_2}{C_2H_4} \tag{12}$$

Using the 360 samples, the five techniques are used for diagnosing the fault type, and these diagnoses are compared with the actual fault. Table 4 shows which of the five methods is more accurate in diagnosing each fault type separately.

TABLE 3. Integrated techniques used for developing the new proposed technique.

Technique No.	Description
(1)	Conditional probability technique [32]
(2)	Clustering technique [33]
(3)	Duval technique [11]
(4)	Rogers refined technique [34]
(5)	ANN technique [35]

The technique (1) is the more accurate one in all fault types except for low thermal fault, which can be accurately diagnosed by techniques (4) and (5). Technique (2) has high diagnostic accuracy for partial discharge and high energy discharge fault types. The technique (3) is better in detecting the

TABLE 4. The techniques of higher accuracy for each fault type.

	Conditional probability	Clustering	Duval	Rogers refined	ANN
PD	•	•			
D1	•		•		
D2	•	•			
T1				•	•
T2	•				
T3	•			•	

low energy discharge. These results were taken into account during the construction of the new technique.

According to the accuracy of the five techniques for each fault type, the proposed technique is constructed based on the integration between them. Its procedures are based on the combination of the most accurate techniques in each individual fault. Preparing and proceeding with the proposed technique can be accomplished via the flowchart in Fig. 2. The procedures of the proposed technique are implemented based on the diagnosis (Dig) of five techniques as follows:

Stage 1: If the detection result of conditional probability and clustering is partial discharge, the fault type is diagnosed as partial discharge.

Stage 2: If the detection result of conditional probability and clustering is high energy discharge, the fault type is diagnosed as high energy discharge.

Stage 3: If Rogers refined result is low thermal fault type, the diagnosis is low thermal fault type.

Stage 4: If the diagnosis of Duval is low energy discharge and that of conditional probability is low or high energy discharge, the fault type is diagnosed as low energy discharge.

Stage 5: If Rogers and conditional probability methods diagnosed high thermal fault type, the proposed technique result is high thermal fault type.

Stage 6: Medium thermal fault type is detected if the result of conditional probability is medium thermal fault type and the results of clustering, Duval, Rogers refined, and ANN are low, medium or high thermal fault types.

If no condition is satisfied, the diagnosis result is that of conditional probability.

B. PERFORMANCE EVALUATION OF THE PROPOSED TECHNIQUE

The accuracy of the proposed technique is compared with the five techniques, conditional probability, clustering, Duval, Rogers refined, and ANN. In addition, it is compared with

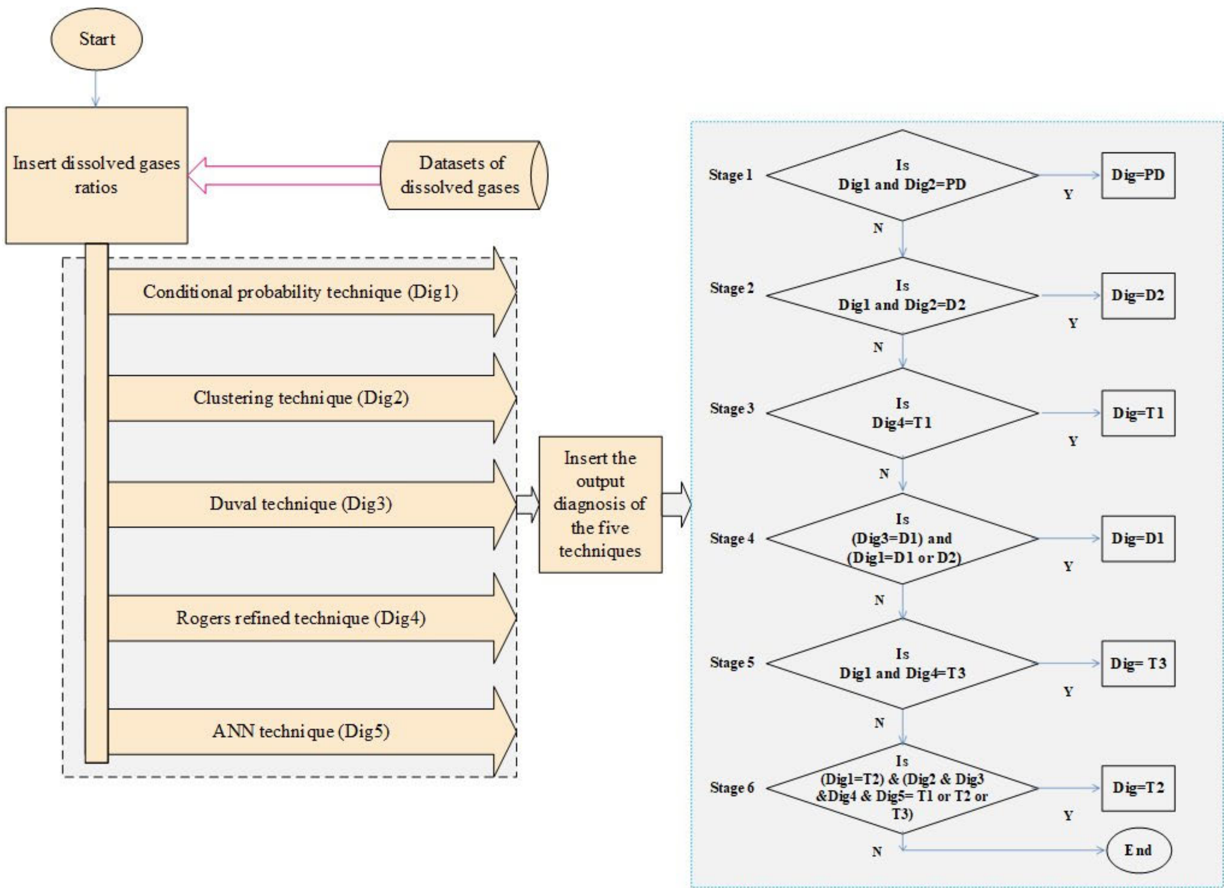

FIGURE 2. Flowchart procedures of the proposed technique.

TABLE 5. The accuracy of the proposed technique and its construction techniques for each fault type.

Incipient Fault	No. of Samples	Techniques					Proposed Technique
		(1)	(2)	(3)	(4)	(5)	
PD	60	93.3%	70%	16.6%	11.6%	60%	93.3%
D1	44	81.8%	52.2%	68.1%	18.1%	63.6%	86.3%
D2	56	98.2%	96.4%	25%	67.8%	85.7%	98.2%
T1	100	85%	30%	47%	90%	94%	96%
T2	43	83.7%	34.8%	41.8%	32.5%	32.5%	83.7%
T3	57	98.2%	50.8%	89.4%	98.2%	61.4%	98.2%
All	360	90%	53.6%	47.2%	59.1%	70.8%	93.6%

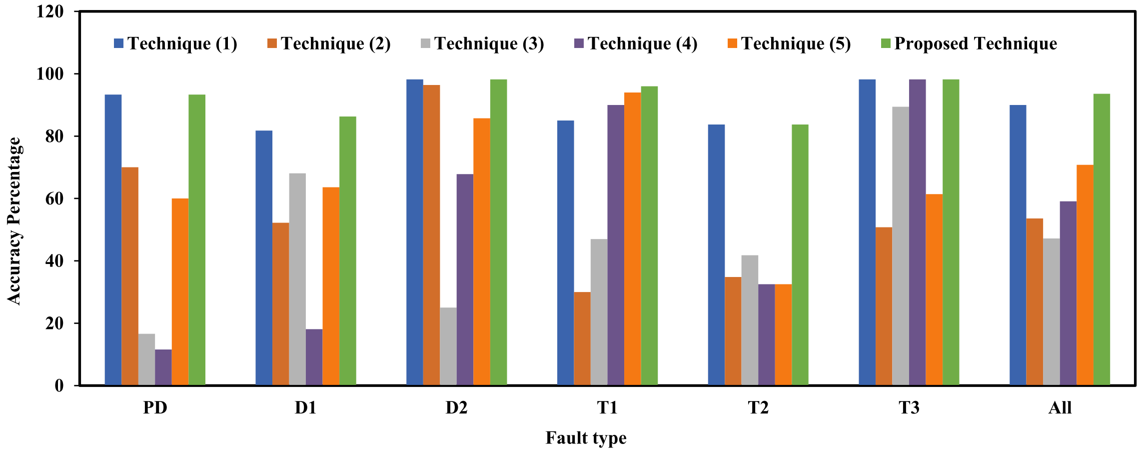

FIGURE 3. The accuracy of the proposed technique and its construction techniques.

TABLE 6. The accuracy of the proposed techneque and previous published techniques [17] for each fault type.

Incipient Fault	No. of Samples	Technique (a)	Technique (b)	Technique (c)	Technique (d)	Proposed Technique
PD	60	25%	91.6%	60%	58.3%	93.3%
D1	44	50%	79.5%	63.6%	79.5%	86.3%
D2	56	55.3%	98.2%	85.7%	94.6%	98.2%
T1	100	91%	87%	96%	96%	96%
T2	43	34.8%	81.3%	32.5%	81.3%	83.7%
T3	57	96.4%	98.2%	96.4%	96.4%	98.2%
All	360	63.6%	89.7%	76.9%	85.8%	93.6%

the previous four techniques published in [17], denoted as (a), (b), (c), and (d). These previous techniques were constructed by combining the results of previous studies. The technique (a) was formed based on the outputs of three methods, Roger's four ratios refined, Duval, IEC refined techniques, while technique (b) was constructed based on three (DGA) methods (Duval triangle, clustering, and conditional probability). The technique (c) was built depending on the outputs of two (DGA) methods (Roger's refined method and the ANN). Finally, technique (d) was based on the combined outputs of techniques (b) and (c) [17]. The improved accuracy of the proposed technique is proven using a large number of datasets (360) of known actual faults. For these samples, the convergence between the number of samples for each fault type is taken into account. The accuracy of the proposed technique is 93.3% for PD, 86.3% for D1, 98.2 % for D2, 96 % for T1, 83.7% for T2, and 98.2 % for T2.

The comparison of the proposed technique accuracy to that of its construction techniques is depicted in Table 5 and Fig. 3. The proposed technique accuracy is similar to that obtained from technique (1) in the diagnosis of PD, D2, T2, and T3. But the proposed technique could improve the diagnostic performance of for D1 and T1 fault types. Table 6 and Fig. 4 present a comparison between the proposed technique accuracy and that of the recently published four techniques in [17]. This is prepared and presented for the 360 data samples. With the application of recently four techniques for the datasets, the overall accuracies are 63.6%, 89.7%, 76.9%, and 85.8%, for techniques (a), (b), (c), and (d), respectively. However, the proposed technique improved the overall accuracy to

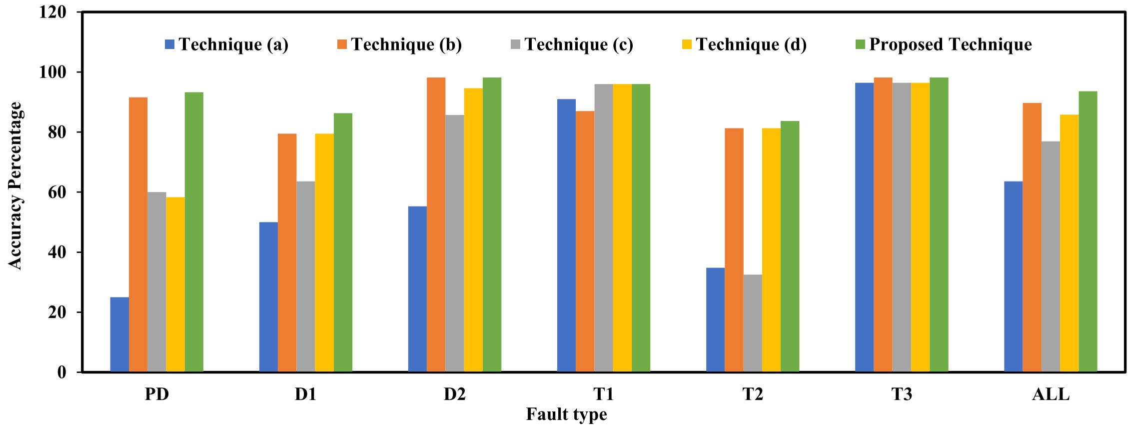

FIGURE 4. The accuracy of the proposed technique with comparison to previous published techniques [17].

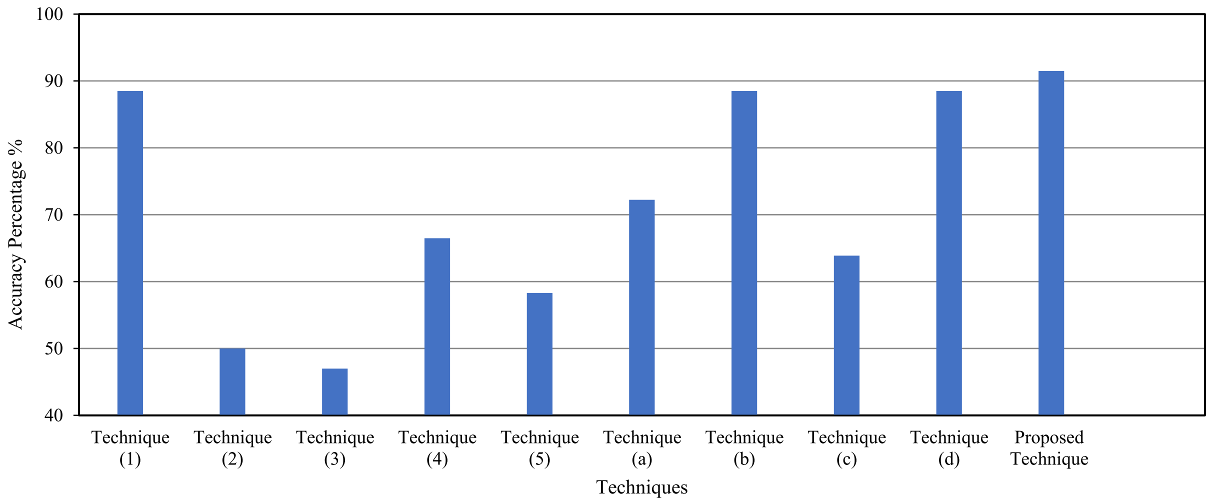

FIGURE 5. The proposed technique accuracy compared to its construction techniques and previous techniques [17] for the 36 validation datasets.

TABLE 7. Number of validation datasets used for evaluating the proposed technique accuracy.

Item	PD	D1	D2	T1	T2	T3	All
Literature datasets [17, 19, 32-34]	1	4	6	4	6	1	22
Laboratory datasets	2	0	0	5	4	3	14
Total datasets	3	4	6	9	10	4	36

93.6%. moreover, individual fault diagnosis accuracy through using the proposed technique achieved the highest accuracy compared to the four techniques.

For further checking the accuracy of the proposed technique, additional 36 validation datasets of known incipient faults have been collected from the literature [17], [19], [32]–[34] and laboratory, as shown in Table 7. The proposed technique accuracy, for these datasets, was compared with its five construction techniques as well as with previously published techniques (a), (b), (c), and (d). The overall accuracy of the proposed technique keeps up its superiority compared to all these techniques, as shown in Table 8 and Fig. 5. The proposed technique achieved an accuracy of more than 91.5% for these validation samples.

III. TRANSFORMER CASE STUDY

This part introduces a real case study for a new transformer with a rating (40 MVA, 66/11 kV) filled with NYTRO 10XN oil type. The first section of this part presents the breakdown voltage test for the oil type of the study case and its comparison with another type (HyVolt III) and their mixtures. The second section studies the temperature rise test effect on winding resistance and DGA. Then, in the third section, acidity and moisture are measured for the same case study, and the healthy index is calculated using these measurements together with the breakdown voltage measurement and dissolved gases concentrations. The health index is calculated for several case studies on the considered new transformer and a case study on an aged transformer.

A. BREAKDOWN VOLTAGE TEST

This section presents the breakdown voltage test as an indicator for the dielectric severity in power system

TABLE 8. The proposed technique diagnosis against its construction techniques and previous techniques [17] for validation datasets.

No. of Samples	Dissolved Gases					Actual Fault	DGA Techniques									
	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2		(1)	(2)	(3)	(4)	(5)	(a)	(b)	(c)	(d)	Proposed
1	505.57	475.35	242.3	524.45	3.29	T1	T2	D2	T3	T2	T1	T1	T2	T2	T1	T2
2	36	30	10	93	7.1	T3	T3	T3	T3	T3	T3	T3	T3	T3	T3	T3
3	103	74	80	9	0.001	T1	T1	D2	T1	T1	T1	T1	T1	T1	T1	T1
4	124	166	87	59	0.001	T1	T1	D2	T2	T1	T1	T1	T1	T1	T1	T1
5	231	3997	1726	5584	0.001	T2	T2	T2	T3	T2	Unknown	T3	T2	T2	T3	T2
6	507	1053	297	1440	17	T2	T3	T2	T3	T3	Unknown	T3	T3	T3	T3	T3
7	240	20	5	28	96	D1	D1	Unknown	D1	D1	D1	D2	D1	D1	D1	D1
8	217	286	14	458	884	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2
9	441	207	43	224	261	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2
10	127	24	0.001	32	81	D2	D2	D2	D2	D2	D1	D2	D2	D2	D1	D2
11	176	205.9	47.7	75.7	68.7	D2	D2	D2	D1	D2	D2	D1	D2	D2	D2	D2
12	68	8	3	8	11	D1	D1	UD	D2	D1	D2	D2	D1	D1	D2	D1
13	33.9	36.7	31.5	39.2	0	T2	T2	D2	T3	T2	T1	T2	T2	T2	T1	T2
14	24	27.9	24.3	30	0	T2	T2	D2	T3	T2	T1	T2	T2	T2	T1	T2
15	230	15.9	16.3	1.9	2.4	PD	PD	PD	D1	PD	PD	PD	PD	PD	PD	PD
16	124	14	4	0.0001	13	D1	D1	D1	D1	D1	D2	D1	D1	D1	D2	D1
17	102	6	6	7	10	D1	D1	UD	D2	D1	D2	D2	D1	D1	D2	D1
18	99	170	20	200	190	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2
19	310	230	54	610	760	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2
20	24	109	69	0.0001	0.0001	T1	PD	T1	PD	PD	T1	T1	PD	T1	T1	T1
21	10	26	147	6	0.0001	T1	T1	T1	T1	T1	T1	T1	T1	T1	T1	T1
22	88.7	460.8	94.9	184.6	18.3	T2	T2	T1	T2	T2	T2	T2	T2	T2	T2	T2
23	119	670	286	934	19	T2	T2	T2	T3	T2	T2	T3	T2	T2	T2	T2
24	1550	2740	861	5450	184	T3	T3	T2	T3	T3	T3	T3	T3	T3	T3	T3
25	12	5	1	4	0	T3	T3	D2	T2	T3	T1	T3	T3	T3	T3	T3
26	12	3	2	4	0	T2	T2	D2	T3	T2	T1	T1	T2	T2	T1	T2
27	10	2	2	3	0	T2	PD	D2	T3	PD	T1	T3	PD	PD	T3	PD
28	9	113	149	16	0	T1	T1	D2	T1	T1	T1	T1	T1	T1	T1	T1
29	112	17	10	2	0	PD	PD	PD	T1	PD	PD	PD	PD	PD	PD	PD
30	3	38	13	4	0	T1	T1	T1	T1	T1	T1	T1	T1	T1	T1	T1
31	32	21	2	7	0	PD	PD	D2	T2	PD	T1	T2	PD	PD	T1	PD
32	15	56	19	7	0	T1	T1	T1	T1	T1	T1	T1	T1	T1	T1	T1
33	17	61	22	55	0	T2	T2	T1	T2	T2	T1	T2	T2	T2	T1	T2
34	3	5	1	5	0	T3	T3	T1	T2	T3	T1	T3	T3	T3	T3	T3
35	6	14	9	12	0	T2	T2	D2	T2	T2	T1	T2	T2	T2	T1	T2
36	8	57	59	17	0.5	T1	T1	T1	T2	T1	T1	T1	T1	T1	T1	T1

equipment [36], [37]. Two practical transformer oil types, NYTRO 10XN and HyVolt III, alongside with their 50/50% mixture were evaluated for breakdown voltage to indicate the dielectric severity of these types. The properties of these oil types are shown in Table 9. The mixing between oils was carried out to study the effect of mixing that could happen inside the transformer in the absence of one of these oils. The breakdown voltage test, for each oil sample, was carried out 12 times. In this test, the electrodes of the test are mushroom-shaped copper electrodes spaced by 2.5 mm according to IEC 60156 standard [38]. The test was carried out using a BAUR oil breakdown voltage tester (Model: DTA 100 C) in ELMACO company, Egypt. The test was applied on fresh samples of these oil types. For each sample, it was magnetically stirred for five minutes before the first measurement, then 12 measurements were carried out. Between each two successive measurements, the oil was magnetically stirred for two minutes. The results were analyzed using Weibull distribution. The cumulative distribution function for a random variable x is computed as in the following

TABLE 9. The characteristics of the used oil types.

Properties	Nytro 10XN			HyVolt III		
	Specified limits		Typical	Specified limits		Typical
	Min	Max		Min	Max	
Viscosity						
-30°C	-	600	730	-	1800	924
40°C	-	8.0	7.6	-	12.0	9.2
Density 20°C	-	0.895	0.877	-	0.895	0.875
Acidity mg KOH/g	-	0.01	<0.01		0.01	<0.01
Water Content mg/kg	-	30	<20	-	30	13
Flash Point °C	140	-	144	135	-	141
Pour Point °C	-	- 45	- 63	-	-40	-65
Dielectric Strength kV						
Before treatment	30	-	40-60	30	-	57
After treatment	70	-	>70	70	-	73
Dielectric Dissipation factor at 90°C	-	0.005	<0.001	-	0.005	0.001

equation [39], [40].

$$f(x) = 1 - e^{-\left(\frac{\beta}{\alpha}\right)x} \tag{13}$$

where α and β are defined as the scale and the shape parameters, respectively. These parameters are calculated by the following equation [39].

$$\ln(\ln[\frac{1}{1-f(x)}]) = \beta \ln x - \beta \ln \alpha \tag{14}$$

In the BDV test, the variable x is referred to the breakdown voltage, and the probabilities of different breakdown voltages were estimated using Weibull distribution. Hence, the BDV at the probability of 50% refers to the mean value. The 12 measurements of breakdown test for the two oil types and their mixture are depicted in Fig. 6(a). According to the breakdown test for NYTRO 10XN, HyVolt III, and their mixture, the mean values at the probability of 50% was 71.1 kV, 48.9 kV, and 50.6 kV, respectively, as shown in Fig. 6(b). By mixing 50% of the two oil types, the dielectric strength was slightly improved compared to pure HyVolt III. However, the type of NYTRO 10XN oil remains the best in terms of dielectric strength.

For Nytro 10XN oil type, an additional aged oil samples were extracted from a real in-service aged transformer of rating (40 MVA, 66/11 kV) with different operation durations; 9, 10, 11, 12, and 13-years. These samples have been tested for a breakdown voltage test. Twelve measurements were performed for each sample, and their average breakdown values were 77, 75, 27, 65, and 38 kV for 9, 10, 11, 12, and 13-years, respectively, as shown in Fig. 7. Comparing the BDV of the aged samples and fresh samples, the average BDV was good after 9 and 10-years in-service. After 11-years in-service, the BDV was reduced drastically till reaching 27 kV, which is below the acceptable limit, due to the aging occurrence. Hence, the transformer was taken out of service and the oil was treated and filtered, before returning again to the service. After the oil treatment and with one more year in-service, the breakdown voltage attained 65 kV after 12-years in-service. Finally, after 13-years in operation, the BDV decreased to 38 kV.

The breakdown voltage of the fresh and aged samples (13-years in-service) shall be used as an indication for the health index of oil quality for a new transformer and another aged one [41], [42].

B. TEMPERATURE RISE TEST

Temperature is a quantitative measure of thermal energy contained in an object, the higher the thermal energy, the higher the temperature. The temperature rise is always defined as the difference between the temperature of an object and the temperature of the corresponding cooling medium (e.g., oil). The thermal run test or overheat test is one of the tests that are applied on power transformers.

The mean purpose of this test is to check whether the oil and winding temperatures of the transformer meet the values specified in the standards and by technical projects. Temperature rise test is performed according to IEC 60076-2 standard [43], in which the low voltage winding is short circuited, and the voltage is applied to the high voltage winding, then the temperature rise test for the top oil of transformer is performed continuously until the winding and oil in the tank have reached a stable temperature. This test was carried out on a transformer of rating (40 MVA- 66/11 kV) with oil type (Nytro 10 XN). The temperature rise test objective is to measure the winding resistance and to predict the fault possibility based on the rate of change in dissolved gases concentrations before and after the test. Also, the health index for this transformer is calculated using DGA plus acidity, moisture, and breakdown tests.

1) MEASUREMENT OF THE WINDING RESISTANCE

According to IEC 60076-2, the measurement values should be carried out under the following conditions: ONAN, ONAF (100% loading), and ONAF (110% loading for two

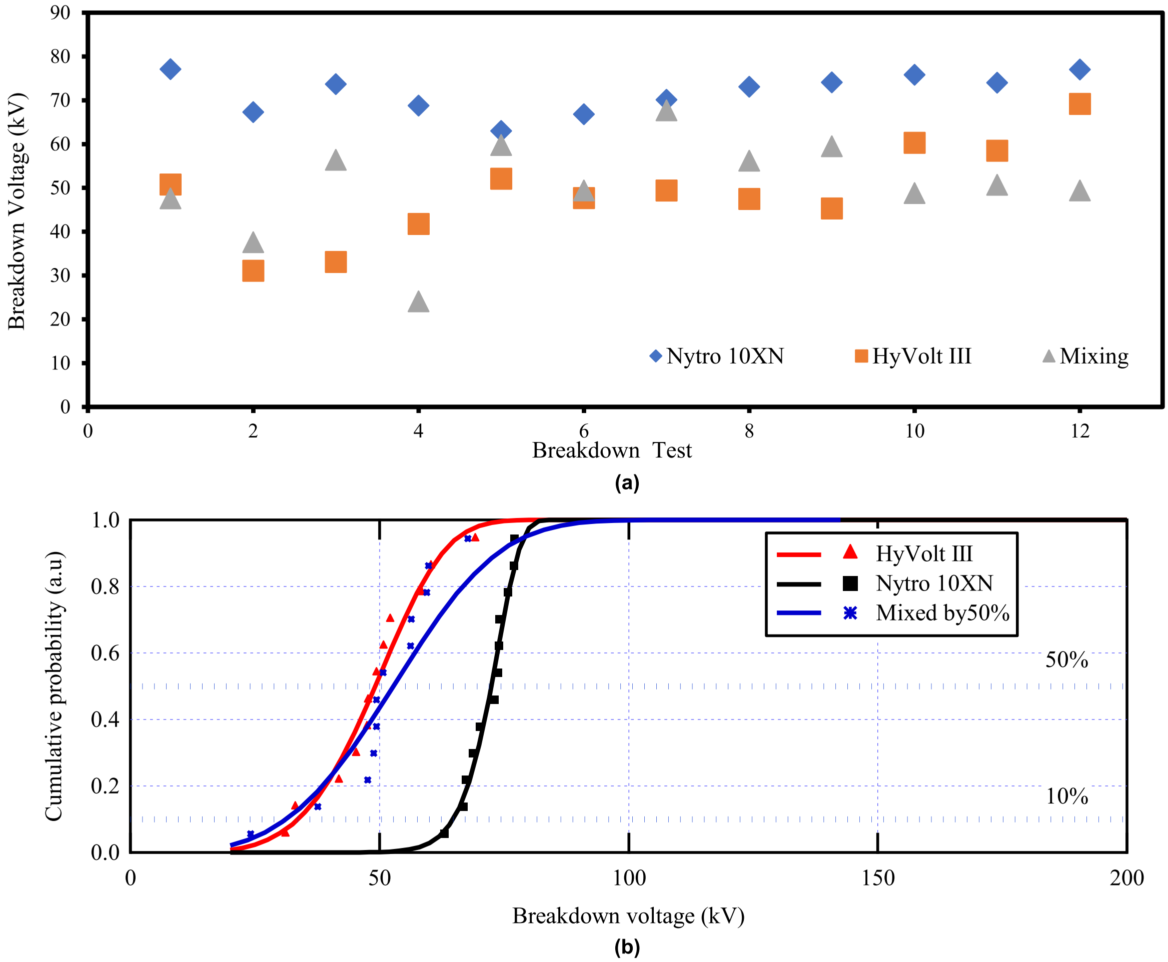

FIGURE 6. **Breakdown voltage of Nytro 10 XN, HyVolt III and their 50/50% mixture; (a) 12 measurements, and (b) Weibull distribution.**

hours) [43]. The measurement of the winding resistance is performed by the connection of the winding to the DC measuring device after the shutdown of the test power. The top oil temperature rise ($\Delta\theta_{\text{oil-max}}$) does not correspond to the real hot spot winding temperature ($\Delta\theta_{\text{hot-spot}}$) as indicated from the following equation.

$$\Delta\theta_{hot-spot} = \Delta\theta_{oil-max} + g.H \tag{15}$$

This is due to the influence of the increased stray loss caused by the horizontal component of stray flux. The winding oil gradient g at the top of the winding has to be multiplied by the factor H. This factor H may vary from 1.1 to 1.5 depending on the transformer size, short circuit impedance, and winding design. In this case study, it is taken as 1.3.

The instrumentation used for the measurement is of automatic recording, where a considerable number of discrete readings are being made over a period of time, and these have to be evaluated for extrapolation backward in time to the instant of the shutdown. The change of winding resistance against time are shown in Fig. 8 and Fig. 9 for high voltage winding and low voltage winding, respectively.

2) DISSOLVED GAS ANALYSIS BEFORE AND AFTER THE TEMPERATURE RISE TEST

DGA has been performed for the transformer oil. The first sample was taken before the temperature rise test, while the second sample was taken approximately 24 hours after the temperature rise test, according to IEC 60076-2 [43]. This study was performed on five new transformers of the same rating and oil type before and after the test. In addition, for the 13-years in-service transformer, DGA has been performed. These studying cases were to confirm the results obtained. For the new five cases, the gases H_2, CO, CO_2, CH_4, C_2H_6, C_2H_4, and C_2H_2 are generated with the increase in temperature. Oil samples are analyzed in the Central Chemical Laboratories of the Egyptian Ministry of Electricity. The oil sampling was manually performed according to IEEE Std. C57.104 and IEC 60567 [9], [44]. The samples were taken from a certain point in the transformer tank, through which the oil is circulating. This is to increase the chance to catch gases generated in various locations in the transformer tank rather than that generated locally at the sampling point.

The oil syringe used for sampling and transporting to the Chemical Laboratories is in the 50 ml range. For extracting the oil sample, the sampling valve is wiped for cleaning.

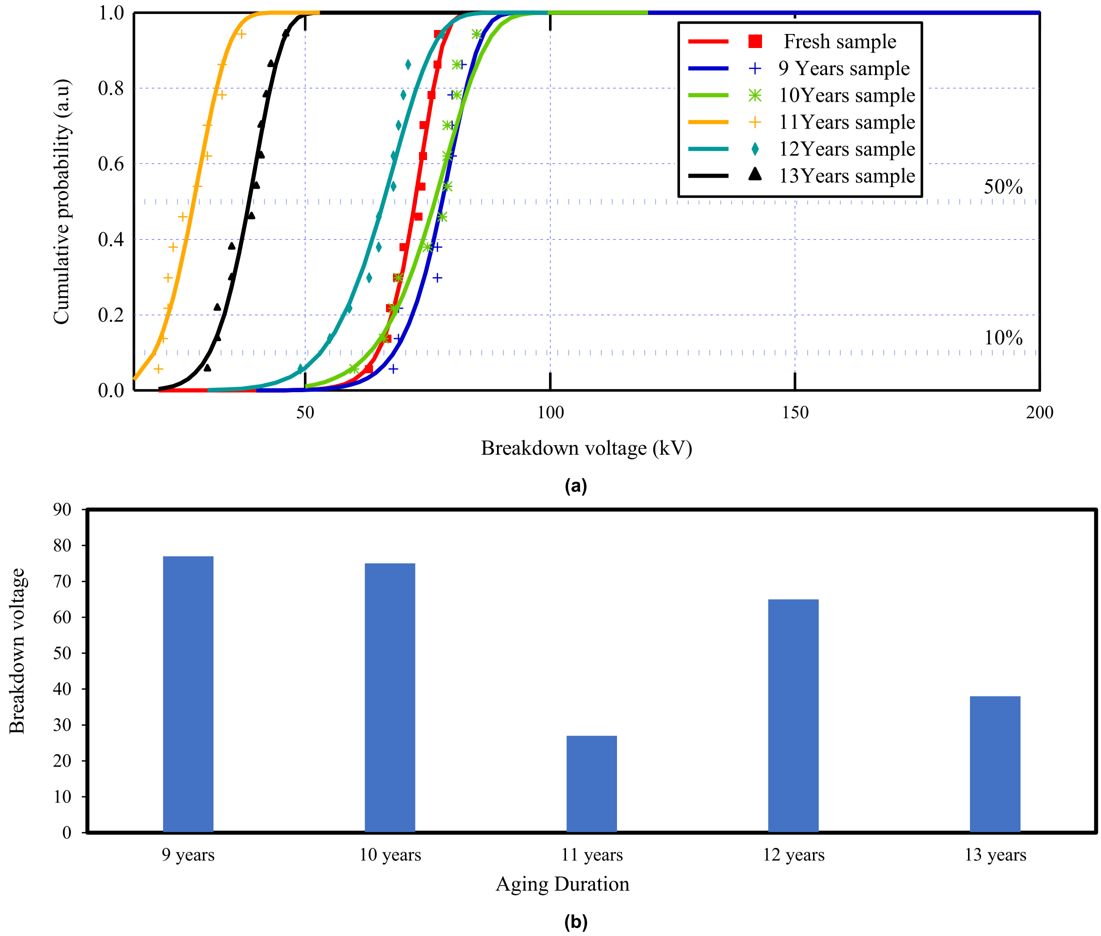

FIGURE 7. The measured breakdown voltages with different in-service durations; 9, 10, 11, 12, and 13 years for Nytro 10 XN; (a) Weibull distributions, and (b) average measured values.

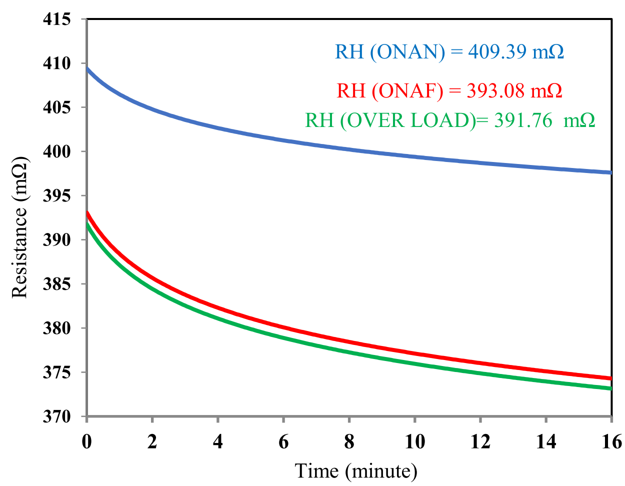

FIGURE 8. Average winding temperatures for high voltage winding.

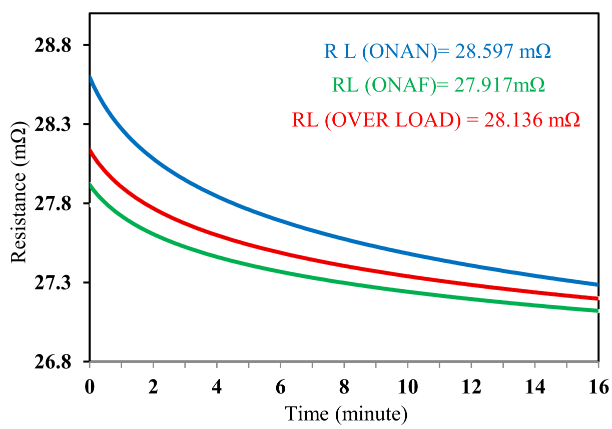

FIGURE 9. Average winding temperatures for low voltage winding.

Then, the valve is allowed to flush 2 to 3 times to remove water and debris before a sufficient amount of oil is filled inside the syringe without causing aeration/bubble. Finally, the oil temperature is recorded, and the syringe is closed, sealed, and stored for transport. Fig. 10 shows the considered position and used tools for extracting oil samples. For each case of the new five transformers, two samples of oil are analyzed using DGA, before and after the temperature rise test. The first sample for each case was taken two hours before the temperature rise test, while the second sample was taken after 24 hours of the temperature rise test, as recommended in IEC 60076-2 [43].

The results of DGA before and after the temperature rise for the new five cases of transformers are presented in Table 10 alongside with the DGA result for the aged case. According to these results, the diagnosis of new transformer

FIGURE 10. Dissolved gas analysis sampling process and used tools.

cases before and after temperature rise is normal because the gases concentration is not exceeding the limits specified IEEE Std. C57.104 [9]. While by analyzing the rate of increase in dissolved gases for case study No. 1, there was an increase in the gases CO_2, CO, and H_2 after the temperature rise test. The concentration of CO_2 gas increased approximately twice, while the concentration of H_2 and CO increased approximately three times. The CO_2 gas was an indicator for the paper health condition. For the case study No. 2, CO and CO_2 concentrations were reduced by the temperature rise test, which were considered illogical. This may be because of the exposure of samples to atmospheric leaks. However, the C_2H_6concentration was 24 times higher than that before the test. Case study No. 3 was not highly affected by the temperature rise test, since the rise in gases was only 1 ppm, 9 ppm, and 1 ppm for H_2, CO, and CH_4, respectively. CO_2 concentration was reduced slightly after the test due to possible atmospheric leaks. Whereas the temperature rise test resulted in a rise in three gases H_2, CO_2, and CO by 11 ppm, 62 ppm, and 4 ppm, respectively for case study No. 4. The diagnosis of the transformer case study No. 5 before and after the temperature rise is normal according to IEEE Std. C57.104. While by analyzing the rate of increase in dissolved gases for this case, there were three gases (CO_2, CO then H_2) that had the greatest effect by the temperature rise, in addition to a slight increase in CH_4 and C_2H_4 concentrations. Fig. 11 summarizes the change in dissolved gases before and after the temperature rise test for the new five cases of transformers. For the aged case, it has higher values of gas concentrations, as shown in Table 10, which has been diagnosed as a high thermal fault type.

C. ACIDITY AND MOISTURE MEASUREMENTS

By the chemical reactions in the oil, carboxylic acids are produced. Increased acidity of the oil affects the electrical properties of the oil itself, and it may also cause abnormal deterioration of the paper insulation used in transformer windings [45], [46]. For the moisture, its presence can deteriorate transformer oil. Moisture content can cause the bubble formation risk in transformer oil when water desorption increases the local concentration of gases in the transformer oil. Hence, this section presents acidity and moisture measurements for oils extracted from the new five transformers (66/11 kV) of oil type (Nytro 10 XN). These were collected from ELMACO Company, Egypt, during their first-year in-service. Another sample extracted from the 13-year in-service transformer was tested.

Using volumetric syringes, the samples were taken, and their moisture and acidity were measured in the Central Laboratory of the Egyptian Ministry of Electricity. Table 11 and Fig. 12 show the measured acidity and moisture in mg KOH/g and ppm, respectively, for the new five cases and the aged case study.

TABLE 10. The dissolved gases before and after temperature rise test.

Items	Case Study No.	Status	H_2	CO	CO_2	CH_4	C_2H_6	C_2H_4	C_2H_2
New Transformer	Case study No. 1	Before temperature rise	7	10	176	3	3	3	0
		After temperature rise	21	29	360	3	3	3	0
	Case study No. 2	Before temperature rise	21	274	2512	4	3	2	0
		After temperature rise	3	162	1805	5	72	1	0
	Case study No. 3	Before temperature rise	7	52	2255	4	6	3	0
		After temperature rise	8	61	2202	5	6	3	0
	Case study No. 4	Before temperature rise	93	43	801	5	1	1	0
		After temperature rise	104	47	863	5	1	1	0
	Case study No. 5	Before temperature rise	4	32	465	5	1	1	0
		After temperature rise	9	45	573	8	1	2	0
Aged Transformer	Case study No. 6	13 years in-service	36	146	2506	117	89	707	7

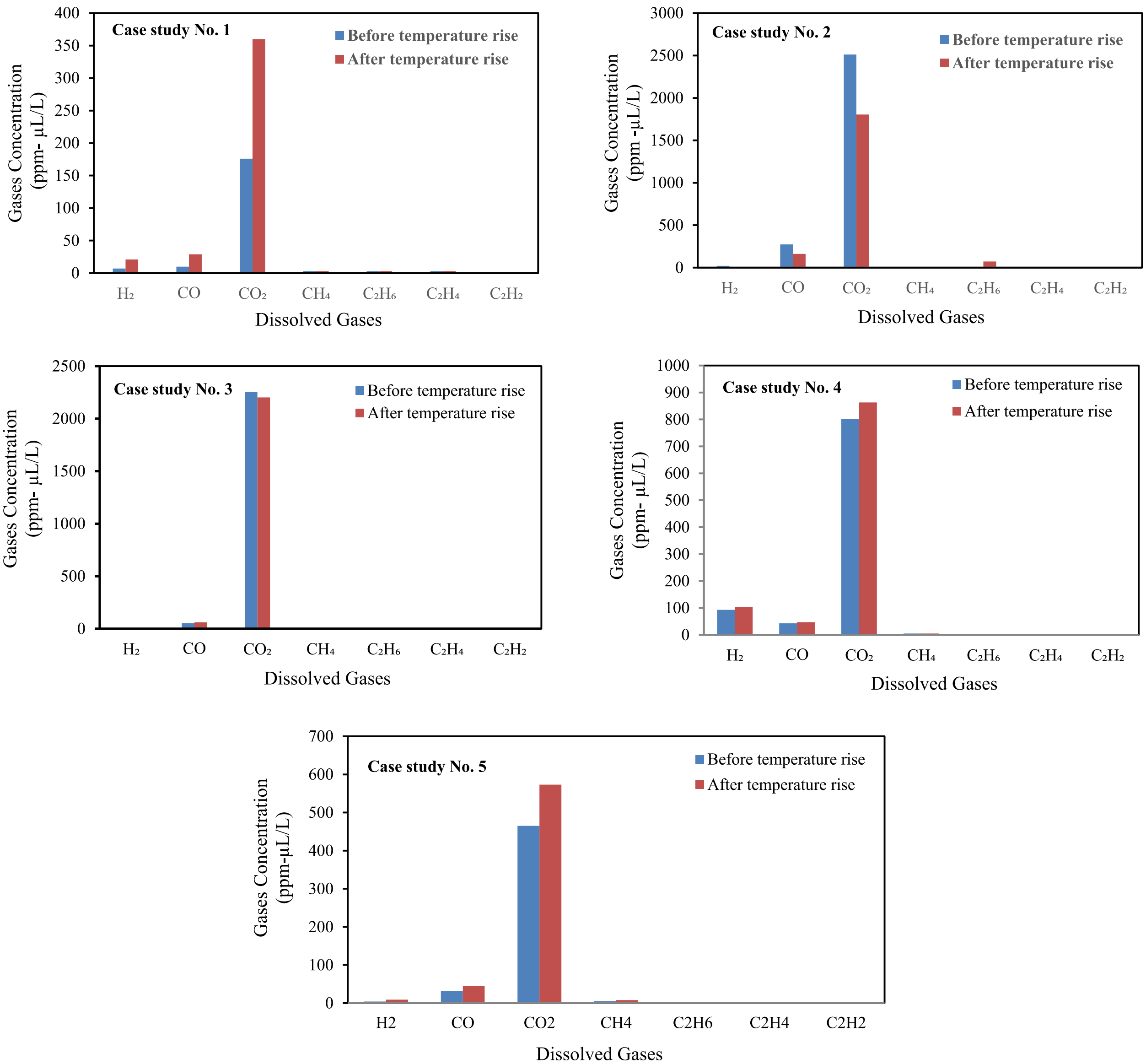

FIGURE 11. Dissolved gases before and after the temperature rise test for five cases of transformers; No. 1, No. 2, No. 3, No. 4, and No. 5.

TABLE 11. Acidity and moisture content measurement for five transformer case studies.

	Case study	Acidity (mg KOH/g)	Acidity limit (mg KOH/g)	Moisture (ppm)	Moisture limit (ppm)
New transformer	No. 1	0.01	<0.15	7.5	10
	No. 2	0.02	<0.15	6.4	10
	No. 3	0.03	<0.15	7.1	10
	No. 4	0.06	<0.15	6.8	10
	No. 5	0.01	<0.15	6.2	10
Aged transformer	13-years in-service	0.19	<0.15	12.5	10

The acidity measurement showed that mg KOH/g was between 0.01 and 0.06 for the new five transformers, less than the maximum limit [45]–[47]. In addition, the moisture content for the same new five transformers was 7.5 ppm, 6.4 ppm, 7.1 ppm, 6.8 ppm, and 6.2 ppm, which has not been exceeded the limit value [48]. For the 13-years in-service transformer, the acidity and moisture were 0.19 mg KOH/g and 12.5 ppm, respectively. These values exceeded the maximum limits due to the diagnosed thermal fault. These acidity and moisture measurements can be used to evaluate the health index of the transformer as a diagnosis factor.

D. HEALTH INDEX OF TRANSFORMER INSULATION SYSTEM

The transformer Health Index (HI) represents a practical method to quantify the results of operating observations, field inspections, and site and laboratory testing into an objective and quantitative index, providing the overall health of the

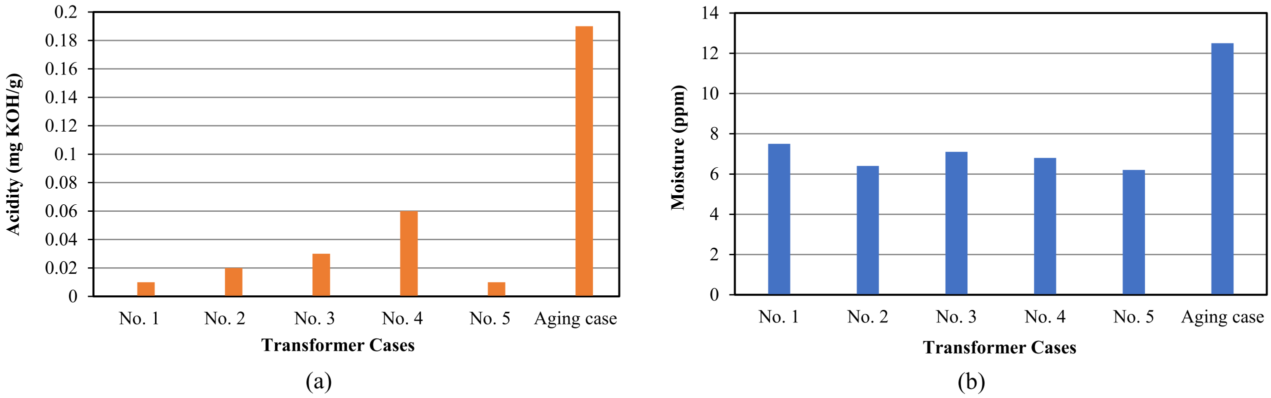

FIGURE 12. Acidity and moisture content measurements for transformer cases; (a) Acidity in mg KOH/g, and (b) Moisture in ppm.

assets. The HI is helpful in the predictive maintenance plan of transformers. This section presented two techniques for calculating the HI of transformer oil. The first technique used only DGA for HI calculation, while the second one used DGA with the BDV and typical chemical properties.

1) HEALTH INDEX OF TRANSFORMER INSULATION SYSTEM USING DGA BEFORE AND AFTER TEMPERATURE RISE TEST

The HI of transformer oil can be predicted using the individual DGA approach before and after the temperature rise test. The time interval (t) required for the temperature rise test is 3 hours after the top-oil temperature rise is kept within at least 80% of the final value in the steady-state condition [43]. The Gases Rate Increase (GRI) can be calculated for each gas according to the following equation:

$$GRI_i = \frac{1}{t}\left(G_{2i} - G_{1i}\right) \tag{16}$$

where G_{1i} represent the gas concentration before the temperature rise and G_{2i} represent the gas concentration after the temperature rise. GRIs are calculated separately for each gas as depicted in Table 12. After that, GRIs are compared with admissible limits of GRIs in IEC 60076-2 [43].

For cases No. (1) and (5), the GRIs for CO and CO_2 exceeded the limits of the first series in IEC 60076-2. For cases No. (4) and (5), the summation of GRIs for the main five gases H_2, CH_4, C_2H_6, C_2H_4, and C_2H_2 exceeded the limit of the first series in IEC 60076-2. Hence, for these three cases, the possibility of local overheating exists. Consequently, it is recommended that oil samples be taken at regular intervals from the transformer and the gas analysis be performed. For case study No. (3), the values of GRIs fulfill all the limits of the first series in IEC 60076-2, thereby it may be concluded that the transformer has no possibility of local overheating. For case study No. (2), the values of gases concentration reduced after the temperature rise test due to possible atmospheric leaks. In general, most cases predicted the possible existence of local overheating. After in-service observation of these transformers, these results proved that HI calculation based on only DGA is unreliable since no local overheating occurred.

2) HEALTH INDEX OF TRANSFORMERS INSULATION SYSTEM USING BDV, ACIDITY, MOISTURE, AND DGA

By using the results of breakdown, DGA, moisture content, and acidity, the health index was calculated for the new five transformer cases and the aged one. The description factor for breakdown, DGA, moisture, and acidity can be computed according to the following equation [25].

$$\text{Description factor (DF)} = \frac{\sum_{i=1}^{n} S_i \times W_i}{\sum_{i=1}^{n} W_i} \tag{17}$$

where the score (S_i) is an assessment of the testing results of each parameter. According to the standards of the testing for these parameters, it can be represented in the form of numbers with ranges. The weight of a parameter (W_i) is a factor of the test parameter influencing a transformer; it can take the integer value for 1 to 5 [47]. According to Table 13, the score (S_i) and weight factor (W_i) of each gas after the temperature rise test can be determined for new cases and for an aged one. Hence, the DGA description factor was calculated. As well, calculation of the description factor for breakdown, moisture content, and acidity was performed according to Table 14. By calculating the description factor for DGA, acidity, moisture, and dielectric strength according to their scoring and weight factor, the rating code and condition can be known according to Table 15. For the new transformer study cases, the average DGA description factor after the temperature rise test can be calculated according to equation (17). Therefore, the rating code was determined. Table 16 shows that for (66/11 kV) transformer of NYTRO 10XN oil type. The DFs for DGA were 1, 1.16, 1, 1.11, and 1 for the new five cases, respectively, giving a rating code (A). The DF for dielectric strength was 1 and the rating code was (A). For all moisture and acidity measurements, except acidity of case No. 4, the rating code was (A). On the other hand, using equation (17), the DF for the 13 years in-service transformer based on DGA, dielectric strength, acidity, and moisture content was 2.88, 2, 3, and 1 of rating code D, D, E, and A, respectively, as showing in Table 16.

The rating (A, B, C, D, E) is converted to a factor between 4 and 0, respectively, called the health index factor (HIF) in Table 17. Then, the health index percentage was calculated

TABLE 12. The gases rate increases (GRIS) for the five transformers.

Items	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	CO	CO_2
GRI for case No. (1)	4.6	0	0	0	0	6.3	61.3
GRI for case No. (2)	-6	0.3	23	-0.3	0	-37	-235
GRI for case No. (3)	0.3	0.3	0	0	0	3	-17
GRI for case No. (4)	3.6	0	0	0	0	1.3	20.6
GRI for case No. (5)	1.6	1	0	0.3	0	4.3	36

TABLE 13. Weight factor and scoring for gas level (PPM).

ppm	Score (S_i)						W_i
	1	2	3	4	5	6	
H_2	≤ 100	100 – 200	200 – 300	300 – 500	500 – 700	> 700	2
CH_4	≤ 75	75 – 125	125 – 200	200 – 400	400 – 600	> 600	3
C_2H_6	≤ 65	65 – 80	80 – 100	100 – 120	120 – 150	> 150	3
C_2H_4	≤ 50	50 – 80	80 – 100	100 – 150	150 – 200	> 200	3
C_2H_2	≤ 3	3 – 7	7 – 35	35 – 50	50 – 80	> 80	5
CO	≤ 350	350 – 700	700 – 900	900 – 1100	1100 – 1400	> 1400	1
CO_2	≤ 2500	≤ 3000	≤ 4000	≤ 5000	≤ 7000	> 7000	1

TABLE 14. Weight factor and scoring for dielectric strength.

Items	U ≤ 69 kV	69 kV < U < 230 kV	U ≥ 230 kV	Score	W_i
Dielectric Strength (kV)	≥ 45	≥ 52	≥ 60	1	3
	35 – 45	45 – 52	50 – 60	2	
	30 – 35	35 – 45	40 – 50	3	
	≤ 30	≤ 35	≤ 40	4	
Acid number	≤0.05	≤0.04	≤0.03	1	1
	0.05 – 0.1	0.04 – 0.1	0.03 – 0.07	2	
	0.1 – 0.2	0.1 – 0.15	0.07 – 0.1	3	
	≥0.2	≥0.15	≥0.1	4	
Moisture		≤20		1	4
		20 – 30		2	
		30 – 40		3	
		≥40		4	

TABLE 15. Transformer rating based on description factor.

Rating code	Condition	Description
A	Good	Description factor < 1.2
B	Acceptable	1.2 ≤ Description factor < 1.5
C	Need caution	1.5 ≤ Description factor < 2
D	Poor	2 ≤ Description factor < 3
E	Very poor	Description factor ≥ 3

according to the following equation (18).

$$\text{Health Index }\% = \frac{\sum_{j=1}^{n} K_j \times HIF_j}{4\sum_{j=1}^{n} K_j}\% \tag{18}$$

By using the DGA, breakdown voltage test, moisture content, and acidity measurements of the oil, HI % for new cases was approximately 100%. According to Table 18 [25], the condition was very good; the expected lifetime was more than 15 years, keeping normal maintenance requirement. For the aged transformer case with 13 years in-service, HI % was approximately 36%. Hence, the aged transformer lifetime is 3 years with poor condition. With studying the state of transformers in the service, the health index results using DGA, breakdown, and the measurement of the chemical property was closer to the reality compared to using DGA only.

IV. DISCUSSIONS

In this research, the discussions can be summarized as:

- For improving the diagnostic accuracy of transformer faults using the DGA approach, a proposed technique was presented. It is based on the integration of five of the previous DGA methods but with novelty procedures. The proposed technique proved its high accuracy in

TABLE 16. Case study rating based on description factor of DGA and dielectric strength.

Item	Tests	Case Study	Description factor	Rating code
New Transformer	DGA	Case Study No. 1	DF = 1	A
		Case Study No. 2	DF = 1.16	A
		Case Study No. 3	DF = 1	A
		Case Study No. 4	DF = 1.11	A
		Case Study No. 5	DF = 1	A
	Dielectric Strength		DF = 1	A
	Acidity	Case Study No. 1	DF = 1	A
		Case Study No. 2	DF = 1	A
		Case Study No. 3	DF = 1	A
		Case Study No. 4	DF = 2	D
		Case Study No. 5	DF = 1	A
	Moisture	Case Study No. 1	DF = 1	A
		Case Study No. 2	DF = 1	A
		Case Study No. 3	DF = 1	A
		Case Study No. 4	DF = 1	A
		Case Study No. 5	DF = 1	A
Aged Transformer	DGA	In-service transformer	DF = 2.88	D
	Dielectric Strength	In-service transformer	DF = 2	D
	Acidity	In-service transformer	DF = 3	E
	Moisture	In-service transformer	DF = 1	A

TABLE 17. Scoring of the health index.

	Number	Item	K_j	Condition rating	HIF
Oil quality	1	DGA	10	A, B, C, D, E	4, 3, 2, 1, 0
	2	Dielectric strength	10	A, B, C, D, E	4, 3, 2, 1, 0
	3	Acidity measurement	8	A, B, C, D, E	4, 3, 2, 1, 0
	4	Moisture measurement	8	A, B, C, D, E	4, 3, 2, 1, 0

TABLE 18. Health index and transformer expected lifetime.

HI%	0 - 30	30 - 50	50 - 70	70 - 85	85 – 100
Expected Lifetime	Near to the end of life	Less than 3 years	From 3 – 10 years	More than 10 years	More than 15 years
Condition	Very Poor	Poor	Fair	Good	Very Good

diagnosing faults. The results of this part are based on a number of datasets that are collected from the Egyptian Electricity network and from literature. The diagnostic accuracy using the proposed technique was improved compared to the previous techniques.

- For studying a transformer of rating (66/11 kV), a health index of its insulation system was evaluated using firstly DGA alone, then DGA plus breakdown voltage test, moisture content, and acidity measurement. For this objective, the breakdown test was carried out on the study case oil type and another oil type as well as a mixture of them by 50/50%. Mixing 50% of the two oil types; NYTRO 10XN and HyVolt III, was slightly higher than pure HyVolt III. But the type of NYTRO 10XN oil remains the best in terms of dielectric strength.
- The aim of this section was firstly to clarify the effect of mixing the two types of oils on the dielectric strength to consider the condition that could happen inside the transformer in the absence of one of these oils. In addition, this breakdown voltage measurements were used to calculate the health index of oil quality of the study cases. A secondary, the dissolved gases in oil before and after the temperature rise test were analyzed and compared with each other. The objective of the temperature rise test was to determine the oil health index and the predicted fault based on the rate of change in dissolved gases concentrations before and after the test. A thirdly, moisture and acidity were measured for five new cases and an aged transformer of the same rating. The acidity results were ranged between 0.01 and 0.06 mg KOH/g, and moisture measurements were not exceeded 10 ppm. Accordingly, a health index was measured using DGA alone, then using DGA plus breakdown voltage, acidity, and water content. The dissolved gas analysis before and after the temperature rise test predicted the existence of possibility for local overheating. While according to the breakdown and DGA results plus chemical properties, the health index was calculated and resulted that the insulation condition was good, expecting lifetime more than 15 years for the new transformers with normal

maintenance requirements. For the aged transformer case with 13 years in-service, the health index results that the aged transformer lifetime is 3 years with poor condition. With studying the state of transformers in the service, the health index results using DGA, breakdown, and the measurement of the chemical property was closer to the reality compared to using DGA only.

V. CONCLUSION

A proposed combined DGA technique has been presented based on the integration between the results of five existing techniques used in literature. The new DGA technique had an accuracy higher than its constructing techniques as well as the recently published techniques, where the diagnosis accuracy results of the proposed technique were 93.3% for PD diagnosis, 86.3% for D1, 98.2% for D2, 96% for T1, 83.7% for T2, and 98.2 % for T3. Hence, the overall accuracy of the proposed DGA technique improved significantly, reaching 93.6%. While the techniques used in constructing this proposed technique were 90%, 53.6%, 47.2%, 59.1%, and 70.8%, respectively. In addition, the accuracy of the recently published four techniques were 63.6%, 89.7%, 76.9%, and 85.8%, respectively. In addition, new validation datasets (36 datasets) have been used for checking the proposed technique accuracy. It exhibited a diagnostic accuracy of 91.5%, which is a higher value than the construction techniques and the previously published techniques.

For transformer study case (11/66 kV), the breakdown voltage test for the transformer oil indicated that; by mixing 50/50% of two oil types, NYTRO 10XN and HyVolt III, the dielectric strength was slightly improved compared to HyVolt III. But the type of NYTRO 10XN oil remains the best in terms of dielectric strength. In addition, the temperature rise test was carried out on several study cases. The dissolved gases before and after the test were analyzed and compared. In addition, winding dc resistance was measured. The most affected gases by the temperature rise test were (CO_2, CO, and H_2). Using DGA, moisture, acidity, and BDV results, the health index of the transformer insulation system was evaluated using DGA only, and using DGA plus BDV, moisture and acidity. By using DGA before and after the temperature rise test, it can expect the probability of local overheating. Though according to the breakdown, DGA, moisture content, and acidity results, the health index was computed and indicated that the insulation condition was superior for the new case with an expected lifetime more than 15 years keeping normal maintenance needs. The health index for the aged transformer case indicated that the lifetime is 3 years with poor condition. Hence, the health index of the transformer oil quality using more than one diagnosis factor is more accurate than using only DGA.

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