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Hybrid Dissolved Gas-in-Oil Analysis Methods

Leonidha Londo[1], Rajmonda Bualoti[2], Marialis Çelo[2], Nako Hobdari[2]

[1]Transmission System Operator, Tirana, Albania
[2]Electric Engineering Faculty, Polytechnic University of Tirana, Tirana, Albania
Email: bualoti@icc-al.org

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Abstract

Dissolved gas analysis is the most widely used diagnostic test in power transformers. The aim of this paper is to introduce the dissolved gas analysis (DGA) methods able to diagnose the transformer conditions. The faults cause the transformer oil, pressboard, and other insulating materials to decompose and generate gases, some of which dissolve in the oil. The results of DGA must be accurate if faults are to be diagnosed reliably. There are different established methods used in industry for interpreting DGA results. We will compare the result of IEEE Key Gas Methods and Rogers' Ratios. The transformer conditions are evaluated by the Key Gas Method with total combustible gas method (TCGM) and then verified by the Rogers' Ratios. As result, the aging pattern and trend of the power transformer deterioration can be determined. The 30 sample data from IEEE with known faults and dissolved gas concentrations were used as the basis of comparison.

Keywords

Dissolved Gas Analysis, Key Gas Methods, Rogers' Ratios, Transformer

1. Introduction

A transformer is the most important equipment for power supply to consumers. Failure of one power transformer may cause long interruptions in supply, costly repairs and loss of revenue. For uninterrupted power supply to consumers, proper maintenance, particularly preventive maintenance, is very necessary. The failure in magnetic, electric and dielectric circuits as well as structural failure may cause extensive damage to the equipment and surroundings. Proper operation and maintenance procedure may help to prevent failure and extend life of operation of the transformer.

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2. Risk of Failure of Transformers

The mineral oil uses in transformers, acts as a dielectric medium and also as a heat transfer agent. The breakdown of electrical insulating materials and related components inside the transformer liberates gases within the unit. The distribution of these gases can be related to the type of electrical fault, and the rate of gas generation can indicate the severity of the fault. The identity of the gases being generated by a particular unit can be very useful information in any preventive maintenance program [1]-[3]. There are several techniques in detecting those fault gases and DGA was recognized as the most informative method. This method involves sampling of the oil to measure the concentration of the dissolved gases. The risk of failure of transformers in service, based on dissolved gas analysis (DGA), depends on three main parameters: the type of fault involved, the location of the fault (in oil or in paper), and the amount of gases formed (concentrations and rates).

- The most dangerous faults are: high-energy arcing faults in oil and paper (D2), low-energy arcing faults in paper (D1), and hot spots in paper of high temperatures (>700˚C T3 and 300˚C - 700˚C T2).
- Less dangerous faults are: low-energy arcing faults in oil (D1), hot-spots in oil (>700˚C T3 and 300˚C - 700˚C T2), and hot spots in paper of low temperature (<300˚C T1).
- Non-dangerous faults are: hot spots in oil (<300˚C T1), producing only "stray gassing" of oil, corona partial discharges (PD) (unless very high levels of hydrogen are formed), catalytic reactions with water, and aging of paper.

A risk model for transformer failures [4]-[6], based on aging, can be represented by Perks formula:

$$f(t) = \frac{A + \propto e^{\beta t}}{1 + \mu e^{\beta t}}. \quad (1)$$

Figure 1 is the corresponding exponential curve for 50% failure rate at the age of 50 year. To include the random events (lighting, vandalism, etc.) separate from the aging component, the constant "A" is set at 0.005. In **Figure 2** is represented the age of the main transformers of Albanian Transmission System. We can see that for some transformers the failure rate is higher than 10%. They are expensive equipments; that's why there has been a growing interest in the technique to diagnose, determine and decide the condition assessment of transformer insulation [7] [8].

3. Identification of Type of Faults

The general type of fault (PD, D1, D2, T1, T2, and T3) can be identified by several methods: e.g., Rogers, Key Gas, IEC ratios, and Duval Triangle [9] [10]. Electrical and thermal stresses such as arching, partial discharges and overheating cause degradation of dielectric oil and solid dielectric cellulose materials.

The degradation of insulation produces different gases. Different degradation mechanisms generate different gases thus making it possible to determine the degrading part of the transformer. Power transformer gas-in-oil analysis (DGA) can be used for effective diagnostics and monitoring. The IEEE and IEC guides [11] [12] offer a variety of ratio-based tools to diagnose DGA data. A quick summary of the different tools found in the current IEEE guide and the IEC guide is in **Table 1**.

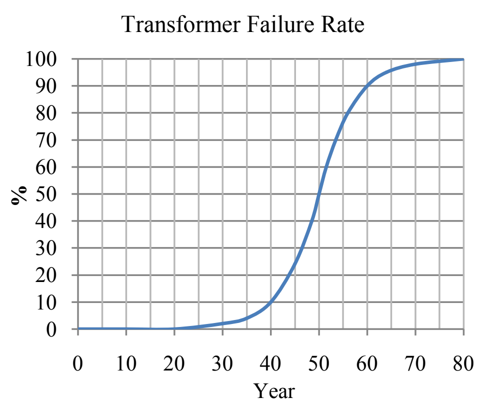

Figure 1. The curve for transformer failure rate.

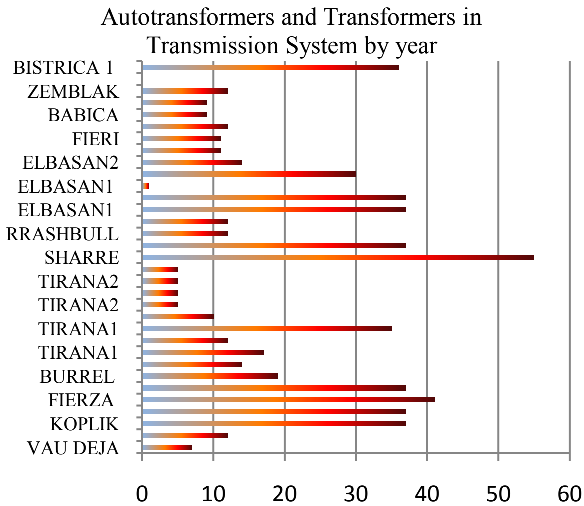

Figure 2. Autotransformers and Transformers ages in Albanian Transmission System.

Table 1. A summary of the different tools.

Tool	Reference Standard	
	IEEE C57. 104-1991	IEC 60599-1999
Key Gas Procedure	X	
Rogers Ratios	X	
TDCG Procedure	X	
Basic Gas Ratios		X
Duval Triangle		X
Doernenburg Ratios	X	

DGA diagnostic tools vary in their complexity and accuracy. **Table 2** shows the comparison among the most widely used DGA diagnostic methods.

The Albanian Power Companies started to invest to DGA laboratory tests from two years, so there is no previous dissolved gas history data. In IEC Standards 60599 is suggested a four-level criterion to classify risks to transformers evaluating individual gas and TDCG concentrations when there is no previous dissolved gas history. That is why among different methods for interpreting DGA results, we will use hybrid method based in the Key Gas Method with total dissolved combustible gas method to be evaluated and then verified by the Rogers' Ratios.

4. Gases Detected and Their Relevance

Typical gases generated from mineral oil/cellulose (paper and pressboard) insulated transformers include: Hydrogen, H_2; Methane, CH4; Ethane, C_2H_6; Ethylene, C_2H_4; Acetylene, C_2H_2; Carbon Monoxide, CO; Carbon Dioxide, CO_2. Additionally, oxygen and nitrogen are always present; their concentrations vary with the type of preservation system used on the transformer. In addition, gases such as propane, butane and others can be formed as well, but their use for diagnostic purposes is not widespread. The concentration of the different gases provides information about the type of incipient-fault condition present as well as the severity. In **Table 3** and **Table 4** are shown fault interpretations from dissolved gases according [13].

5. Key Gas Method and TDCG method

The key gas method is mainly depends on the quantity of fault gases release in mineral oil when fault occur.

Table 2. Comparison of DGA diagnostic methods.

Features	Rogers Ratio	Key Gas	TDCG
Data can be quickly and easily interpreted		□□	□
Early detection of fault	□□	□□	□□
Fault types can be identify accurately	□□	□□	
Able to identify in detail a specific fault type	□□		
Can interpret based on individual or incomplete fault gases		□	
Oil volume independent	□□		
Transformer type independent	□□		□

Table 3. Fault interpretation from dissolved according.

Gas	**Normal** ppm	**Abnormal** ppm	Interpretation
H_2	150	1000	Arcing corona
CH_4	25	80	Sparking
C_2H_6	10	35	Local overheating
C_2H_4	20	100	Severe overheating
C_2H_2	15	70	Arcing
CO	500	1000	Severe overloading
CO_2	10,000	15,000	Severe overloading
TDCG	720	2285	

Table 4. Fault interpretations from gases detected in the insulation oil.

No.	Gases Detected in Oil Sample	Fault Interpretations
1	Nitrogen plus 5% or less oxygen	Normal operation
2	Nitrogen, carbon monoxide, and carbon dioxide	Transformer winding insulation overheated; Key gas is carbon monoxide **CO**
3	Nitrogen, ethylene, and methane—some hydrogen and ethane	Transformer oil is overheated; minor fault causing oil breakdown. Key gas is ethylene C_2H_4
4	Nitrogen, hydrogen, small quantities of ethane and ethylene	Corona discharge in oil; key gas is hydrogen H_2
5	Same as 4 with carbon dioxide and carbon monoxide	Corona involving paper insulation; key gas is hydrogen H_2
6	Nitrogen, high hydrogen and acetylene; minor quantities of methane and ethylene	High-energy arcing; key gas is acetylene C_2H_2
7	Same as 6 with carbon dioxide and carbon monoxide	High-energy arcing involves paper insulation of winding; key gas is acetylene C_2H_2

Fault gases are caused by corona (partial discharge), thermal heating and arcing. The Key Gas Method considers the following four general fault types:

1) Thermal fault due to overheated oil;
2) Thermal fault due to overheated cellulose;
3) Electrical fault due to corona;
4) Electrical fault due to arcing.

The standard of IEEE Std C57.104-1991 indicates the key gases and their relative proportions for four fault types (**Table 5**). Generally, the thermal decomposition of oil produced more than 60% of ethylene (C_2H_4) and thermal decomposition of cellulose produce key gas carbon monoxide (CO) is 90%. In case of corona in oil mainly produce large amount principal gas hydrogen nearly 80% and due to arcing key gas acetylene produced 30% with trace quantity of hydrogen.

The total dissolved combustible gas (TDCG) is the definition of the sum of the combustible gas concentrations as follows:

$$TDCG = H_2 + CH_4 + C_2H_6 + C_2H_4 + C_2H_2 + CO \quad (2)$$

InIEC Standards 60599 it is suggested a four-level criterion (**Table 6**) to classify risks to transformers when there is no previous dissolved gas history as follow:

Condition 1: TDGC below this level indicates the transformer is operating satisfactorily;

Condition 2: TDGC within this range indicates greater than normal combustible level. Action should be taken to establish a trend;

Condition 3: TDGC within this range indicates a high level of decomposition. Immediate action should be taken to establish a trend;

Condition 4: TDGC within this range indicates excessive decomposition. Continued operation could result in failure of the transformer.

6. Roger's Ratio Method

This method uses five gases (H_2, C_2H_6, CH4, C_2H_2 and C_2H_4) to generate codes based on their composition ratio [14]. The codes are then used to categorize a range of ratios used to diagnose the fault as shown in **Table 7**.

The method utilizes the ratio of gas concentration to indicate fault types. Rogers Ratio method can be used when any of individual gases exceeds its normal limit and it does not depend on specific gas concentrations. The Rogers Ratio method utilizes four ratios; C_2H_6/CH_4, C_2H_2/C_2H_4, CH_4/H_2, and C_2H_4/C_2H_6 that leads to twenty-two proposed diagnosis as shown in **Table 8** [15]. Rogers Ratio method diagnosis provides more interpretation details in terms of temperature range of decomposition.

In [16], the Rogers Ratio method diagnosis was revised, as shown in **Table 9**, to include only six diagnosis interpretations; normal, low-energy density arcing-PD, arcing-high-energy discharge (D2), low temperature thermal (T1), thermal 300˚C - 700˚C (T2) and thermal >700˚C (T3).

This method does not consider dissolved gases below normal concentration limits; also certain ratio values are inconsistent with the diagnostic assigned and lead to invalid codes [17].

7. A Hybrid DGA Analysis Methods

The hybrid method proposed in this paper is a step-by-step procedure (flow chart **Figure 3**) to diagnose faults

Table 5. The key gases and their relative proportions for four fault types.

Faults/Gases	CO	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2
Overheated oil	0	2	16	19	63	0
Overheated cellulose	92	0	0	0	0	0
Corona in oil	0	85	13	1	1	0
Arcing in oil	0	60	5	2	3	30

Table 6. Dissolved gas concentrations (ppm).

Status	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO	CO_2	TDCG
Condition 1	<100	<120	<35	<50	<65	<350	<2500	<720
Condition 2	101 - 700	121 - 400	36 - 50	51 - 100	66 - 100	351 - 570	2500 - 4000	721 - 1920
Condition 3	701 - 1800	401 - 1000	51 - 80	101 - 200	101 - 150	571 - 1400	4001 - 10,000	1921 - 4630
Condition 4	>1800	>1000	>80	>200	>150	>1400	>10,000	>4630

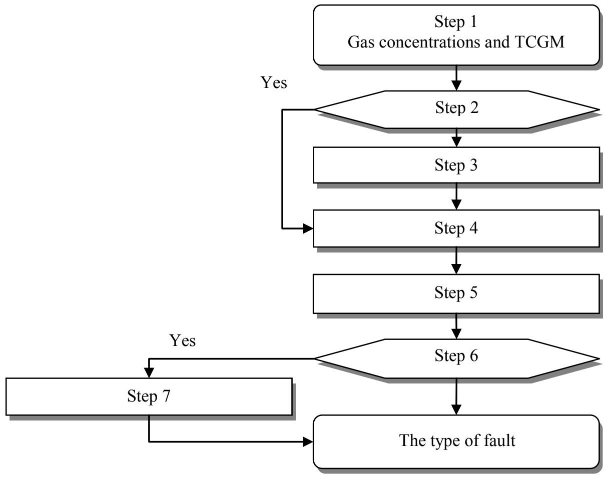

Figure 3. The flow chart of the hybrid Methods.

Table 7. Code definition of Rogers refined ratio method.

Gas Ratio	Range	Code
CH_4/H_2 (R1)	Not greater than 0.1	5
	Between 0.1 and 1.0	0
	Between 1.0 and 3.0	1
	Not less than 3.0	2
C_2H_6/CH_4 (R_4)	Less than 1.0	0
	Not less than 1.0	1
C_2H_4/C_2H_6 (R5)	Less than 1.0	0
	Between 1.0 and 3.0	1
	Not less than 3.0	2
C_2H_2/C_2H_4 (R_2)	Less than 0.5	0
	Between 0.5 and 3.0	1
	Not less than 3.0	2

using the Key Gas Method with total combustible gas method (TCGM) and then verified by the Rogers' Ratios.

Step 1. Gas concentrations are obtained by DGA and TCGM is evaluated;

Step 2. If at least one of the gas concentrations (in ppm) for H_2, CH_4, C_2H_2, C_2H_4, C_2H_6 and TCGM exceeds the values for abnormal limit (see **Table 3**), the unit is considered faulty; proceed to Step 4;

Step 3. If at least one of the gas concentrations (in ppm) for H_2, CH_4, C_2H_2, C_2H_4, C_2H_6 and TCGM exceeds the values for limit C_2 (see **Table 6**), the unit is considered faulty; precede to Step 4, otherwise "No fault condition";

Step 4. Determining the values of ratio obtained from **Table 7** in the order of ratio CH_4/H_2, $C2H_2/CH_4$, C_2H_4/C_2H_6 and C_2H6/CH_4 procedure. Define the codes from **Table 7**;

Step 5. Each successive code is compared to the values obtained from **Table 8** to define the fault;

Step 6. If all succeeding ratios for a specific fault type fall within the values (column) given in **Table 9**, the type of fault is defined;

Step 7. The gas concentrations for H_2, CH_4, C_2H_2, C_2H_4, C_2H_6 in % of TCGM is evaluated; If relative proportions of the keys gases for a specific fault type fall within the values given in **Table 5**, the suggested diagnosis is valid. The report of fault is defined.

Table 8. Fault diagnosis table for Rogers ratio method.

No.	Codes	Fault Type
1	5000	B: Partial discharges of low energy density or hydrolysis
2	5001	E: Partial discharges of increasing energy density
3	5010	D: Coincidental partial discharges and conductor overheating
4	5100	C: Partial discharges of high energy density, possibly with tracking
5	0000	A: No fault: normal deterioration
6	0001	N: Thermal fault of temperature range 100˚C - 200˚C
7	0010	I: Insulated conductor overheating
8	0011	J: Complex thermal hotspot and conductor overheating
9	0100	F: Low energy discharge: flashover without power follow through
10	0101	K: Coincidental thermal hotspot and low energy discharge
11	0110	G: Low energy discharge: continuous sparking to floating potential
12	0120	H: High energy discharge: arc with power follow through
13	0200	F: Low energy discharge: flashover without power follow through
14	0210	G: Low energy discharge: continuous sparking to floating potential
15	0220	H: High energy discharge: arc with power follow through
16	1000	M: Thermal fault of low temperature range < 150˚C
17	1001	N: Thermal fault of temperature range 100˚C - 200˚C
18	1010	O: Thermal fault of temperature range temperature range 150˚C - 300˚C overheating of copper due to eddy currents
19	1020	P: Thermal fault of high temperature range 300˚C - 700˚C: bad contacts/joints: core and tank circulating currents
20	1100	K: Coincidental thermal hotspot and low energy discharge
21	2001	N: Thermal fault of temperature range 100˚C - 200˚C
22	2020	P: Thermal fault of high temperature range 300˚C - 700˚C: bad contacts/ joints: core and tank circulating currents

Table 9. Latest version of RRM diagnosis.

Case	R_2 C_2H_2/C_2H_4	R1 CH_4/H_2	R5 C_2H_4/C_2H_6	Suggested Fault Diagnosis
0	<0.1	>0.1 to <1	<1	Unit normal
1	<0.1	<0.1	<1	Low-energy density arcing-PD
2	0.1 to 3	0.1 to 1	>3	Arcing–High-energy discharge
3	<0.1	>0.1 to <1	1 to 3	Low temperature thermal
4	<0.1	>1	1 to 3	Thermal less than 700˚C
5	<0.1	>1	>3	Thermal exceeding 700˚C

8. Results

The method was tested against all the 30 cases in the data set [18]. In **Table 10**, we show a set of data that illustrate the method as well as the evaluation of the key gases concentrations according **Table 6** (Step 1).

In **Table 11** are represented the result of application of step 2 and 3 of above methods and the first step evaluation of faults. In **Table 12** are represented the Rogers' Ratios and the fault according to the Rogers Code Method.

Table 10. Set of data used in analysis and the evaluation the key gases concentrations.

No.	H_2 (ppm)	CH_4 (ppm)	C_2H_2 (ppm)	C_2H_4 (ppm)	C_2H_6 (ppm)	CO (ppm)	TDGC (ppm)	Actual Fault	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO	TDGC
1	33	79	5	215	30	56	418	DHE	C1	C1	C1	C4	C1	C1	C1
2	266	584	1	862	328	230	2271	TF	C2	C3	C1	C4	C4	C1	C3
3	9474	4345	12,752	6517	353	504	33,945	TF-H	C4	C4	C4	C4	C4	C2	C4
4	507	1053	17	1440	297	3034	6348	DHE	C2	C4	C1	C4	C4	C4	C4
5	441	207	261	224	43	234	1410	TF-M	C2	C2	C4	C4	C1	C1	C2

Table 11. Set of data used in evaluation of fault according the key gases concentrations.

No.	H_2 %	CH_4 %	C_2H_2 %	C_2H_4 %	C_2H_6 %	CO %	Fault
1	Normal	Normal	Normal	Severe Overheating	Normal	Normal	TF
2	Normal	Sparking	Normal	Severe Overheating	Local Overheating	Normal	TF
3	Arcing, Corona	Sparking	Arcing	Severe Overheating	Local Overheating	Normal	TF-H
4	Normal	Sparking	Normal	Severe Overheating	Local Overheating	Severe Overloading	DHE
5	Normal	Sparking	Arcing	Severe Overheating	Local Overheating	Normal	TF

Table 12 represented the result of application of step 4 and 5 of above methods based in the following reasoning:

1) Since total combustible gases (TDCG) are LESS the 720 ppm, the Rogers' Ratios result indicated below is considered less significant. Since C_2H_4 is ABNORMAL a Core & Tank circulating currents overheated joints;

2) Since total combustible gases (TDCG) are GREATER than 720 ppm, the Rogers' Ratios result indicated below should be considered more significant. Winding circulating currents;

3) Since total combustible gases (TDCG) are GREATER than 720 ppm, the Rogers' Ratios result indicated below should be considered more significant. Arc, with power follow through;

4) Since total combustible gases (TDCG) are GREATER than 720 ppm, the Rogers' Ratios result indicated below should be considered more significant. Core & Tank circulating currents overheated joints;

5) Since total combustible gases (TDCG) are GREATER than 720 ppm, the Rogers' Ratios result indicated below should be considered more significant. Arc, with power follow through.

From **Tables 10-12**, we can see the evaluation of the results for 5 cases has given a successful prediction with the Key Gas Method with total combustible gas method (TCGM) for cases 2 - 5 and a successful prediction with the Rogers' Ratios for case 2.

The evaluation of the results for 30 cases in the data set give a successful prediction of the Key Gas Method with total combustible gas method (TCGM) of about 78%, a successful prediction of the Rogers' Ratios of about 45% and the successful prediction of the Hybrid Method of about 87%.

9. Case Study Albanian Power Companies

The Albanian Power Companies started to invest in the last years to DGA laboratory tests to monitor main HPPs transformer units [19]. The data consists of numerical measurement of each individual key gas in ppm. In **Table 13** are represented the data measured in transformer of HEC Koman, one of the main power plant in Albania in two consecutive months.

By looking at the relative proportions of gases in the DGA results and the monthly increase it could be possible to identify the type of fault occurring in the transformer. It is evident an increase of Carbon Dioxide, Oxygen and humidity, while TDCG are LESS the 720 ppm. So, the rehabilitation of oil through degasification and dehumidification was necessary. After this process, as presented in **Table 14**, the relative proportions of gases in the DGA results at normal value.

Table 12. Set of data used in evaluation of fault according the Rogers Code Method.

No.	H_2 (ppm)	CH_4 (ppm)	C_2H_2 (ppm)	C_2H_4 (ppm)	C_2H_6 (ppm)	CO (ppm)	TDGC (ppm)	Actual Fault	R1 CH_4/H_2	R4 C_2H_6/CH_4	R5 C_2H_4/C_2H_6	R2 C_2H_2/C_2H_4	Roger Codes	Fault
1	33	79	5	215	30	56	418	DHE	2.39	0.38	7.17	0.02	1020	TF
2	266	584	1	862	328	230	2271	TF	2.20	0.56	2.63	0.00	1010	TF-M
3	9474	4345	12,752	6517	353	504	33,945	TF-H	0.46	0.08	18.46	1.96	0021	DHE
4	507	1053	17	1440	297	3034	6348	DHE	2.08	0.28	4.85	0.01	1020	TF-H
5	441	207	261	224	43	234	1410	TF-M	0.47	0.21	5.21	1.17	0021	DHE

Table 13. The data measured in transformer of HEC Koman.

Unit	Sample Date	Hydrogen (ppm)	Methan (ppm)	Acetylen (ppm)	Ethylene (ppm)	Ethan (ppm)	Carbon Monoxid (ppm)	**Carbon Dioxid (ppm)**	**Oxygen (ppm)**	TDCG (ppm)	**Water (ppm)**
TR4 HEC KOMAN	5/1/2015 18:00	13.7	16.3	0	17.8	64	314.8	**3565**	**19937.4**	427	**34.7**
	3/12/2014 23:00	12.6	14.1	0	8	74.8	238.2	**2744**	**17353.7**	347	**39.9**
	Monthly increase	1.1	2.2	0	9.8	−10.8	76.6	**821**	**2583.7**	80	**-5.2**

Table 14. The data measured in transformer of HEC Koman after the rehabilitation of oil.

Unit	Sample Date	Hydrogen (ppm)	Methane (ppm)	Acetylene (ppm)	Ethylene (ppm)	Ethan (ppm)	Carbon Monoxide (ppm)	Carbon Dioxide (ppm)	Oxygen (ppm)	TDCG (ppm)	Water (ppm)
TR4	16/02/2015 18:00	0	1	0	1	3.5	0	100	500	5.5	9

10. Conclusions

For uninterrupted power supply to consumers, proper maintenance of transformer, particularly preventive maintenance, is very necessary. The IEC standards 60599 and IEEE standards C57.104-1991 help in interpretation of DGA results, which together with further field inspections and experienced personnel judgment can give an answer to what is going on inside a suspected unhealthy transformer. The Key Gas Method in principal gives no answer in multiple fault condition.

To increase the accuracy of the interpretation and the certainty of the transformer condition, a hybrid method based on the Key Gas Method with total combustible gas method (TCGM) verified by the Rogers' Ratios is used to improve the accuracy of interpretation of DGA results.

The result of the prediction done to test the accuracy of the method shows the improvement of accuracy with 9% compared with the simple Key Gas Method.

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