Evaluating the Accuracy of Different DGA Techniques for Improving the Transformer Oil Quality Interpretation

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***Abstract*—In each power utility, a numbers of different tests are conducted for evaluating the quality of transformer oil. The information provided by each measurement and analysis techniques has varying degree of significance towards the identification of quality of oil. Consequently, it is important to understand the accuracy of different interpretations. In this paper, Dissolved Gas in oil Analysis (DGA), one of the most important tools for transformer fault diagnosis is investigated. In a case study different DGA diagnosis methods are compared at different rated voltage levels and based on the obtained results accuracy of each method is calculated. The examined dataset consists of 120 different fault cases from a power utility.**

***Index Terms*—Transformer Mineral Oil, Health Index, DGA Techniques.**

I. Introduction

In the majority of liquid-filled power transformers, mineral oil is used as the predominant insulating liquid due to its availability and low cost compared to other alternatives, such as silicone oil and natural esters. Mineral oil is used in transformers in order to provide adequate cooling, to avoid direct contact between air and paper insulation and as an electrical insulation.

Under operating conditions, oil and paper/pressboard are subjected to thermal, electrical and oxidative stresses, which can cause molecular rearrangements resulting in a variety of decomposed products. These reactions may form a number of undesirable polar compounds, which includes acids, and sludge, which contributes to change the overall composition of oil.

Due to these changes in the chemical composition of the insulating oil and inclusion of impurities, electrical and chemical properties of the oil may be significantly affected. As a result, a numbers of chemical, electrical and mechanical tests are conducted for identifying the quality of insulating oil. The information provided by different measurement techniques has varying degree of significance towards the identification of different properties of oil. Consequently, utilities may prefer to use an index derived from the results of different diagnostic measurements. When calculating such a health index using all other measured parameters, appropriate weighing factors should be assigned for the diagnostic results from each individual measurement. This will allow incorporating the degree of significance of different measurements for the final estimation of a health index. Use of wrong weighing factors can lead to an erroneous interpretation. Some studies have been done to quantify the condition of power transformer and derive the transformer health index through combining all available data from operating observations, field inspections, and site and laboratory testing [1], [2]. However for improving the oil quality interpretation, it is necessary to evaluate the accuracy of different analysis techniques.

In this paper performance of DGA techniques in correct diagnosis of transformer oil condition is investigated. According to the obtained results from case study, accuracy of different DGA analysis techniques is compared.

II. Gas Dissolved in Transformer Insulating Oil

Transformer oils (mineral oils) are made from mixture of various hydrocarbon molecules having CH_3, CH_2 and CH chemical groups that are connected through carbon-carbon molecular bonds [3]. Due to the thermal and electrical faults, a number of the C-H and C-C bonds may separated in unbalanced fragments in either ionic or radial form [3]. Some example of these unstable fragments among various complex forms can be $C^{\bullet}$, $H^{\bullet}$, $CH_3^{\bullet}$, $CH_2^{\bullet}$ or $CH^{\bullet}$ which are react rapidly and form some of the following gas molecules [3]:

- o Hydrogen (H-H);
- o Methane (CH_3-H);
- o Ethane (CH_3-CH_3);
- o Ethylene (CH_2=CH_2);
- o Acetylene (CH=CH).

There are other types of possible recombination products including the C_3 and C_4 hydrocarbon gases, as well as solid particle of carbon and hydrocarbon polymers (X-wax) [3]. If transformer oil is oxidize may produce small quantities of CO and CO_2.

In the other side, the solid cellulosic insulation contains a abundance of anhydroglucose rings along with glycosidic bonds and weak C-O molecular bonds [3]. Thermally, these bonds are less stable than hydrocarbon bonds in oil therefore they decompose at lower temperatures [3]. Typically, carbon

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monoxide (CO), carbon dioxide (CO_2) and water (H_2O) are produced in extremely high amounts than oil oxidation at similar temperature, along with small quantities of furanic compounds and hydrocarbon gases [3]. The additional sources of generated gases can be the result of other chemical reactions such as rusting involving uncoated surfaces, steel or protective paints [4].

According to the several studies on the different concentration of dissolved gases in oil, it has been found that it is possible to predict transformer fault from volume of gases in insulating oil. In the following, most common techniques to diagnose DGA data, which have been offered from IEEE and IEC standards, are discussed.

A. Key Gas Method

In this method diagnoses result is based on determining the relative magnitude of the key gases to the other gases dissolved in transformer insulating oil [4]. This method can only predict four general fault types. Fig. 1 indicates theses fault types and their corresponded proportions of gases (in percentage) according to the IEEE guide [4].

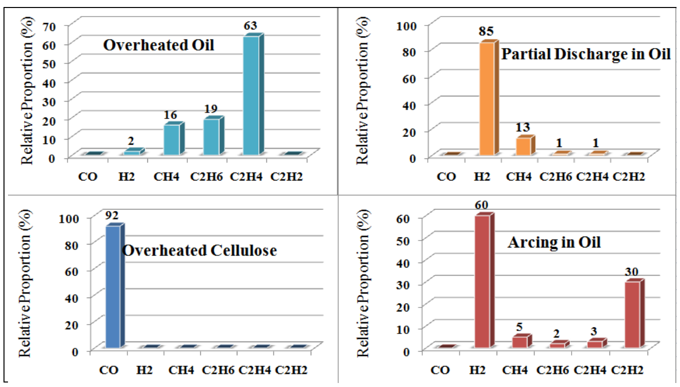

Fig. 1. Key Gases Evaluation [4]

B. Ratio Methods

The ratio methods may consist of single ratios of gases along with guidelines to evaluate different levels of normal, caution and warning [5]. The ratio techniques can also compose of multiple ratios. These methods determine the transformer oil condition, by fitting the calculated ratios in specific range of value. Table I shows some of the common ratios that have been used in majority of the diagnostic methods.

TABLE I
KEY GAS RATIOS

Ratio 1 (R_1)	**Ratio 2 (R_2)**	**Ratio 3 (R_3)**	**Ratio 4 (R_4)**	**Ratio 5 (R_5)**
CH_4/H_2	C_2H_2/C_2H_4	C_2H_2/CH_4	C_2H_6/C_2H_2	C_2H_4/C_2H_6

In this paper, five ratio methods are investigated and compared as follow:

1) Doernenburg Ratio Method

The Doernenburg method utilizes ratios R_1 through R_4 [4]. This method is more complicated compared to the other methods since the value of gases requires being greater than the concentration limit L1 (Table II). This condition is necessary to determine whether sufficient gases are generated in insulating oil for performing the Doernenburg ratio analysis [4]. After accomplishing this condition, the typical ratios for analysis will be compared with the ratio values indicated in Table III and based on that transformer oil condition will be predicted.

TABLE II
LIMIT CONCENTRATIONS OF DISSOLVED GAS [4]

Key Gas	**H_2**	**CH_4**	**CO**	**C_2H_2**	**C_2H_4**	**C_2H_6**
Concentrations L1[μL/L(ppm)]	100	120	350	1	50	65

TABLE III
RATIOS FOR KEY GASES- DOERNENBURG [4]

Fault Case	**R_1**	**R_2**	**R_3**	**R_4**
Thermal decomposition	>1	<0.75	<0.3	>0.4
Partial discharge	<0.1	Not significant	<0.3	>0.4
Arcing	>0.1 to <1	>0.75	>0.3	<0.4

2) Rogers and IEC Ratio Methods

The Rogers method introduced in IEEE [4] and IEC ratio method introduced in IEC [3] utilize ratios R_1, R_2 and R_5. Among these methods, the Rogers technique developed from the Doernenburg method and the IEC ratios has been improved over the Rogers technique [5]. Table IV and Table V illustrate the specified ratio values and their related fault cases for Rogers and IEC methods.

TABLE IV
ROGERS RATIOS FOR KEY GASES [4]

Fault Case	**R_2 (C_2H_2/C_2H_4)**	**R_1 (CH_4/H_2)**	**R_5 (C_2H_4/C_2H_6)**
Unit normal	<0.1	>0.1 to <1	<1
Partial discharge	<0.1	<0.1	<1
Arcing	0.1 to 3.0	0.1to 1	>3
Low thermal temperature	<0.1	>0.1to <1	1 to 3
Thermal <700º C	<0.1	>1	1 to 3
Thermal > 700 ºC	<0.1	>1	> 3

TABLE V
DGA INTERPRETATION IEC [3]

Fault Case	**R_2 (C_2H_2/C_2H_4)**	**R_1 (CH_4/H_2)**	**R_5 (C_2H_4/C_2H_6)**
Partial discharge	NS[a]	<0.1	<0.2
Discharge of low energy	>1	0.1-0.5	>1
Discharge of high energy	0.6-2.5	0.1-1	>2
Thermal < 300°C	NS	>1 but NS	<1
Thermal: 300°C < T < 700°C	<0.1	>1	1-4
Thermal >700°C	<0.2	>1	>4

a. Non significant whatever the value

One of the major weaknesses of the ratio based methods is that some of the obtained gas ratio does not fit in the particular range of values and cause the diagnosis of the fault not to be evaluated [5].

3) Duval Triangle

In the early 1970's, Michel Duval developed the Duval Triangle method, empirically [3]. Mainly, it is based on the values of the three gases CH_4, C_2H_4 and C_2H_2 which correspond to the increasing level of the gas formation [3].

The advantage of this method over others is its highly accurate diagnostic result [5].

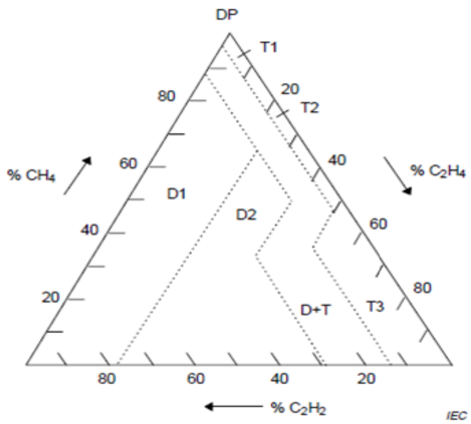

Fig. 2. Duval Triangle [3]

As illustrated in the Fig. 2, each side of the triangle plots the corresponding percentage of the three gases from 0% to 100%. There are six main zones of faults (PD, D1, D2, T1, T2, T3) in which the D+T zone indicates the combination of thermal and electrical faults [3]. However, calculation of uncertainty leads to more comprehensive results in fault diagnosis [6]. This requires analysis of the DGA data results according to the accuracy of laboratory DGA measurements [6], [7].

4) Single Gas Ratio Method

Three other single ratios have been introduced by IEC, which may be used as complement tool for the main diagnostic methods described above [4]. Those gas ratios are CO_2/CO ratio, the O_2/N_2 ratio and the C_2H_2/H_2 ratio. CO_2/CO ratio indicates the influence of the paper insulation in a fault being diagnosed. If the value of this ratio is below three, strong indication of paper involvement will be denoted [5]. O_2/N_2 ratio in transformer oil indicates air composition. At the equilibrium point base on the solubility's of the O_2 and N_2, this ratio value is 0.5 [5]. A decrease of this value is an indication of excessive heating. Since, the combination of the obtained results this single gas ratio together with other diagnostic methods that predict thermal faults could provide additional confidence toward thermal fault diagnostic result. C_2H_2/H_2 ratio (>2 to 3), can be an indication of the contamination in transformer main tank by Load Tap Changer (LTC) compartment [3].

III. Case Study

A. Methodology

In this paper, 120 DGA data sets of 9 fault gases (H_2, CH_4, C_2H_6, C_2H_4, C_2H_2, CO, CO_2, O_2 and N_2) obtained from 120 different transformers are investigated. These results were grouped based on the transformer rated voltage level and in each category there are an equal number of transformers as shown in Table VI. This data set is evaluated based on utility expert knowledge and categorized in four types of fault; low and high thermal faults (T1 and T2), partial discharge (PD) and arcing fault (Ar); together with a normal condition (Ok).

TABLE VI
SET OF DATA USED IN ANALYSIS

		Transformer Voltage			
		11 kV	**22 kV**	**33 kV**	**66 kV**
Expert Assessment	**T1**	6	4	12	9
	T2	4	6	0	4
	PD	8	6	4	10
	Ar	3	1	1	2
	Ok	9	13	13	5
Total		30	30	30	30

A MATLAB program has been developed to test each method. This program obtains the gas data from the specified input excel file and publish the output diagnosis result into the output excel file (see Appendix). The test MATLAB code is written based on the IEC and IEEE guides [3], [4].

For comparison purpose, each DGA technique response is grouped in six identical diagnosis outputs. Table VII illustrates how these methods are grouped.

TABLE VII
GROUPING FOR DIAGNOSIS RESPONSES

Method	T1	T2	PD	Ar	Ok	UD
Key Gas	Principle gas: CH_4 & C_2H_6	Principle gas: C_2H_4	Principle gas : H_2	Principle gas: C_2H_2	Healthy Transformer	Unresolved Diagnoses
Doernenburg	Thermal decomposition		Partial Discharge	Arcing	Healthy Transformer	Unresolved Diagnoses
Roger	Low temperature thermal Thermal < 700C	Thermal > 700C	Partial Discharge	Arcing	Healthy Transformer	Unresolved Diagnoses
IEC	Thermal t<300C Thermal 300C< t <700C	Thermal Fault t >700C	Partial Discharge	Discharge of high energy Discharge of low energy	Healthy Transformer	Unresolved Diagnoses
Duval Triangle	Thermal Fault t <300C Thermal Fault 300C< t <700C	Thermal Fault t >700C	Partial Discharge	Discharge of low energy Discharge of low energy	Healthy Transformer	Unresolved Diagnoses
Single Gas[a]	Paper involvement (Cell), Oxygen consumption (Cons) & Communicating OLTC (OLTC)				Healthy Transformer	Unresolved Diagnoses

a. Single gas ratio is ratio-based diagnostic method complement. It can support ratio-based diagnostic methods and gives more confidence decision [7].

B. Result of case study

All set of data is tested against each method. In order to evaluate diagnosis results, a number of factors have been introduced. The percentage of correct prediction of each diagnosis method response is calculated using the following formula:

$$C_d = \frac{t_d}{P_d} \times \frac{t_d}{E_d} \times 100 \qquad (1)$$

where:

d: type of diagnosis response (i.e. T1 or T2 or Ar or PD or Ok);

t_d: number of true prediction of DGA method for considered "d";

P_d: total number of prediction of DGA method for considered "d";

E_d: number of correct "d" (base of Table VI).

For example if in 11 kV voltage level, a DGA method predicts 6 T1 (P_d) and all 6 T1 are correct (t_d) and according to Table VI, number of T1 faults are 6 (E_d) therefore, this DGA method predicted T1 100 % correctly.

In a study that compared DGA techniques [8], the percentage of successful prediction was calculated without considering the first part of Equation 1. This leads to exempt overestimation of a fault and in some cases ranks the DGA method as 100% successful at predicting a fault, while it overpredicts that fault.

The overall reliability of each method in different voltage level (R_V) is obtained by averaging the percentage of correct predictions.

$$R_V = \frac{\sum_{n=1}^{n=5} C_d}{5} \qquad (2)$$

The percentage of unresolved diagnosis is another factor, which may be beneficial to measure the validity (capability) of each method in correctly estimating the fault types.

$$U_V = \frac{UD}{30} \times 100 \qquad (3)$$

In above formula, number 30 indicates the total number of transformers in each voltage level. The results of this study are summarized in following table and graphs.

TABLE VIII
CORRECT PREDICTION PERCENTAGES (% C_D)

Voltage	Method	T1[a]	T2[b]	PD[c]	Ar[d]	Ok[e]
11 kV	**Key Gas**			10%		
22 kV				22%		
33 kV				25%		
66 kV				13%		
11 kV	**Doernenburg**	17%		61%		50%
22 kV		9%		25%		41%
33 kV		9%				27%
66 kV		22%	100%	32%	100%	25%
11 kV	**Roger**			57%	33%	22%
22 kV				22%		2%
33 kV				25%	50%	10%
66 kV			25%	36%	100%	
11 kV	**IEC**	40%	25%	52%	33%	
22 kV		30%		17%		
33 kV		55%		25%		
66 kV		50%	25%	27%	100%	
11 kV	**Duval Triangle**	43%	75%	63%	67%	46%
22 kV		37%		53%	25%	28%
33 kV		92%		80%	33%	54%
66 kV		50%	57%	60%	100%	20%

a. Low thermal fault, b. High thermal fault, c. Partial discharge, d. Arcing fault, e. Normal condition

Refer to Table VIII; key gas method predicted around 20 % of PD correctly and it is unable to predict any other type of faults. In other hand, Doernenburg method diagnosed PD fault and Ok conditions better than other fault types. While, Roger ratio predicted higher number of arcing and partial discharge faults compare to other types. In case of basic gas method, it has correctly detected majority of thermal faults (T1) and a reasonable amount of arcing and partial discharge faults, while it couldn't identify any of the healthy cases. Among these DGA techniques, Duval triangle method showed the correct highest prediction rate for most diagnosis response types that are considered in this study.

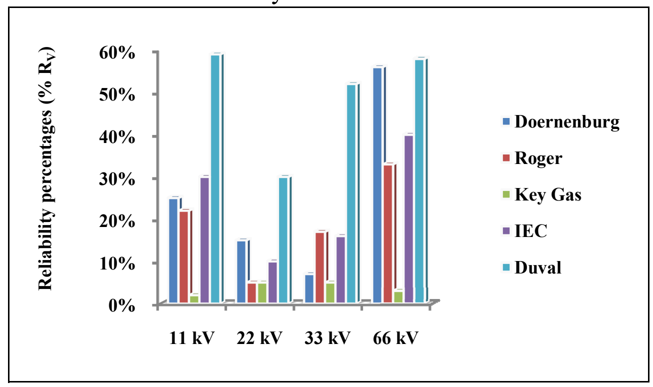

Fig. 3. Reliability percentages (% R_V) of DGA methods

Fig. 3 illustrates the reliability percentage of each method in different voltage level. Majority of the DGA methods have minimum reliability percentage in 22 kV and maximum reliability percentage at 66 kV. In overall, Duval triangle method has the highest reliability percentage followed by IEC ratio, Doernenburg ratio, Roger's ratio and key gas method.

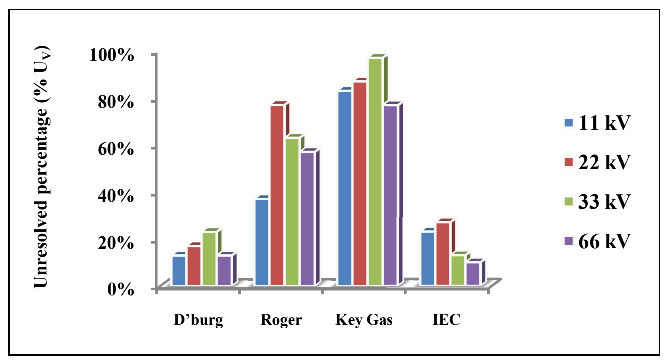

Fig. 4. Unresolved percentage (% U_V) of DGA methods

According to Fig. 4, key gas method is unable to predict the transformer condition about 85 % of time which is a big disadvantage of this technique. Roger's ratio also has high percentage of unresolved diagnosis response. However, percentages of unresolved diagnosis for IEC and Doernenburg ratio methods are reasonably low. Voltage level doesn't have significant effect on %U_V.

IV. CONCLUSION

This performed preliminary study illustrates that a particular DGA technique can evaluate a specific fault better than other techniques. The reliability of some DGA techniques is also significantly higher than other methods. It is also shown that the percentage of reliability is different for each DGA analysis technique and varies with rated voltage level of transformers.

The results of the presented study indicate that further investigations are required to improve the oil quality interpretation through different DGA techniques. Hence in future work, a similar analysis should be performed on a large database. Additionally, the influence of other factors such as oil collection point, transformer age and transformer loading history should be investigated to improve transformer oil quality interpretation. It is also intended to introduce some of the artificial intelligent (AI) techniques for better interpretation.

V. APPENDIX

TABLE IX

RESULT OF DGA METHODS DIAGNOSES FOR 11 KV

Sr.	DR[a]	RR[b]	KG[c]	IEC[d]	SG[e]	DT[f]	Fault[g]
1	Ok	UD	UD	T2	OLTC	T2	T2
2	UD	UD	UD	UD	Cons/	Ar	Ar
3	PD/	PD/	PD/	PD/T1/	Cons/	PD	PD
4	PD/	PD/	UD	PD/T1/	Cons/	PD	PD
5	PD/	PD/	UD	PD/T1/	Cons/	T1	PD
6	UD	Ok	UD	T1/	Cons/	T1	Ok
7	Ok	Ok	UD	T1/	Cons/	T1	Ok
8	UD	Ok	UD	T1/	Cons/	T1	T1
9	Ok	Ok	UD	T1/	UD	Ok	Ok
10	PD/	UD	PD/	UD	Cons/	T2	T2
11	PD/	UD	PD/	UD	Cons/	T2	T2
12	Ok	UD	UD	T1/	Cons/	T1	T1
13	Ok	Ar	UD	Ar/	OLTC	Ok	Ar
14	Ok	UD	UD	UD	Cons/	Ar	Ar
15	UD	Ok	UD	T1/	Cons/	PD	PD
16	PD/	UD	PD/	PD/T1/	Cons/	PD	PD
17	PD/	PD/	UD	T1/	Cons/	T1	PD
18	PD/	PD/	UD	PD/T1/	Cons/	PD	PD
19	PD/	PD/	UD	T1/	Cons/	T1	PD
20	Ok	Ok	UD	T1/	Cons/	T1	T1
21	Ok	PD/	UD	PD/T1/	Cons/	T1	Ok
22	Ok	UD	UD	T1/	Cons/	T1	Ok
23	T	UD	UD	T1/	Cons/	T1	T1
24	Ok	Ok	UD	T1/	Cons/	T1	T2
25	Ok	UD	UD	T1/	Cons/	T1	T1
26	PD/	PD/	PD/	PD/T1/	Cons/	T1	T1
27	Ok	Ok	UD	T1/	UD	Ok	Ok
28	Ok	UD	UD	UD	UD	Ok	Ok
29	Ok	T1/	UD	UD	UD	Ok	Ok
30	Ok	T1/	UD	UD	UD	OK	Ok

a. Doernenburg Ratio method, b. Rogers Ratio method, c. Key Gas method, d. IEC method, e. Single gas ratio method, f. Duval triangle method, g. Fault predicted by utility expert assessment.

TABLE X

RESULT OF DGA METHODS DIAGNOSES FOR 22 KV

Sr.	DR	RR	KG	IEC	SG	DT	Fault
1	Ok	UD	UD	UD	Cons/OLTC	Ar	Ar
2	Ar/	UD	UD	Ar/	Cons/OLTC	Ar	PD
3	PD/	PD/	UD	PD/T1/	Cons/	PD	PD
4	UD	Ok	UD	T1/	Cons/	T1	T2
5	PD/	PD/	PD/	PD/T1/	Cons/	PD	Ok
6	UD	Ok	UD	T1/	Cons/	PD	PD
7	Ok	UD	UD	T1/	Cons/	T1	T2
8	PD/	PD/	PD/	PD/T1/	Cons/	PD	PD
9	Ok	UD	UD	T1/	Cons/	T1	T1
10	PD/	PD/	UD	PD/T1/	Cons/	T1	Ok
11	UD	Ok	UD	T1/	Cons/	T1	T1
12	UD	Ok	UD	T1/	UD	T1	T1
13	Ok	UD	UD	UD	Cons/	T1	Ok
14	T	UD	UD	T1/	Cons/	T1	T1
15	Ar/	Ar	UD	Ar/	Cons/OLTC	Ok	T2
16	UD	Ok	UD	T1/	Cons/	PD	PD
17	Ar/	UD	UD	UD	Cons/OLTC	Ar	T2
18	Ok	T1/	UD	UD	Cons/	Ok	Ok
19	Ok	UD	UD	UD	Cons/	OK	Ok
20	T	T2/	UD	T2	Cons/	T2	Ok
21	T	T2/	UD	T2	Cons/	T2	Ok
22	Ar/	UD	UD	UD	OLTC	Ar	T2
23	Ok	UD	UD	UD	OLTC	Ok	T2
24	PD/	PD/	UD	T1/	Cons/	T1	Ok
25	PD/	PD/	PD/	T1/	Cons/	T1	PD
26	Ok	UD	UD	UD	Cons/	Ok	Ok
27	Ok	PD/	UD	T1/	Cons/	T2	Ok
28	Ok	UD	T2/UD	T1/	Cons/	T1	Ok
29	Ok	Ok	UD	T1/	Cons/	Ok	Ok
30	Ok	UD	UD	T1/	UD	Ok	Ok

TABLE XI

RESULT OF DGA METHODS DIAGNOSES FOR 33 KV

Sr.	DR	RR	KG	IEC	SG	DT	Fault
1	UD	Ar	UD	T1/	Cons/	Ar	Ar
2	Ok	Ok	UD	T1/	Cons/	PD	PD
3	Ok	PD/	PD/	PD/T1/	Cons/	PD	PD
4	UD	Ok	UD	T1/	Cons/	T1	T1
5	UD	Ok	UD	T1/	Cons/	PD	PD
6	UD	Ok	UD	T1/	Cons/	PD	PD
7	T	UD	UD	T1/	Cons/	T1	T1
8	Ok	UD	UD	T1/	Cons/	T1	T1
9	Ok	UD	UD	T1/	Cons/	T1	T1
10	Ok	UD	UD	T1/	Cons/	T1	T1
11	Ok	UD	UD	T1/	Cons/	T1	T1
12	Ok	UD	UD	T1/	Cons/	T1	T1
13	Ok	UD	UD	T1/	Cons/	Ok	Ok
14	UD	Ok	UD	T1/	Cons/	PD	Ok
15	Ok	UD	UD	T1/	Cons/	T1	T1
16	Ok	UD	UD	T1/	Cons/	T1	T1
17	Ok	UD	UD	UD	Cons/	Ok	Ok
18	UD	UD	UD	UD	Cons/	T2	Ok
19	Ar/	UD	UD	Ar/	Cons/	Ar	Ok
20	Ok	UD	UD	UD	Cons/	T2	Ok
21	Ok	UD	UD	Ar/	OLTC	Ok	Ok
22	Ar/	UD	UD	Ar/	Cons/	Ar	Ok
23	Ok	UD	UD	T1/	Cons/	T1	T1
24	Ok	UD	UD	T1/	Cons/	T1	T1
25	Ok	Ok	UD	T1/	Cons/	T1	T1
26	Ok	Ok	UD	T1/	Cons/	Ok	Ok
27	Ok	Ar	UD	UD	Cons/	Ok	Ok
28	UD	Ok	UD	T1/	Cons/	T1	Ok
29	Ok	UD	UD	T1/	Cons/	Ok	Ok
30	Ok	UD	UD	T1/	Cons/	Ok	Ok

TABLE XII

RESULT OF DGA METHODS DIAGNOSES FOR 66 KV

Sr.	DR	RR	KG	IEC	SG	DT	Fault
1	Ar/	Ar	UD	Ar/	Cons/	Ar	Ar
2	Ok	PD/	PD/	T1/	Cons/	PD	PD
3	PD/	PD/	UD	PD/T1/	Cons/	T1	PD
4	UD	UD	UD	T1/	Cons/	PD	PD
5	PD/	PD/	PD/	PD/T1/	Cons/	PD	PD
6	UD	Ok	UD	T1/	Cons/	PD	PD
7	Ok	PD/	PD/	PD/T1/	Cons/	PD	PD
8	Ar/	Ar	UD	Ar/	Cons/	Ar	Ar
9	T	UD	UD	T1/	Cons/	T1	T2
10	UD	UD	PD/	T1/	Cons/	PD	PD
11	PD/	PD/	UD	T1/	Cons/	T1	PD
12	UD	Ok	UD	T1/	Cons/	T1	PD
13	T	UD	UD	T1/	Cons/	T1	T1
14	T	UD	UD	UD	Cons/	T2	T2
15	Ok	UD	UD	T1/	Cell/Cons/	T1	T1
16	Ok	UD	UD	T1/	Cons/	T1	T1
17	Ok	UD	UD	T1/	Cons/	T1	T1
18	T	T1/	UD	T1/	UD	T2	T2
19	T	T2/	UD	T2	UD	T2	T2
20	Ok	UD	UD	T1/	Cons/	T1	T1
21	Ok	UD	UD	T1/	Cons/	T1	T1
22	T	UD	UD	T1/	Cons/	T1	T1
23	Ok	UD	UD	T1/	Cons/	T1	T1
24	Ok	UD	PD/	T1/	Cons/	D+T	Ok
25	Ok	UD	UD	UD	Cons/	Ok	Ok
26	Ok	PD/	UD	PD/T1/	Cons/	T2	T1
27	Ok	PD/	PD/	PD/T1/	Cons/	T1	Ok
28	PD/	UD	PD/	PD/T1/	Cons/	T1	Ok
29	Ok	UD	UD	UD	Cons/	D+T	Ok
30	PD/	UD	UD	PD/T1/	Cons/	T1	PD

VI. REFERENCES

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VII. Biographies

Atefeh Dehghani Ashkezari (SM'10) was born in Iran in 1987. She received her B. Eng (electrical and computer engineering) in 2009 from Sohar University, Oman and M. Eng (electrical engineering) in 2010 from the University of Queensland, Australia. She is currently a research higher student at the University of Queensland. Her research interests include condition monitoring, transformer diagnosis and power system.

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Dr. C.M.B. Ekanayake (M' 00) received his B.Sc.Eng.(Hons) in 1999 from University of Peradeniya. He obtained his Tech. Lic. and PhD from Chalmers University of Technology Sweden in 2003 and 2006 respectively. Currently he is a postdoctoral research fellow in the School of Information Technology and Electrical Engineering, the University of Queensland, Brisbane, Australia. Before joining UQ he was attached to the department of Electrical and Electronic Engineering, University of Peradeniya Sri Lanka as a Senior lecturer. During his PhD studies he was working for a European Union Project called REDIATOOL where he engaged in research related to Diagnostics of Transformer Insulation from dielectric response measurements. Also he has carried out several dielectric response measurements at ETH, Switzerland as a part of his research work. From 2001, he has been involving on condition monitoring of transformers installed at Ceylon Electricity Board, Sri Lanka. He was the Chair of IEEE Sri Lanka Section in year 2006 and 2007. His research interests are condition monitoring of power apparatus, Alternatives for insulating oil, transient studies on power systems and energy related studies.

Hui Ma (M'1995) was born in Xi'an, China. He received his B.Eng and M.Eng degrees from Xi'an Jiaotong University, Xi'an, China in 1991 and 1994, M.Eng (research) from Nanyang Technological University, Singapore in 1998, and Ph.D. degree from the University of Adelaide, Adelaide, Australia in 2008. Currently Dr. Ma is a postdoctoral research fellow in the School of Information Technology and Electrical Engineering, the University of Queensland, Brisbane, Australia. Prior to joining the University of Queensland, Dr. Ma has many years research and development experience. From 1994 to 1995, he was a researcher in Xi'an Jiaotong University, China. From 1997 to 1999, he worked as a firmware development engineer in CET Technologies Pte. Ltd., Singapore. He was with Singapore Institute of Manufacturing Technology as a research engineer from 1999 to 2003. Dr. Ma's research interests include industrial informatics, condition monitoring and diagnosis, power system, wireless sensor networks, and sensor signal processing.