Comparison of Dissolved Gas Interpretation Techniques in Mineral Oil Immersed Transformers

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***Abstract*—One of the most important techniques for recognizing the potential fault in a power transformer at an early stage, i.e., incipient state, can be done through the interpretation of Dissolved Gas Analysis (DGA). Depending on the nature and seriousness of the fault, the insulation breakdown starts instantaneously, and the decomposition products will be distinct. DGA is periodically used to test the transformer's insulation oil to obtain dissolved gases that developed as an outcome of degradation in interior insulating materials. A conclusion can be drawn from the data obtained by DGA using distinct interpretation techniques. However, for the same instance, they could diagnose different fault categories. The purpose of this research is to examine the performance of different DGA interpretation techniques, i.e., Doernenburg Ratio Method (DRM), Rogers Ratio Method (RRM), IEC Ratio Method (IRM), Duval Triangle Method (DTM) and Duval Pentagon Method (DPM), [1] and evaluate these methods from fifty predetermined fault cases obtained from the IEEE Dataport in Enwen Li datasheet [2] using python. This study not only compares these techniques' overall accuracy but also focuses on the effectiveness of each method's ability to identify a particular fault separately.**

***Index Terms*—Power transformer, Dissolved gas analysis, Incipient fault.**

I. Introduction

One of the essential components of electrical systems is the transformer, which trades voltage for current in a circuit without affecting the total electrical power, which makes the usage of a transformer inevitable in the transmission and distribution systems of the electrical system. Thus, the transformer is the heart of the transmission and distribution systems. A reliable electrical supply depends on the fault-free operation of power transformers. Nevertheless, preventing transformer failure is quite challenging, particularly for transformers that are used for a specific amount of time. Since transformer performance may degrade with ageing, higher operating voltages, and atmospheric conditions [3].

A transformer fault, which can be catastrophic and nearly invariably results in irrevocable internal damage, can be caused by any mixture of mechanical, electrical, or thermal stresses, which may lead to gradual damage to the transformer in service that dampens the whole performance of the transformer. Therefore, the tests for diagnosing and monitoring the transformer's operation are critical. In order to reduce the risk of failure and increase operational effectiveness and service life, new techniques will enable improvements in the maintenance procedures of the transformer. Among the methods used to determine the incipient faults in the transformer, DGA is the cost-efficient technique, which can be used for monitoring the transformers periodically, and any abnormalities from the data can be monitored closely.

Because transformer mineral oils are combinations of numerous distinct hydrocarbon compounds, the processes by which these hydrocarbons decompose in electrical or thermal faults are intricate. The breaking of C-H (carbon-hydrogen) and C-C (carbon-carbon) bonds generate different gases. As a result, active hydrocarbon fragments and hydrogen atoms are formed. These free radicals can interact to create molecular hydrogen, gases, ethane, methane etc., or recombine to generate new molecules. In addition, products are formed as a result of different processes of breakdown and rearrangement, causing the production of ethylene, acetylene, and, in the most extreme cases, particles made of substantially hydrogenated carbon. When a fault arises, the insulation degrades more quickly, and the decomposition products vary depending on the kind and severity of the fault. Thus, the formation of these chemical compounds indicates the incipient faults that may happen in the transformer [4]. The dissolved gases in the insulating liquid are identified, measured, and interpreted using DGA. The principal gases used in the identification of faults are ethane (C_2H_6); methane (CH_4); hydrogen (H_2); acetylene (C_2H_2); carbon monoxide (CO); ethylene (C_2H_4); carbon dioxide (CO_2); oxygen (O_2) and nitrogen (N_2) in Parts Per Million (PPM). However, O_2 and N_2 are non-fault gases because their presence did not indicate fault. The rest of the gases are called fault gases because their presence indicates the fault that may occur in the transformer.

II. Methods for DGA Interpretation

One of the most crucial steps in classifying the different type of faults is the DGA interpretation. Numerous interpretation techniques are employed, such as methods from IEEE Std C57.104TM-2019 [1] and IEC 60599 [5]. The Table I below lists and abbreviates the six fundamental types of defects that can be identified after collecting samples in the laboratory as per ASTM D3612-02 [6] and evaluating the gas concentrations obtained using various interpretation techniques that are described in Table II.

The DGA interpretation techniques are broadly classified as

TABLE I
INCIPIENT FAULTS IN ELECTRIC POWER TRANSFORMERS

S.no.	Fault	Abbreviation
1	Partial discharges of corona type	PD
2	Thermal fault, t $<$ 300 ºC	T1
3	Thermal fault, 300 ºC $<$ t $<$ 700 ºC	T2
4	Thermal fault, t $>$ 700 ºC	T3
5	Discharges of low energy	D1
6	Discharges of high energy	D2

TABLE II
DIFFERENT DGA INTERPRETATION TECHNIQUES

S.no.	Technique	Abbr.	Type
1	Doernenburg Ratio Method	DRM	R
2	Rogers Ratio Method	RRM	R
3	I.E.C Ratio Method	IRM	R
4	Duval Triangle Method	DTM	P
5	Duval Pentagon Method	DPM	P

a) Ratio Methods (R)
b) Pictographic Methods (P)

III. RATIO METHODS

All the ratio methods are based on the pre-specified values and based on the ratios present in the zones, the faults are classified. The ratios used to investigate the ratio methods, i.e. DRM, RRM and IRM, are illustrated below.

TABLE III
DIFFERENT RATIOS

Ratio	Concentrations
1-Ratio-1 (R1)	CH_4/H_2
2-Ratio-2 (R2)	C_2H_2/C_2H_4
3-Ratio-3 (R3)	C_2H_2/CH_4
4-Ratio-4 (R4)	C_2H_6/C_2H_2
5-Ratio-5 (R5)	C_2H_4/C_2H_6

A. Doernenburg Ratio Method (DRM)

It is one of the earliest techniques to be suggested and used for finding transformer incipient faults. It utilises R1, R2, R3, and R4 to classify the faults(ref. Table III). However, it cannot classify the faults considerably as it cannot differentiate between the Thermal faults T1, T2, and T3 and also cannot differentiate between the energy discharges D1 and D2. However, it groups all the thermal faults T1, T2 & T3 as the Thermal decomposition and all the energy discharges (D1 & D2) as the Arcing faults. For that ratio analysis for DRM, ref. to Table IV [1].

B. Roger's Ratio Method (RRM)

This approach considers R2 and R1, two of the four Doernenburg ratios, and R5, a new ratio. (ref. Table III). This method is more effective than the DRM because it can classify

TABLE IV
ANALYSIS OF THE GAS CONCENTRATION RATIOS FOR THE DOERNENBURG RATIO METHOD

S.no.	Suggested fault diagnosis	R1	R2	R3	R4
1	Thermal decomposition	$>$1.0	$<$0.75	$<$0.3	$>$0.4
2	Corona (low intensity PD)	$<$0.1	NS	$<$0.3	$>$0.4
3	Arcing (high intensity PD)	0.1-1.0	$>$0.75	$>$0.3	$<$0.4

NS:- Non-significant, whatever the value

all Thermal faults as T1, T2 & T3, unlike DRM for each case. The Rogers ratio approach was more widely used in maintenance procedures. Table V illustrates that this approach employs three gas ratios to recognise five different kinds of faults. However, it groups both Partial discharge and Low discharge faults, i.e. PD and D1, as a single fault, i.e. Partial discharge [7].

TABLE V
ANALYSIS OF THE GAS CONCENTRATION RATIOS FOR THE ROGERS RATIO METHOD

S.no.	Suggested fault diagnosis	R2	R1	R5
1	Partial discharge	$<$0.1	$<$0.1	$<$1.0
2	Thermal fault (T1)	$<$0.1	0.1-1.0	1.0-3.0
3	Thermal fault (T2)	$<$0.1	$>$1.0	1.0-3.0
4	Thermal fault (T3)	$<$0.1	$>$1.0	$>$3.0
5	Arcing	0.1-3.0	0.1-1.0	$>$3

C. IEC Ratio Method (IRM)

IRM, a DGA interpretation method, is recommended by the IEC 60599 [6]. The IRM also employs the same three gas ratios used in RRM. This method is more effective because it classifies thermal faults, i.e. T1, T2 & T3, unlike DRM, and also separately classify between the PD, D1 & D2, unlike RRM, by interpreting the dissolved gas analysis in the transformer oil for each case, as shown in Table VI.

TABLE VI
ANALYSIS OF GAS CONCENTRATION RATIOS FOR THE IRM

S.no.	Suggested fault diagnosis	R1	R2	R5
1	Partial discharge	$<$0.1	NS	$<$0.2
2	Low energy discharge	0.1-0.5	$>$1.0	$>$1.0
3	High energy discharge	0.1-3.0	0.1-1.0	$>$0.3
4	Thermal fault (T1)	$>$1.0	NS	$<$1.0
5	Thermal fault (T2)	$>$1.0	$<$0.1	1.0-4.0
6	Thermal fault (T3)	$>$1.0	$<$0.2	$>$4.0

NS:- Non-significant, whatever the value

Although several aspect ratios don't match with the diagnostic codes that are assigned to the various faults in all of the above three ratio methods, as illustrated in Table IV, Table V, and Table VI. So, they may not give any conclusion in some cases resulting in ambiguity. These drawbacks in the ratio methods drive the fault detection methods' orientation in the pictographic observation mode.

IV. Pictographic Methods

Pictographic methods, i.e. DTM and DPM, classify the fault zones based on the point that falls inside a particular fault area. It is colour coded to identify the fault. For both DTM and DPM methods, figures are visualized using the matplotlib library in python, where the zones are marked based on [8] and [9].

A. Duval Triangle Method (DTM)

It was developed in 1974 by Michel Duval and is a method for analysing the dissolved gases produced by mineral oil-immersed transformers, which require only three gases, namely, CH_4, C_2H_2 and C_2H_4.

To classify fault types, the relative ratios of gas concentrations are represented inside the Duval triangle and used to determine the intersection of a straight line indicated by the transformer faults' codes. The corresponding zone in the transformers represents the fault type. The seven-unit problem area is depicted in Fig. 1, and Table VII is a guideline through which the fault in the transformer is identified [8].

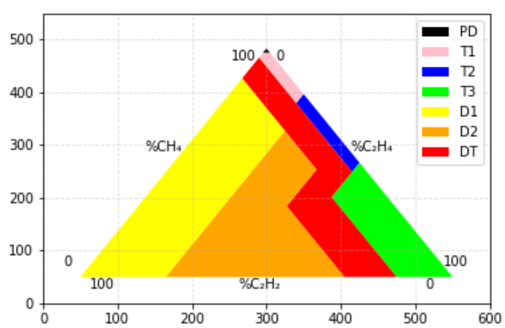

Fig. 1. Duval triangle

TABLE VII
Duval Triangle Colour-Coded Interpretation

S.no.	Fault	Colour
1	Partial discharge (PD)	Black
2	Thermal fault (T1)	Pink
3	Thermal fault (T2)	Blue
4	Thermal fault (T3)	Green
5	Low energy discharges (D1)	Yellow
6	High energy discharges (D2)	Orange
7	Mix of thermal & electrical faults (DT)	Red

B. Duval Pentagon Method (DPM)

It is the most recent technique for DGA interpretation. DPM incorporates two more new gases in addition to the gases utilised by the DTM, i.e. H_2 & C_2H_6. The Duval pentagon has also introduced a stray gas zone (S) to indicate the presence of gases while transformers usually operate which improves the capacity of DPM to differentiate between typical ageing and any fault that can occur in the transformers. The relative percentage of each gas, i.e., C_2H_2, CH_4, C_2H_6, H_2, C_2H_4, and the summation of overall gases, are computed per cent. The pentagon's axes span the length from 0% to 100%. After joining all five points based on the concentrations of each gas, an irregular pentagon will be formed. The centroid of gas concentration from the irregular pentagon is calculated and plotted inside the Duval pentagon. As shown in Fig. 2, the specified fault zone produced through calculation determines the interpreted fault type, and Table VIII is a guideline through which the fault in the transformer is identified [9].

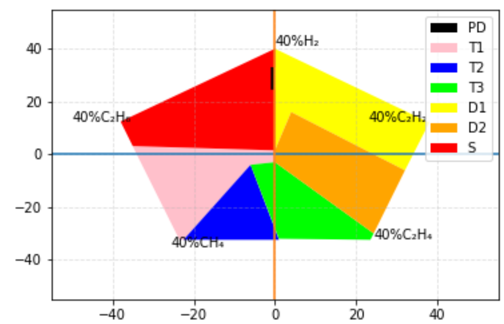

Fig. 2. Duval pentagon-1

TABLE VIII
Duval Pentagon Colour-Coded Interpretation

S.no.	Fault	Colour
1	Partial discharge (PD)	Black
2	Thermal fault (T1)	Pink
3	Thermal fault (T2)	Blue
4	Thermal fault (T3)	Green
5	Low energy discharges (D1)	Yellow
6	High energy discharges (D2)	Orange
7	Stray gassing (S)	Red

V. Results & Discussion

The characteristics associated with the fault categories procured from the previously discussed methodologies that interpret the DGA data were narrowly altered to six kinds of faults, namely PD, T1, T2, T3, D1, & D2. To assess the effectiveness of each DGA interpretation technique, we are using predetermined faults from fifty cases of the Enwen li datasheet from which each method is evaluated. The parameter that is used for evaluating the DGA interpretation technique's performance is accuracy.

A. Accuracy

It may be defined as the ratio between the number of correct predictions (N_c) to the total number of case studies (N).

$$\%\text{accuracy} = \frac{\text{number of correct predictions}}{\text{number of case studies}} * 100$$

In order to compare the results for the individual faults, they are grouped as Partial discharge, Thermal faults, and Discharge faults.

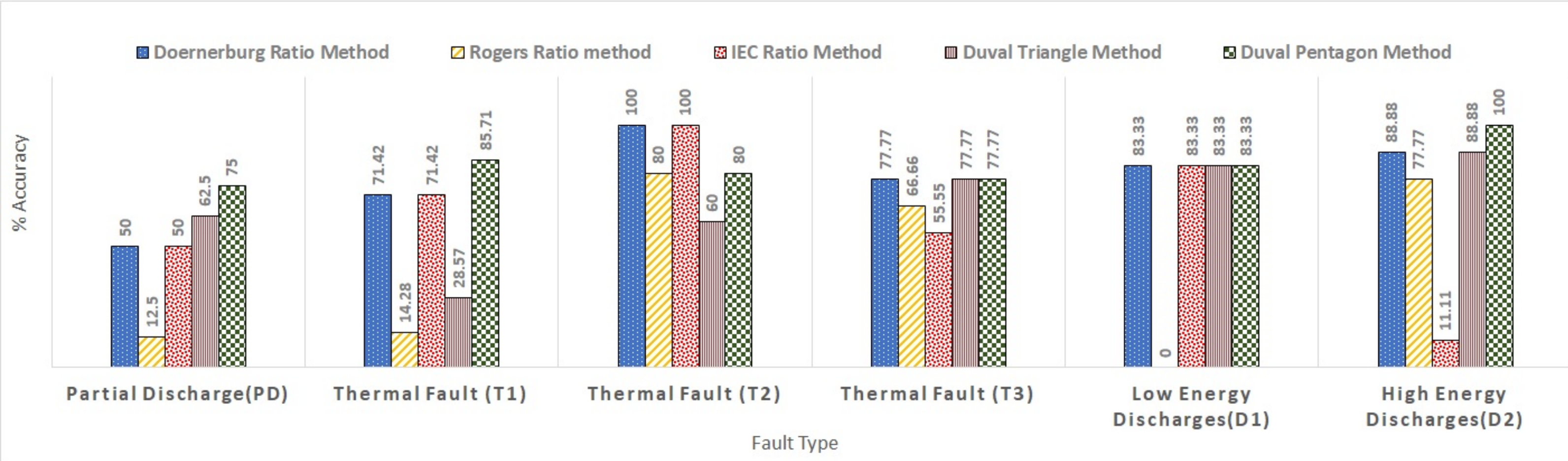

Fig. 3. Comparison of accuracy in identifying individual fault cases and different methods for interpreting DGA

1) Partial Discharge (PD): For detecting the partial discharge fault, the accuracy of DPM is the highest, which is 75%, than the other methods because of the including H_2 gas in the analysis, which is an indication of the partial discharge. The accuracies of partial discharge for each DGA technique are tabulated in Table IX.

TABLE IX
COMPARISON OF ACCURACIES OF PARTIAL DISCHARGE FOR EACH DGA INTERPRETATION TECHNIQUES

S.no.	Method	Accuracy
1	DRM	50.0%
2	RRM	12.5%
3	IRM	50.0%
4	DTM	62.5%
5	DPM	75.0%

2) Thermal Faults (T1,T2&T3): Although DRM provides the maximum thermal accuracy(mean of acc(T1),acc(T2) and acc(T3), where acc(method) = accuracy of the particular method.), i.e. 83.06%, it is not considered the best method in detecting thermal faults because it will not be able to classify the thermal decomposition as T1, T2 & T3 further. As a result, DPM is the better technique for classifying thermal faults. Table X tabulates the accuracies of each DGA technique's thermal faults.

TABLE X
COMPARISON OF ACCURACIES OF THERMAL FAULTS FOR EACH DGA INTERPRETATION TECHNIQUES

S.no.	Method	acc(T1)	acc(T2)	acc(T3)	T
1	DRM	71.42%	100%	77.77%	83.06%
2	RRM	14.28%	80%	66.66%	53.65%
3	IRM	71.42%	100%	55.55%	75.66%
4	DTM	28.57%	60%	77.77%	55.44%
5	DPM	85.71%	80%	77.77%	81.16%

3) Discharge Faults (D1&D2): The accuracy is highest in DPM, i.e. 91.66% for detecting the discharge faults, which makes the DPM technique superior to all other methods in detecting the incipient faults in the transformer. The accuracies of discharge faults for each DGA technique are tabulated in Table XI, where D is the mean of acc(D1) and acc(D2). For the DGA worksheet on which the calculations are done, due to its improper zone classification, RRM is not able to distinguish any actual discharge fault as D1, thus making its accuracy as 0%.

TABLE XI
COMPARISON OF ACCURACIES OF DISCHARGE FAULTS FOR EACH DGA INTERPRETATION TECHNIQUES

S.no.	Method	acc(D1)	acc(D2)	D
1	DRM	83.33%	88.88%	86.11%
2	RRM	0.0%	77.77%	38.88%
3	IRM	83.33%	11.11%	47.22%
4	DTM	83.33%	88.88%	86.11%
5	DPM	83.33%	100%	91.66%

B. Overall Accuracy

Determination of the overall accuracy of each interpretation technique (ref. Table II) was done for some case studies(N), i.e. 50. A CSV file of gas concentrations from the Enwen Li datasheet is processed using Python's pandas library, considering all of the individual gas concentrations, and how each technique interprets the gas concentrations are evaluated. A bar graph was plotted for each fault to illustrate how accurately each DGA interpretation technique could detect each fault, as in Fig. 3. Overall accuracy is defined as the ratio between the no. of correct predictions (N_c) to the total number of case studies (N).

$$N_c = N - N_o - N_r$$

where
N = Total number of test cases = 50
N_c = no. of correct predictions, i.e. the DGA interpretation technique output equals to actual output
N_o = no. of cases where the DGA interpretation technique

TABLE XII
COMPARISON OF ACCURACIES OF EACH INTERPRETATION TECHNIQUES

S.no.	Method	Nc	No	Nr	Accuracy
1	DRM	39	11	0	78.0%
2	RRM	19	26	5	38.0%
3	IRM	30	10	10	60.0%
4	DTM	35	0	15	70.0%
5	DPM	42	0	8	84.0%

output does not predict anything
N_r = no. of wrong predictions where the DGA interpretation result is not equal to the actual result.

Scattering of all the fifty points of the DGA worksheet on the Duval triangle and Duval pentagon is represented in Fig. 4 and Fig. 5, respectively.

Fig. 6 shows the overall accuracy of the various DGA approaches, tabulated in Table XII. Ratio methods have lower accuracies because of their uncertainties in determining the fault. DTM also have low accuracy as it cannot distinguish between the normal and the fault state, thus making the DPM the superior interpretation technique among all the other techniques in detecting the fault [4].

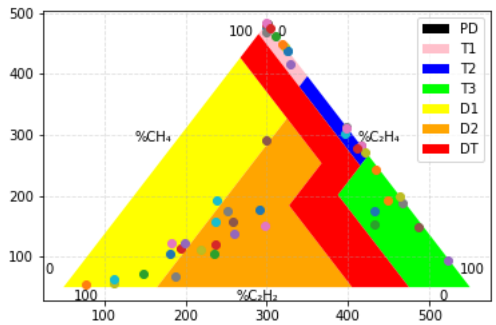

Fig. 4. Duval triangle representing all the points

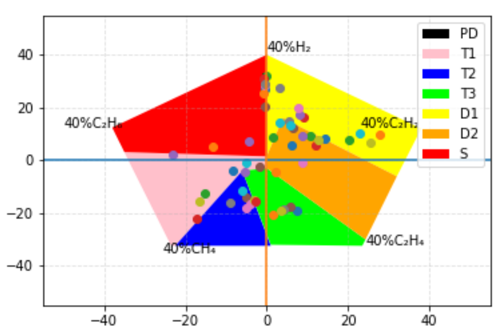

Fig. 5. Duval pentagon representing all the points

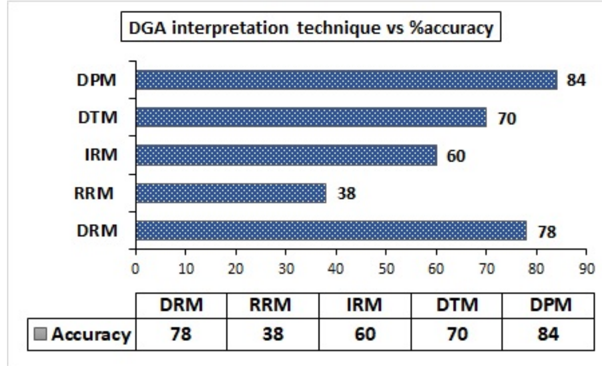

Fig. 6. %accuracy of DGA interpretation techniques

VI. CONCLUSION

In summary, the outcomes demonstrate that the DPM provided appreciative overall accuracy, i.e. 84%. DPM was created to deal with challenges that DTM could not solve. In addition to producing the best accuracy rate, the DPM offered a stray gas zone to describe the transformers' insulation system's typical ageing state. This report also discussed the benefits and drawbacks of every unique DGA interpretation technique. In conclusion, the DGA interpretation using the DPM is a relatively modern technique that holds a lot of potential because it not only offers the best overall accuracy but also offers the highest accuracy for identifying each issue separately, i.e. 75%, 81.16%, & 91.66% in PD, thermal & discharge faults, respectively. However, DGA requires validation. Therefore it requires additional data from the field to enhance the interpretation's accuracy when considering both a defect and natural ageing of the transformers' insulation.

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