Application of Dissolved Gas Analysis for Fault Identification in Natural Ester Filled Power Transformers: A Case Study

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SUMMARY

Mineral insulating liquids are used in the power transformers for cooling as well as for insulation. Sustainable alternatives for mineral oils are natural and synthetic ester fluids, which are widely used in power transformers and distribution systems. Ester based fluids are significantly increased in global energy sector as they offers sustainable, biodegradable and safer alternative of mineral oil. Also, natural esters offers better thermal performance and overload capacity for a transformer due to its characteristic properties. Condition monitoring of power transformers is regular process adopted by utilities. One of the important test for condition monitoring of transformers is Dissolved Gas Analysis (DGA) of insulating oil. DGA is carried out to verify healthiness of transformers as well as condition of insulation.

DGA of insulating oil is one of the most powerful tool for assessing the condition of transformer with mineral oil. Various techniques for interpretation of DGA data have been developed, such as Key gas method, Doernenburg Ratio method, Rogers Ratio method, IEC Gas Ratio method, Duval Triangle and Pentagon methods as mentioned in IEEE C57-104 and IEC 60599 standards. These techniques have been developed specifically for mineral oils using data and knowledge gathered through experience of several years. Fault identification based on DGA data using above techniques require use of multiple interpretation methods (e.g. Duval Triangle, Pentagon, etc.) depending on type of fault. Hence, interpretations of DGA results also largely depends on the expertise of the person diagnosing the fault.

For transformers with ester based fluids these interpretation methods are still under the process of research. Applicability of DGA methods developed for mineral oil for interpretation of faults in ester oil filled transformer require more data, experience and laboratory studies. Therefore, it is critical to investigate each fault in ester oil filled transformer to generate required knowledge and data for maintenance and diagnostic of ester oil based transformer.

This paper investigates the premature failure of a 15 MVA, 66/11 kV natural ester filled power transformer. Within one year in service, the transformer tripped with activation of Buchholz,

differential, and main Pressure Relief Valve (PRV) trip. DGA performed as per IEC 60567, used to diagnose the fault. The study explores the applicability of standard mineral oil DGA interpretation techniques to natural ester, demonstrating their ability to correctly identify high-energy electrical discharges, a finding subsequently confirmed through further investigation of failed transformer.

KEYWORDS

Power transformer, Dissolved Gas Analysis, Natural ester, Electrical fault, Duval triangle, Pentagon

1. INTRODUCTION

In a liquid filled transformer, the insulating liquid plays the role of insulation, heat dissipation and also, protection of the transformer by providing early indications of fault. More sustainable alternatives for mineral oils like ester based natural and synthetic ester, are widely used in power transformers and distribution systems. These ester based fluids are increasingly getting used in transformer applications where less flammable and environmental friendly atmosphere is desirable [1-3]. For mineral oil transformers, DGA is one of the proven and most widely used method for fault identification with proven standard methods of interpretations [4]. During fault conditions, ester based fluids generate similar gases to that of mineral oils, but their proportions vary. Ester fluids being more stray gassing than mineral oil, it is also important to distinguish between stray gassing and any of the severe faults.

DGA interpretation methods of mineral oil is supported by a large number of data-base, but for ester fluids a few such cases are available because these oils have been used only recently and in relatively small number of transformers. The interpretation of DGA results for ester fluids are still under the process of standardization with more and more data bases and laboratory generated fault conditions. Studies where thermal and electrical faults are stimulated in the laboratory indicate that the gas formation patterns are basically the same in mineral and ester fluids. This paper investigates the DGA data of a failed transformer by applying the data in all the available interpretation methods on mineral oil transformers to check its applicability. More and more such actual failure cases with different fault types will contribute for the DGA standardisation process of ester filled transformers.

2. STANDARD DGA INTERPRETATION METHODS OF MINERAL OIL FILLED TRANSORMERS

There are several methods for interpretation of DGA data in which few are based on concentrations of gases while others use ratios of gases. The notations for ratios of gases, which are used, in this paper are given in Table (I). The different fault identification methods are discussed in following sections.

Table (I): Notations for Gas Ratios

R1	R2	R3	R4	R5
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

2.1 KEY GAS METHOD

Every fault in the transformer generates particular gas, which gets dissolved in the oil. The Key Gas method is based on quantity of gases generated, which are due to varying thermal and electrical stress on insulating oil. The particular gases corresponding to the four types of faults are shown in Table (II) [4]. The typical proportion of key gases with other combustible gases is also to be considered to generate more confidence in fault diagnosis.

Table (II): Gases for particular Fault type [4]

Key Gas	**Fault Type**
Ethylene (C_2H_4)	Thermal - Oil
Carbon-Monoxide (CO)	Thermal - Oil and Cellulose
Hydrogen (H_2)	Electrical - Low energy Partial Discharge (PD)
Hydrogen and Acetylene (H_2, C_2H_2)	Electrical - High Energy (Arcing)

2.2 DOERNENBURG RATIO METHOD

This is one of the historic methods [5]. This method utilizes ratios R1, R2, R3 and R4 as shown in Table (I). The Doernenburg method suggests the existence of three general fault types. This procedure requires significant levels of the gases to be present for the diagnosis to be valid. The values for these gases are first compared to specific concentrations as shown in Table (III), to ascertain whether there is really a problem with the unit and then whether there is sufficient generation of each gas for the ratio analysis to be applicable. Out of the four gases H_2, CH_4, C_2H_2 and C_2H_4, if at least one of the gas exceeds twice the value for the limit values given in table (III) and one of the other two gases exceeds the limit value then the unit is considered as containing fault. Further to fulfil this criteria, next step is to determine the ratios. Each successive ratio is compared to the values obtained from Table (IV) in the order R1, R2, R3 and R4. If all succeeding ratios for a specific fault type fall within the values given in Table (IV), the suggested diagnosis is valid. Otherwise, the ratios are not significant, and the unit should be resampled and investigated by alternative procedures [4].

Table (III): The Limit values of Dissolved Gases [4]

Gases	**Concentration (ppm)**
H_2	100
CH_4	120
CO	350
C_2H_2	1
C_2H_4	50
C_2H_6	65

Table (IV): Doernenburg Ratios for key Gases [4]

Suggested Fault diagnosis	**Ratio 1 (R1) CH_4/H_2**	**Ratio 2 (R2) C_2H_2/C_2H_4**	**Ratio 3 (R3) C_2H_2/CH_4**	**Ratio 4 (R4) C_2H_6/C_2H_2**
	Extracted from		Extracted from	
	Oil	Gas space	Oil	Gas space
Thermal decomposition	>1.0	>0.1	<0.75	<1.0
Partial discharge	<0.1	<0.01	Not significant	<0.3
Arcing	>0.1 to <1.0	>0.01 to <0.1	>0.75	>1.0

2.3 ROGERS RATIO METHOD

The Rogers Ratio method is also used in same way as Doernenburg Ratio method, but instead of having significant concentration levels of the key gases, the Rogers Ratio method is used when the concentrations exceed the values listed in Table (III), rather than doubles. This method uses three gas ratios R1, R2 & R5 indicating five different types (cases) of faults, depending on the values of the ratios in column 2 through column 4 of Table (V) [4].

Table (V): Rogers Ratios Method [4]

Case	Ratio 2 (R2) C_2H_2/C_2H_4	Ratio 1 (R1) CH_4/H_2	Ratio 5 (R5) C_2H_4/C_2H_6	Suggested fault diagnosis
0	<0.1	>0.1 to <1.0	<1.0	Unit normal
1	<0.1	<0.1	<1.0	Low energy density Arcing
2	0.1 to 3.0	0.1 to 1.0	>3.0	Arcing-High energy discharge
3	<0.1	>0.1 to <1.0	1.0 to 3.0	Low temperature thermal fault
4	<0.1	>1.0	1.0 to 3.0	Thermal fault < 700 °C

2.4 IEC 60599 BASIC GAS RATIO METHOD

This method also uses the same three gas ratios R1, R2 & R5 as Rogers Ratio method, but suggests different ratio ranges and interpretations as shown in Table (VI) [6]. Graphical representation of ratios is done as shown in Figure 1.

Table (VI): IEC 60599 Basic gas Ratios Method [6]

Notation for Fault	Fault Description	Ratio 2 (R2) C_2H_2/C_2H_4	Ratio 1 (R1) CH_4/H_2	Ratio 5 (R5) C_2H_4/C_2H_6
PD	Partial discharges	NS	<0.1	<0.2
D1	Discharges of Low energy	>1	0.1-0.5	>1
D2	Discharges of High energy	0.6 to 2.5	0.1 to 1.0	>2
T1	Thermal fault T< 300 °C	NS	>1 but NS	<1
T2	Thermal fault 300°C<T< 700°C	<0.1	>1	1-4
T3	Thermal fault T>700 °C	<0.2	>1	>4
NS = Non-significant whatever the value.				

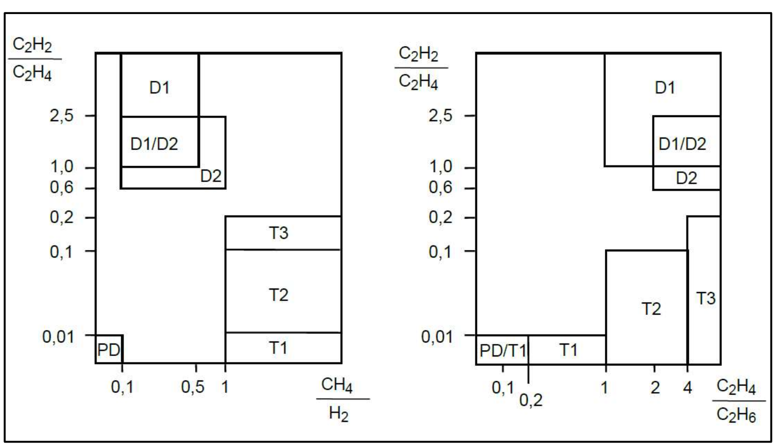
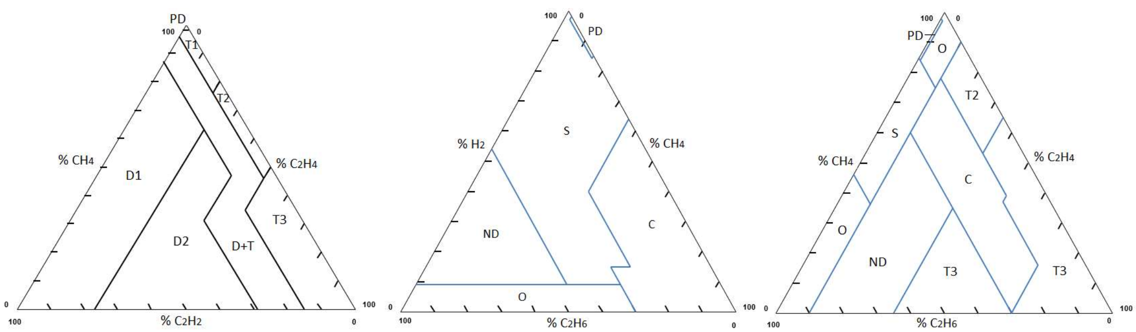


Figure 1. Graphical Representation of IEC 60599 Gas Ratios

2.5 DUVAL TRIANGLE METHOD

The Duval Triangle method was developed from IEC TC10 databases and an existing IEC 60599 Ratio method. Duval Triangle 1 uses three gases corresponding to the increasing energy content or temperature of faults. Methane (CH_4) for low energy/temperature faults, Ethylene (C_2H_4) for high temperature faults and Acetylene (C_2H_2) for very high energy/temperature/arcing faults. On each side of the triangle are plotted the relative percentage of these three gases, as shown in Figure 2. Duval Triangle 1 allows identification of 6 basic types of faults T3, T2, T1, D2, D1 and PD plus mixtures of electrical/thermal faults in zone D+T [1] [6]. When low energy or low temperature faults are identified using Triangle 1 (PD, T1 or T2), more information can be obtained on these faults with Duval Triangle 4 (Refer Figure 2), allowing to distinguish between faults S, O, PD which are of relatively minor concern in transformers, and potentially more dangerous fault C.

When high or very high temperature faults are identified using Duval Triangle 1 (T2 or T3), more information can be obtained on these faults with Triangle 5 (Refer Figure 2), allowing to distinguish between high temperature faults T3 or T2 in oil only of lesser concern in transformers, and potentially more dangerous fault C involving possible carbonization of paper.

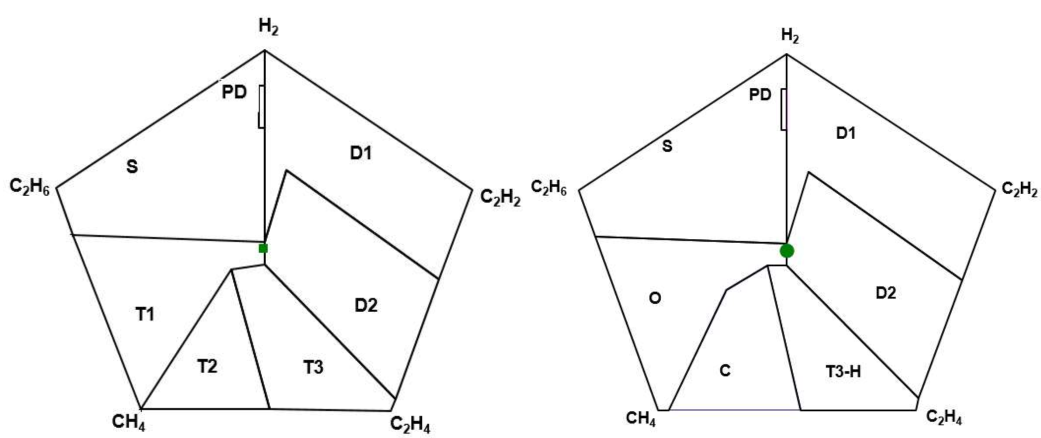


(a) (b) (c)

Figure 2. (a) Duval Triangle 1 Method (b) Duval Triangle 4 Method for low temperature faults (c) Duval Triangle 5 Method for low temperature faults [7]

2.6 DUVAL PENTAGON METHOD

By representing the relative contributions of the five hydrocarbons within the pentagon and finding its geometric centroid, the original Duval Pentagon is established. To define the fault zones within the Pentagon, this method is applied to numerous real DGA samples.



(a) (b)

Figure 3. (a) Duval Pentagon 1 Method (b) Duval Pentagon 2 Method [7]

Within the Pentagon, six main fault zones are outlined: PD (corona partial discharges), D1 (low energy electrical discharges), D2 (high energy electrical discharges), T3 (high temperature phenomena above 700 ºC), T2 (high temperature phenomena between 300 and 700 ºC), and T1 (overheating below 300 ºC). Additionally, the analysis allows for the identification of stray gassing mineral oils or oils that produce combustible gases under thermal stresses. These gases may not necessarily be associated with electrical or thermal faults in the active part or main conductors of the transformer, but they fall under the "S" fault zones.

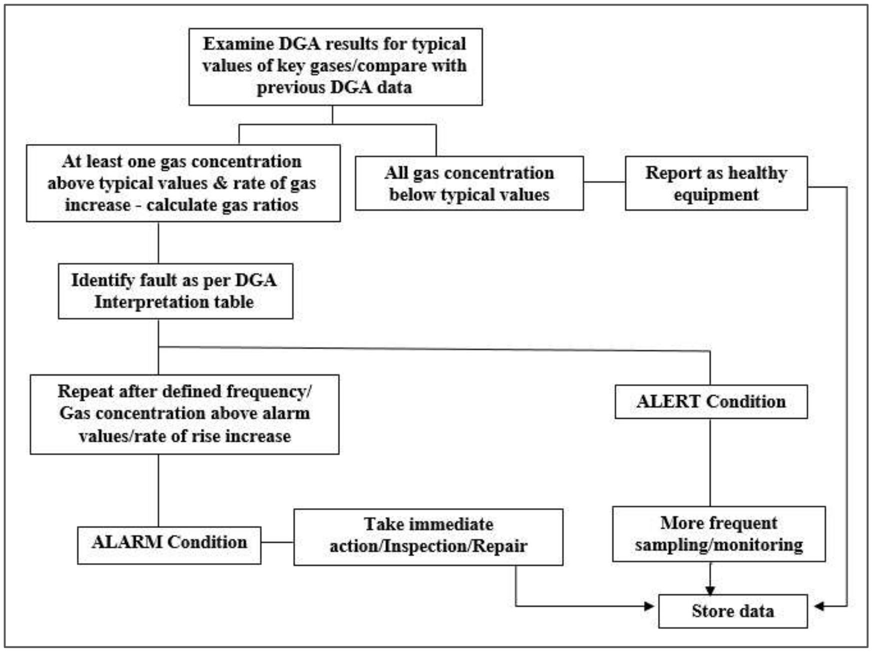


Figure 4. Flow chart for DGA data interpretation [6]

3. CASE STUDY – DGA DATA INTERPRETATION FOR FAULT DIAGNOSIS

The case under study is of a 20 MVA, 66/11 kV natural ester filled power transformer. Within one year of commissioning, the transformer tripped with Buchholz, differential and main PRV. DGA carried out as per IEC 60567 headspace method. DGA historical data are as shown in Table VII.

Table (VII): Dissolved Gas Analysis data

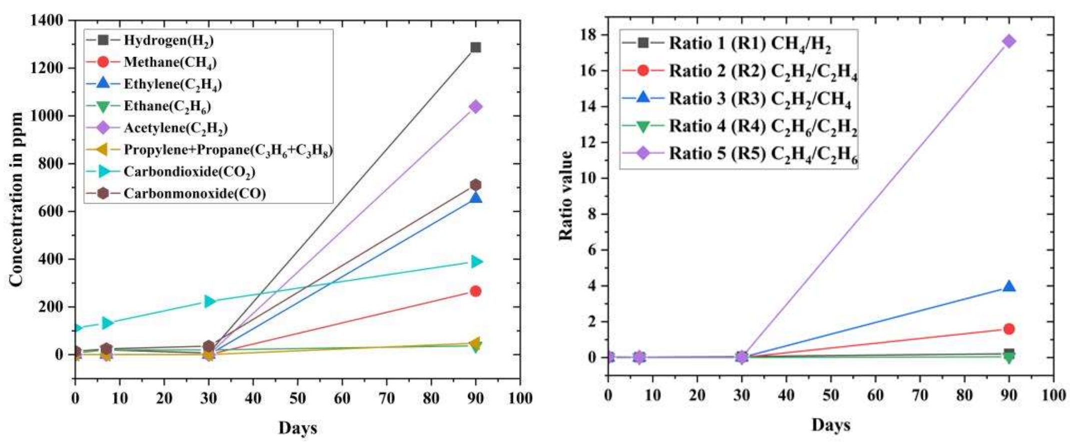
Type of Gases	Initial	After 7 days	After 30 days	After 90 days
Hydrogen (H_2)	7	20	7	1287
Methane (CH_4)	0.23	0.46	0.43	266
Ethylene (C_2H_4)	0.32	0.44	0.38	653
Ethane (C_2H_6)	7	20	20	37
Acetylene (C_2H_2)	NIL	NIL	NIL	1039
Propylene + Propane ($C_3H_6 + C_3H_8$)	0.47	0.24	0.48	48
Carbon dioxide (CO_2)	112	132	223	390
Carbon monoxide (CO)	14	25	36	711

Go to Main Section

For DGA data analysis, all the standard interpretation methods available for mineral oil transformer is applied to this case if ester filled transformer. The gas concentrations (in ppm) and also, ratios of gases with respect to duration are plotted in Figure 5 (a & b). The generation of all the four key gases Ethylene (C_2H_4), Hydrogen (H_2), Acetylene (C_2H_2) and Carbon Monoxide (CO) in higher concentrations satisfies the fault indication by Key Gas Method.

Table (VIII): Ratios of the case under study

Ratios	Initial	After 7 days	After 30 days	After 90 days
Ratio 1 (R1) CH_4/H_2	0.03	0.02	0.06	0.21
Ratio 2 (R2) C_2H_2/C_2H_4	0	0	0	1.59
Ratio 3 (R3) C_2H_2/CH_4	0	0	0	3.91
Ratio 4 (R4) C_2H_6/C_2H_2	NS	NS	NS	0.04
Ratio 5 (R5) C_2H_4/C_2H_6	0.05	0.022	0.02	17.65



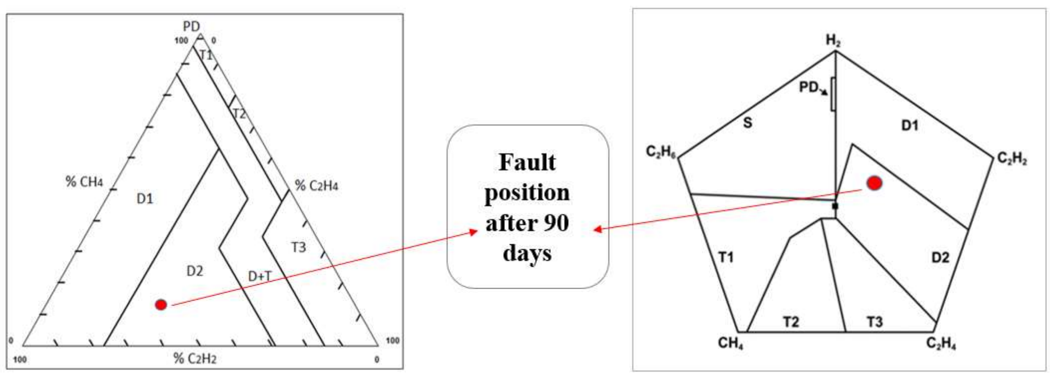
(a) (b)

Figure 5. (a) Dissolved Gas Concentrations as a function of duration (b) Ratios as a function of duration

Table (IX): Fault diagnosis as per various diagnostic methods

	Ratio 1 (R1) CH_4/H_2	Ratio 2 (R2) C_2H_2/C_2H_4	Ratio 3 (R3) C_2H_2/CH_4	Ratio 4 (R4) C_2H_6/C_2H_2	Ratio 5 (R5) C_2H_4/C_2H_6
Fault type-Electrical	Recommended values for Fault type				
Doernenburg method - Arcing	>0.1 to <1.0	>0.75	>0.3	<0.4	NA
Rogers method - Arcing-High energy discharge	0.1 to 1.0	0.1 to 3.0	NA	NA	>3.0
IEC - Discharges of High energy	0.1 to 1.0	0.6 to 2.5	NA	NA	>2
	Observed values for ratios				
	0.21	1.59	3.91	0.04	17.65
NA = Not Applicable					

The DGA data after 90 days of commissioning are compared to the specific limit concentrations in Table (III), to ascertain sufficient generation of each gas for the ratio analysis to be applicable. All the gas concentrations in ppm for H_2, CH_4, C_2H_2 and C_2H_4 exceeds twice the value of the limit values for ratio methods to be applicable. Combinations of all the concerned ratios are compared to that of each methods of interpretation as shown in Table IX. Ratios R1, R2, R3 & R4 of Doernenburg method indicates Arcing. As per Rogers method, the ratios R1, R2 & R5 indicates Arcing-High energy discharge. Also, IEC 60599 ratio method indicated Discharges of High energy. In Duval Triangle and Pentagon also, the fault position got identified as D2, Discharges of High Energy as shown in Figure 5 (a & b). As in Figure 6, the graphical representation of IEC 60599 Gas Ratio indicates fault position as D1/D2, i.e., Discharges of low/high energy. All these methods indicated high energy electrical discharges for this particular case. Afterwards, the utility personnel also confirmed the fault type observed in the transformer under study as 'Arcing' with visible carbon particles and the transformer was declared as failed.



(a) (b)

Figure 6. Graphical representation of (a) Duval's Triangle 1 and (b) Pentagon 1 showing high energy Electrical fault of the case under study

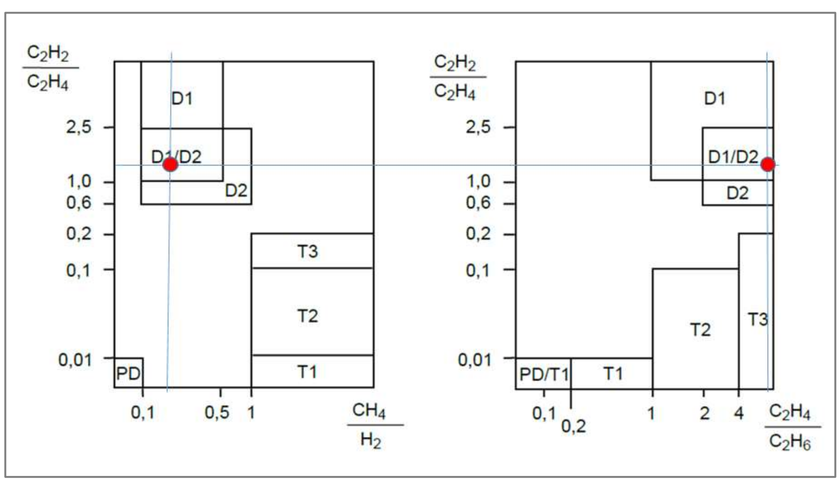


Figure 7. Graphical representation of IEC 60599 Gas Ratio of the case under study

Table (X): Rate of Rise in gas ratios for Electrical Discharges

Ratio 1 (R1) CH_4/H_2	Not Significant
Ratio 2 (R2) C_2H_2/C_2H_4	Significant
Ratio 3 (R3) C_2H_2/CH_4	More Significant
Ratio 4 (R4) C_2H_6/C_2H_2	Not Significant
Ratio 5 (R5) C_2H_4/C_2H_6	Most Significant

As seen in Figure 5 (a), the rate of rise in gases such as, Hydrogen, Acetylene, Ethylene and Carbon monoxide is maximum in the case of electrical fault which is similar to that of mineral oil filled transformers. Apart from the standard fault diagnosis methods, rate of rise of ratios have also been evaluated, and found that the rate of rise in the case of R2, R3 and R5 is most significant for electrical discharges as shown in Figure 5 (b) and Table (X).

4. CONCLUSION

In this paper, transformer condition monitoring has been analysed for fault diagnosis for a 10 MVA, 66/11 kV ester insulated power transformer using all the six DGA interpretation methods i.e., Key Gas, Doernenburg ratio, Rogers ratio, IEC 60599 Basic Gas Ratio, Duval Triangle and Pentagon Methods, which are commonly getting used for mineral oil insulated transformers. It is confirmed that just like mineral oil, for natural ester also the key gas generated during electrical discharge is Acetylene along with Hydrogen, Ethylene and Carbon Monoxide. It is concluded that the same fault gases are generated for ester filled transformers also, but there concentrations vary under similar conditions due to chemical structure changes in both the types. In this particular case, fault type got identified using existing standard methods. More and more such actual data and laboratory studies are required for all fault categories for a common interpretation method irrespective of the oil type to be developed.

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