National Conference on Emerging Trends in Computer, Electrical & Electronics (ETCEE-2015)
International Journal of Advance Engineering and Research Development (IJAERD)
e-ISSN: 2348 - 4470 , print-ISSN:2348-6406,Impact Factor:3.134

Condition Monitoring of Power Transformer Using Dissolved Gas Analysis of Mineral Oil: A Review

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***Abstract*—Condition Monitoring plays a vital role in asset management plan. Power Transformers are most important and critical component in electrical power transmission and distribution. To have a reliable electricity supply it is necessary to give considerable attention to maintenance of the transformer. To maximize the lifetime and reliability of transformers, it is important to be aware of possible faults that may occur and to know how to prevent them. Since a fault in a transformer can have a huge repercussion when failures occur, and as, number of transformers and of those that are difficult to operate in overload conditions is on the rise, it is important to detect incipient faults in a transformer and forecast and prevent failures These faults can all lead to the thermal degradation of the oil and paper insulation in the transformer. The composition and quantity of the gases generated depend on the types and severity of the faults, and regular monitoring and maintenance can make it possible to detect incipient flaws before damage occurs. Any failure in transformer leads to malfunction of whole power system. Unfortunately, the failure rate of these transformers is very high in India, 25 % per annum, which is not favourable as compared to international units of 1-2 %. Failures happen due to internal reasons or operational hazardless. Transformer insulation deteriorates as the function of temperature, moisture and time. The core and winding losses, stray losses in tank and metal support structures are the principle sources of heat which cause oil and winding temperature rise. There are multiple reasons for overheating such as improper cooling, excessive eddy currents, bad joints, blocked radiators, overloading, improper earthing and harmonic contents in power supply. This leads to accelerated aging of oil and cellulosic solid insulation, which generate the gases within transformer and further leads to permanent failure. To prevent such failures, effective analysis and diagnosis needs to be investigated. The type of gases generated and amount of gas concentrations in oil efficiently evaluated using Dissolved Gas analysis (DGA).Generally the degradation products are gases, which will get dissolve in the oil entirely or partially. In the oil these gases are easily detected at the ppm level by dissolved gas analysis.**

Dissolved gas analysis (DGA) is a widely used most powerful method to detect incipient faults on oil filled electrical equipment. The electrical equipment may be a transformer, a load tap changer or a cable

Dissolved Gas Analysis (DGA) of transformer oil is the best indicator of a transformer's overall condition. Hence this widely accepted method is used in routine maintenance of power Transformers. Transformer oils perform at least four functions for the transformer. Oil provides insulation, provides cooling, and helps extinguish arcs. Oil also dissolves the gases which are generated due to degradation of oil, moisture and gas from insulation, deterioration of cellulose, and gases and moisture from the surrounding the oil is exposed to. Any deterioration in the oil can lead to premature failure of the equipment. The most common type of oil used in transformers is of a mineral oil origin.

***Keywords*—**Condition Monitoring, Power Transformer, Dissolved Gas Analysis (DGA), Fault Types, Key Gas Method, Duval's Triangle Method, IEC Gas Ratio Method, Roger's Ratio Method, Dornenburg Method, CIGRE method.

I. INTRODUCTION

Power transformers in utilities are highly valued items and take a long time to replace. They are normally operated 24/7 and difficult to take out of service due to power system constraints. It is vital to monitor their condition throughout operation. Power system operational and maintenance procedures for power transformers include monitoring, evaluation and remedial measures.

When the mineral oil is subjected to high thermal and electrical stresses, it decomposes and, as a result, gases are generated. Different types of faults will generate different gases, and the chemical analysis of these gases, performed through a procedure called DGA (Dissolved Gas Analysis), will provide useful information about the condition of the oil, and help to identify the type of fault in the transformer. Analysis (DGA) is proved accuracy method all over the world for condition assessment of power transformer. Taking the concentration of key gases (CO, CO_2, H_2, C_2H_6, C_2H_4, C_2H_2 and CH_4) incident faults identified by various classical techniques gives different conditions for the same sample unit in this work, the condition based diagnosis system developed to combine five DGA classical methods-Keys Gas Method, Rogers Ratio Method, IEC Ratio method, Dornenburg ratio method and Duval triangle method. DGA helps to diagnosis the present condition of the high voltage power transformer. Further, this method is also applicable to other oil filled high voltage power equipment for assessment of its condition during the operating service period of time.

Fault gases are produced by degradation of the transformer oil and solid insulating materials such as paper, pressboard and transformer board, which are all made of cellulose. The rate of cellulose and oil degradation is significantly increased in the presence of a fault inside the transformer

Transformer oil is mainly composed of the saturated hydrocarbons known as paraffin, generally there are two types of Transformer Oils i.e. Paraffinic Transformer oil and Naphthenic Transformer oil. In our country generally Paraffin Transformer oil is used. Difference between these two types of transformer oil is naphtha oil is more easily oxidised than the other. But due to the oxidation the sludge formed gets easily dissolved than paraffinic oil. Another disadvantage of paraffinic oil is that it has high value of pour point due to wax content but this does not affect its use in India because of its warm climatic condition.

II. GAS INTERPRETATION ANALYSIS

The main two causes of gas formation within an operating transformer are electrical and thermal degradations.

I. Thermal Faults:-

The decomposition of mineral oil from 150°C to 500°C generates low molecular weight gases, such as methane (CH_4), hydrogen (H_2) and low quantity of higher molecular weight gases like ethane (C_2H_6), ethylene (C_2H_4) [18]. If decomposition of mineral oil increases more than 500°C generates large quantity of acetylene (C_2H_2). In case of thermal decomposition of paper insulation and other solid insulation produces carbon dioxide (CO_2), carbon monoxide (CO) [11].

II. Electrical Faults:-

Two type of electrical faults are considered;

1. Corona or Partial Discharge.
2. Arcing (High Energy Discharge)

These faults mainly depend on intensity of energy dissipated per unit time per unit volume by the fault. Among all faults, most severe fault is arcing by developing acetylene and less severity fault is corona by producing large quantity of Hydrogen and Methane but if less severity fault was not correct, it leads to Arcing [14].

1. Corona or Partial Discharge:-

- ✓ Partial Discharge means "The dielectric breakdown of some part of solid (or) liquid when impressed by high voltage". Here when the mineral oil of transformer is stressed by high voltage leads to production of several gases, discharges of cold plasma, bubbles (or) voids and with possible formation of X wax in paper [12].
- ✓ The approximate percentage of gases among all dissolved gases when partial discharge occurs is H_2=85%-90%, CO_2=1%-2%, CO=0.5%-1%, CH_4=6%-10%, C_2H_6=6%-8% and very low quantities of ethylene and acetylene. Hence, during partial discharge occurred in oil leads to develop H_2 gas and in during partial discharge occurred in oil leads to develop H_2 gas and in cellulose is produce carbon oxides including H_2.

2. Arcing:-

- ✓ Arcing in generally means "the electrical breakdown of a gas that developing ongoing plasma discharges, resulting current through normally non-conductive medium such as air" [18]. But in case of transformer severe energy dissipation occurs during arcing and it produces gases in the percentages approximately H_2=35%-40%, C_2H_2=35%-50% and remaining gases in very low volume.
- ✓ In any fault associated with paper, produce gases like CO_2 and CO in very large quantity approximately 85%-90%.

III. GAS GENERATION IN MINERAL OIL OF POWER TRANSFORMER

The cause of gas generation is the breaking of the chemical bonds between the atoms that make up the hydrocarbon molecules of the mineral oil. The faults in the transformer produce the energy that is needed for breaking the chemical bonds. The gases generated include hydrogen (H_2), methane (CH_4), ethane (C_2H_6), Ethylene (C_2H_4), acetylene (C_2H_2), carbon dioxide (CO_2) and carbon monoxide (CO). The chemical structure of these gases is shown in Figure. 1

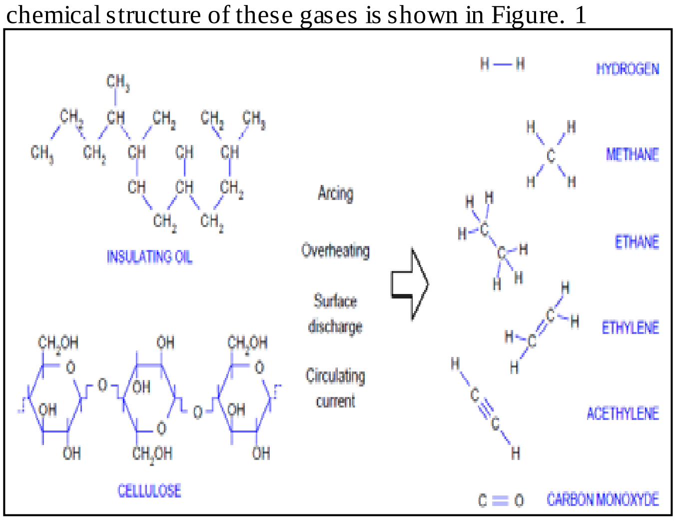

Fig. 1 Gas Production during particular faults [7]

These gases, when generated, will initially dissolve in the oil. As more gases are generated, more will dissolve in the oil.

However, there will come a point when the oil will be totally saturated with dissolved gas, and further generation of gases will result in their being released as they can no longer be dissolved by the oil. Lower amounts of energy or lower temperatures are required to create or break the C-H molecular bonds. Higher amounts of energy or higher temperatures are needed, to create, or break, in ascending order, C-C single bonds, C=C double bonds, and C≡C triple bonds. Methane and ethane will form at lower temperatures because of the single bond (C-H and C-C). Ethylene gas will form at higher temperatures of more than 500° C because of the double bond(C=C). Even higher temperatures, of at least 800° C to 1200° C, are required for the formation of acetylene gas because it has a triple bond (C≡C).

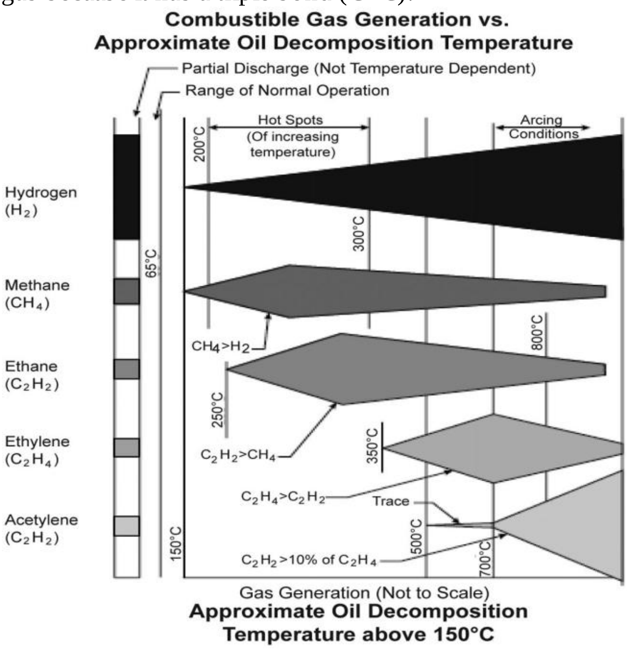

Fig. 2 Gas interpretation chart [21-22]

All of the gases are formed because of the degradation of the oil itself except carbon monoxide and oxygen, Carbon monoxide, carbon dioxide (CO_2), and oxygen are formed from degradation of paper insulation which is made up of cellulose. Carbon dioxide, oxygen, nitrogen (N_2) and moisture can also be absorbed from the air if somehow oil is in contact with atmospheric air which may happen due to leakage in the tank of transformer.

IV. NORMAL AND ACTION VALUES OF DISSOLVED GASES

When mineral oil contains normal values of dissolved gas, it indicates no incipient fault in the transformer. As the value exceeds the normal limit, sample frequency should be increased because exceeding the normal limit indicates some small kind of faults inside the transformer before the fault becomes critical some supplementary actions have to be taken so as to avoid critical faults of other equipment.

As the value exceeds the action limit, that means some critical situation has arrived and removal of transformer from service should be considered [10].

The table for the different limits is derived from information provided within ANSI/IEEE C57.104 [1].The normal and action limits of dissolved gases in the oil are given below in Table 1

TABLE I
NORMAL AND ACTION LIMITS OF DISSOLVED GASES [10]

Gas	Normal Limits (PPM)	Action Limits (PPM)
Hydrogen(H_2)	150	1000
Methane(CH_4)	25	80
Ethylene(C_2H_4)	20	150
Acetylene(C_2H_2)	15	70
Ethane(C_2H_6)	10	35
Carbon Dioxide(CO_2)	10000	15000
Carbon Monoxide(CO)	500	1000

It is the useful informative method for the detection of incipient faults and most used method now a day. DGA involves following steps. The DGA technique detects gas in parts per million (ppm) dissolved oil by the use of gas extraction unit and a gas chromatograph. The DGA analysis is performed in three steps:

1. Collection of Oil sample
2. Extraction of gases from the oil
3. Detection of gases

The following are the advantages of DGA [14].

- ✓ Advance warning of developing of faults.
- ✓ Status check on new and aged mineral oil.
- ✓ Convenient online scheduling of repairs
- ✓ Identifies degradation level before it leads to failure.
- ✓ Monitoring of units under overload case.
- ✓ Checking the improper use of units.

V. DGA DIAGNOSE METHODS

Different types of DGA methods have been implemented in order to determine the fault in a transformer which are analysed as follows;

- ✓ IEC Gas Ratio Method or Basic Gas ratio Method

- ✓ CO_2/CO Method
- ✓ Key Gas Method
    - Overheating of Oil.
    - Overheating of Cellulose.
    - Corona
    - Arcing
- ✓ Rogers Ratio Method
- ✓ Duval Triangle Method
- ✓ Dornenburg Ratio Method
- ✓ CIGRE Method

A. IEC Gas Ratio Method

The “Basic Gas ratios” recognized in the International Electro technical Commission (IEC) standards is equivalent to Dornenberg ratios and Rogers ratios in the ANSI/IEEE C57.104.

Three gas ratios are used in DGA methane/hydrogen, acetylene/ethylene, and ethylene/ethane. Faults often start as incipient, low energy faults which may develop into more serious higher energy or higher temperature faults. When a fault is detected, it is important to determine the trend in the rate of increase of the gas. An increase in gas values of more than 10% per month above the normal values will indicate that the fault is active. It is also important to determine the trend in the occurrence of different types of faults, and to detect early, any deterioration towards a more serious fault. Determining the trend in both the rate of increase of the individual gases, and the occurrence of different types of faults, will provide information on the health of the transformer.

The fault diagnosis scheme recommended by the International Electrotechnical Commission (IEC) originated from the Rogers method except that the C_2H_6/CH_4 ratio was dropped since it only indicated a limited temperature range of decomposition. The four detected conditions are normal ageing, partial discharge of low and high energy density, thermal faults and electrical faults of varying severity. However, it does not classify thermal and electrical faults into precise subtypes.

TABLE II
IEC GAS RATIO [3]

Case	Characteristic Faults	C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6
PD	Partial Discharge	NS	<0.1	<0.2
D1	Discharges of low energy	>1	0.1-0.5	>1
D2	Discharges of High Energy	0.6-2.5	0.1-1.0	>2
T1	Thermal Fault	NS	>1	<1
T2	Thermal Fault	<0.1	>1	<1
T3	Thermal Fault	<0.2	>1	>4

NS-No Significance

B. Key Gas Method

The key gas method is mainly depends on the quantity of fault gases release in mineral oil when fault occur. Figure 2 to Figure 5 indicates the key gases and their relative proportions for four fault types. Generally the thermal decomposition of oil produced more than 60% of ethylene (C_2H_2) 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 [11].

THERMAL FAULTS

Thermal Faults in Oil

- ✓ If thermal faults occurred in mineral oil, mainly methane and ethylene gases are released and very less quantity of ethane and hydrogen gases also produced [16].
- ✓ If the fault is severe or involves electrical contacts, small quantity of acetylene gas produced.
- ✓ The main Key gas exists when thermal faults occurred is ethylene (C_2H_4 (63%)). Fig.3 shows approximate relative proportions (%) for each fault gas.

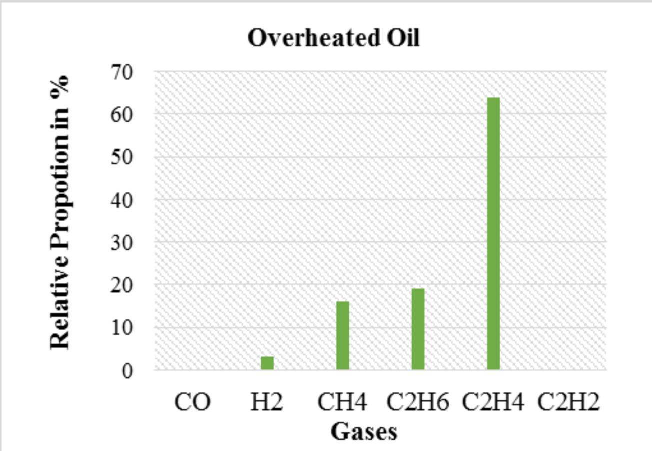

Fig. 3 Approximate percentage (%) of gases found during thermal faults in oil inside the Transformer

Thermal Faults in Cellulose

- ✓ It produced large quantity of carbon monoxide and carbon dioxide.
- ✓ The main key gas is carbon monoxide (CO (92%)).
- ✓ Fig. 4 shows approximate relative proportions (%) for each fault gas. In this case CO Produce more than 90%.

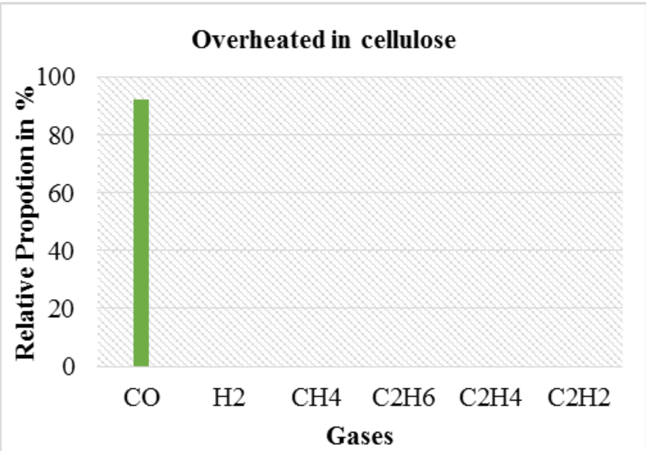

Fig. 4 Approximate percentage (%) of gases found during thermal faults in cellulose inside the Transformer

ELECTRICAL FAULTS:-

Corona:-

- ✓ Due to partial discharge (or) corona in oil, mainly methane and hydrogen gases are produced with less quantity of ethylene and ethane gases.
- ✓ The main key gas produced due to corona in oil is hydrogen (H_2 (85%)).
- ✓ Fig. 5 shows approximate relative proportions (%) for each fault gas in corona.

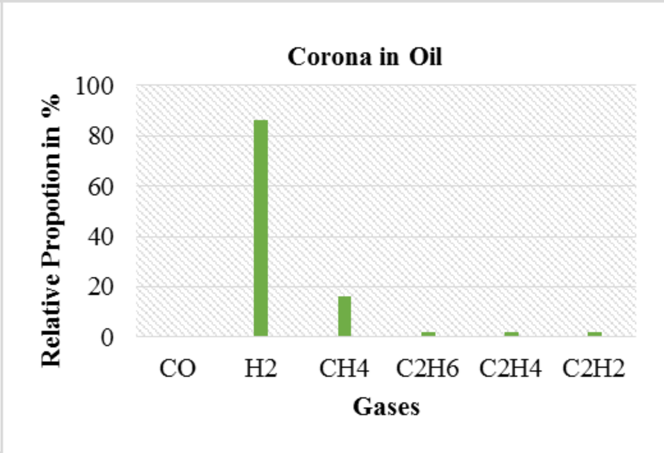

Fig. 5 Approximate percentage (%) of gases found during thermal faults in Corona in oil inside the Transformer

Arcing:-

- ✓ Due to arcing (or) high energy discharge in oil produced mainly acetylene and hydrogen gases.
- ✓ If arcing exists in cellulose releases carbon oxides.
- ✓ The main key gas due to arcing is acetylene (C_2H_2 (30%)) and (H_2 (60%)).
- ✓ Figure 6 shows approximate relative proportions (%) for each fault gas in arcing.

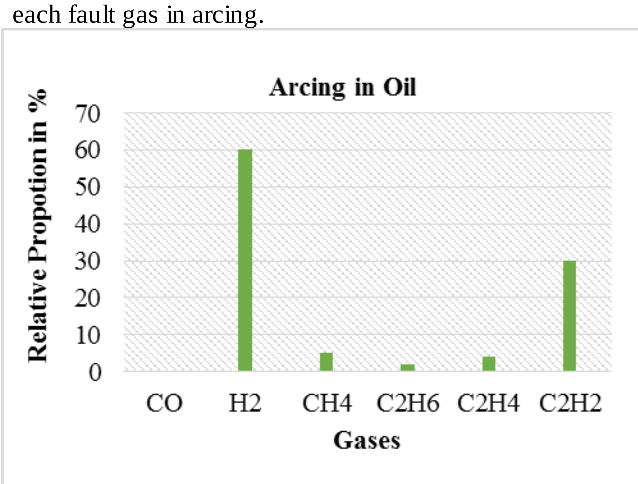

Fig. 6 Approximate percentage (%) of gases found during thermal faults in Arcing in oil inside the Transformer

C. CO_2 / CO Method

- ✓ The ratio of CO_2 / CO is sometimes used as an indicator of the thermal decomposition of cellulose.
- ✓ The rate of generation of CO_2 typically runs 7 to 20 times higher than CO.
- ✓ Therefore, it would be considered normal if the CO_2 / CO ratio were above 7.
- ✓ If the CO_2 / CO ratio is 5 or less, there is probably a problem.
- ✓ If the CO_2 / CO ratio is 3 or under with increased furans it

indicates severe and rapid deterioration of cellulose is occurring and consideration should be given for taking the transformer out of service for further inspection.

D. Dornenburg Ratio Method

For convenient fault diagnosis, gas ratio methods use coding schemes that assign certain combinations of codes to specific fault types. The codes are generated by calculating ratios of gas concentrations and comparing the ratios with predefined values derived by experience and continually modified. A fault condition is detected when a gas combination fits the code for a particular fault. The Dornenburg Ratio method [35] identifies faults by analysing gas concentration ratios such as CH_4/H_2, C_2H_2/CH_4, C_2H_4/C_2H_6 and C_2H_2/C_2H_4, which can be used to identify thermal faults, corona discharge and arcing. This method is based on thermal degradation principles. In this method, the ratio procedure is considered valid if the gas concentrations (in ppm) for H_2, CH_4, C_2H_2, and C_2H_4 exceed twice the value of the fixed limit for each gas and if that for CO and C_2H_6 exceeds thrice the value of the fixed limit. To determine the validity of the four ratios, each successive ratio is then compared with certain values. Finally, if all four succeeding ratios for a specific fault type fall within the predetermined values, the diagnosis is confirmed. This method, which is specified in IEEE Standard C57.104-2008 [1], characterizes dissolved gases of transformer oil. However, the method may obtain numerous "no interpretation," results due to incomplete ratio ranges.

TABLE III
RATIOS FOR KEY GASES IN DORNENBURG METHOD [35]

Suggest Faults Diagnosis	CH_4/H_2	C_2H_2/C_2H_4	C_2H_6/C_2H_2	C_2H_2/CH_4
Thermal Decomposition	>1.0 >0.1	<0.75 <1.0	>0.4 <0.1	<0.3 >0.2
Corona (Low intensity PD)	<0.1 <0.001	NS	>0.4 <0.1	<0.3 >0.2
Arcing (High intensity PD)	>0.1 >0.01	>0.75 >0.1	<0.4 >0.1	>0.3 >0.2

E. Rogers Ratio Method

The most common gas ratio method is the Rogers ratio method [24], which distinguishes more thermal fault types compared to the Dornenburg ratio method [35]. The Rogers method analyses four gas ratios: CH_4/H_2, C_2H_6/CH_4, C_2H_4/C_2H_6 and C_2H_2/C_2H_4. Faults are diagnosed via a simple coding scheme based on ranges of the ratios. The Rogers ratio is a simple scheme based on ranges of ratios used for diagnosing faults. The four detectable conditions of an oil-insulated transformer are normal ageing, partial discharge with or without tracking, and electrical and thermal faults of varying severity. By using these four gas ratios, it diagnosis the faults like normal ageing, winding circulating currents, electrical faults, low energy discharge faults and thermal faults in various ranges(1500^0c-7000^0c) [9]. The main advantage of gas ratio analysis is "it is independent on volume of oil involved and it is only depends on ratios of gases involved" [1].

TABLE IV
ROGERS RATIO METHOD RATIO CODE REPRESENTATION [24]

Sr. No	Gas Ratio	Ratio Codes
1	CH_4/H_2	i
2	C_2H_6/CH_4	j
3	C_2H_4/C_2H_6	k
4	C_2H_2/C_2H_4	l

By using four gas ratios in Table 5, as IEEE Standard C57.104-1991 gives more information to find exact faults [9]. Table 5 indicates the gas ratio codes for Rogers's ratio method and it indicates type of faults occurred. Table 5 shows gas ratios range and codes in 0-5, codes used in Table 5 is only the software implementation purpose of Rogers ratio method and by using gas ratios range in Table 5 different faults conditions are developed. If any fault gases ratio range is beyond ratios shown in Table 5, this method is unable to find Incipient faults status and shows Rogers ratio method is not valid.

TABLE V
ROGERS RATIO CODE REPRESENTATION [24]

Ratio Code	Range	Code
i (CH_4/H_2)	<=0.1 0.1-1.0 >=1.0,<3.0 >=3.0	5 0 1 2
j (C_2H_6/CH_4)	<1.0 >=1.0	0 1

k (C_2H_4/C_2H_6)	<=1.0 >=1.0,<3.0 >=3.0	0 1 2
l(C_2H_2/C_2H_4)	<0.5 >=0.5,<3.0 >=3.0	0 1 2

TABLE VI
TOTAL POSSIBLE DIAGNOSIS FAULTS FOR ROGERS RATIO METHOD [24]

Sr. No	i (CH_4/H_2)	j (C_2H_6/CH_4)	k (C_2H_4/C_2H_6)	l (C_2H_2/C_2H_4)	Diagnoses
1	0 (>0.1,<1.0)	0 (<1.0)	0 (<1.0)	0 (<0.5)	Normal deterioration
2	5 (<=0.1)	0	0	0	Partial discharge
3	1-2	0	0	0	Slight overheating(<150^{0}c)
4	1-2	1 (>=1.0)	0	0	Overheating(150^{0}c-200^{0}c)
5	0	1	0	0	Overheating(200^{0}c-300^{0}c)
6	0	0	1	0	General conductor overheating
7	1	0	1	0	Winding circulating currents
8	1	0	2	0	Core & circulating currents (300^{0}c-700^{0}c)
9	0	0	0	1	Flash over without power follow through
10	0	0	1-2	1-2	Arc with power follow through
11	0	0	2	2	Continuous sparking to floating potential
12	5	0	0	1-2	Partial discharge with tracking

F. CIGRE Method

The CIGRE Method [8] of fault diagnosis analyses key gas ratios and gas concentrations. The five key gas ratios considered in this method are C_2H_2/C_2H_6, H_2/CH_4, C_2H_4/C_2H_6, C_2H_2/H_2 and CO/CO_2. The key gas concentrations are C_2H_2, H_2, the sum of carbon hydrides, CO and CO_2. Suggested ratio ranges and concentration limits were published earlier in [8]. A transformer is considered healthy if separate applications of these methods obtain ratios and concentrations that are below limits. The advantage of this method is that two or more faults can be detected simultaneously. According to CIGRE [8], DGA identifies the fault location as the winding, cleats and leads, the tank, the selector switch, or the core. However, DGA may not reliably predict rapidly occurring instantaneous faults. Instantaneous failures that cannot be prevented by DGA are [8]: (1) flashover with power follow-through, and (2) serious failures that develop too rapidly for detection by DGA.

G. Duval's Triangle Method

The Duval Triangle method; another DGA diagnostic method for oil insulated equipment (mainly transformer) developed by Michael Duval [4] in 1974.In this method concentration (ppm) of methane (CH_4), ethylene (C_2H_4), and acetylene (C_2H_2) are expressed as percentages of the total ($CH_4 + C_2H_4 + C_2H_2$) and plotted as a point (%CH_4, %C_2H_4, %C_2H_2) in a triangular coordinate system on a triangular chart which has been subdivided into fault zones. The fault zone in which the point is located designates the likely fault type which produced that combination of gas concentrations. It is the graphical representation of fault determination is performed focused around visualization of the area of broke down gasses in the triangular map. The main merit of this technique is "it is always diagnosis the faults with low rate of wrong results'' [6]. Figure 6 indicates the Duval Triangle representation of three types of faults such as Thermal Faults in various ranges, low and high energy densities and partial discharge. These three types of faults is categorised into seven zones like D1, D2, T1, T2, T3, PD and DT shown in Table 6 Here there is no region for indicating the normal condition, so careless use of Duval Triangle gives any type fault condition among seven diagnosis incipient faults conditions. The three sides of triangle mentioned in Figure 6 are %CH_4, %C_2H_4, and %C_2H_2 and these values should be within 0 to 100% for each gas [5].

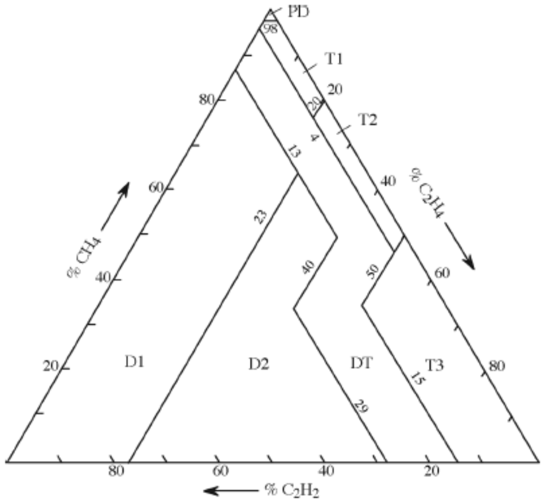

Fig. 6 Duval Triangle Method representation of three types of fault zones

TABLE VII
FAULTS DETECTED BY DGA FOR DUVAL TRIANGLE [19]

Symbol	**Fault**	**Examples**
PD	Partial Discharge	Discharges of the cold plasma (corona) type in gas bubbles or voids, with the possible formation of X-wax in paper
D1	Discharges of low energy	Partial Discharge of the sparking type, including pin holes, carbonized puncture in paper. Low energy arcing inducing carbonized perforation or surface tracking of paper or the formation of carbon particles in oil
D2	Discharges of high energy	Discharges in paper or oil, with power follow-through, resulting in extensive damage to paper or large formation of carbon particles in oil, metal fusion, tripping of the equipment and gas alarms.
T1	Thermal Fault $T<300^0$ C	Evidenced by paper turning brownish($>200^0$ C) or carbonized ($>300^0$ C)
T2	Thermal Fault 300^0 C$<T<700^0$ C	Carbonization of the paper, formation of carbon particle in oil.
T3	Thermal Fault $T>700^0$ C	Extensive formation of carbon particles in oil, metal coloration (800^0 C) Or metal fusion($>1000^0$ C)

V CONCLUSION

Condition monitoring of power transformer is necessary to diagnose its incipient faults so we can come to know the life cycle of power transformer as well how to avoid its premature failure. So till now we have learnt on different techniques of dissolved gas analysis which will help to diagnose different types of gases as well as different types of faults ultimately lead towards to identify and analyse the incipient faults and avoid catastrophic failure of power transformer.

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