Different DGA Techniques for Monitoring of Transformers

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***Abstract*—The DGA(dissolved gas analysis) provides the inside view of transformer. By analyzing the gases we can observer the inner condition of any transformer. Many faults like arcing, overheating, partial discharge can only be detected by analyzing the gases only. In this paper different algorithms used for DGA analysis are described with their principles. This paper focuses on the literature review of different gas analysis techniques. It provides the overview of all techniques with their working methodology.**

***Index Terms*—gas chromatography; key gas analysis; roger's ratio; dornenburg's; duval's triangle; TDCG.**

I. Introduction

Condition monitoring of transformer is a critical and exigency task to lift up the performance and enhance the life of transformer. Condition monitoring of any transformer can only be successful if it is possible to have a early fault detection. The dissolved gas analysis (DGA) of transformers can provide an insight view related to thermal and electrical stresses during operations of oil immersed power transformers [1]. DGA is accustomed to detect elementary faults in the transformer. It is found that the abrupt changes in concentration and ratio of various gases interpret the health of transformer. So to improve the transformer health it is required to continuously monitor all the gases. Gases are necessary to be monitored at every instant as every gas contribute either in some parameter or will be the reason of rise of any other gas. The two stresses could break down insulation materials and release gaseous decomposition products [2], although all oil-filled transformers generate a small quantity of gas, particularly carbon monoxide (CO) and carbon dioxide (CO_2), to some extent at normal operation conditions. Each of these types of faults produces certain gases that are generally combustible. The total of all combustible gases (TCG) with increases of gas generating rates may indicate the existence of any one or a combination of thermal, electrical or corona faults. The rise in acetylene is accompanied by an increase in hydrogen gas and rather most modest increase in levels of other hydrocarbon gases. Such type of DGA signature is typical of arcing/sparking, overheating and partial discharge fault in the main tank of a power transformer. Certain combinations of each of separate gases, called key gases. These combinations are unique for different fault temperatures and the ratios of certain key gas concentrations are indicative to fault types.

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II. Methods of Measuring Concentration in Gas

A. Photo Acoustic Spectroscopy

1) Oil sample injected into oil sample container.

2) Oil stirred with magnetic stirrers

3) Gases released circulate through the sampling loop.

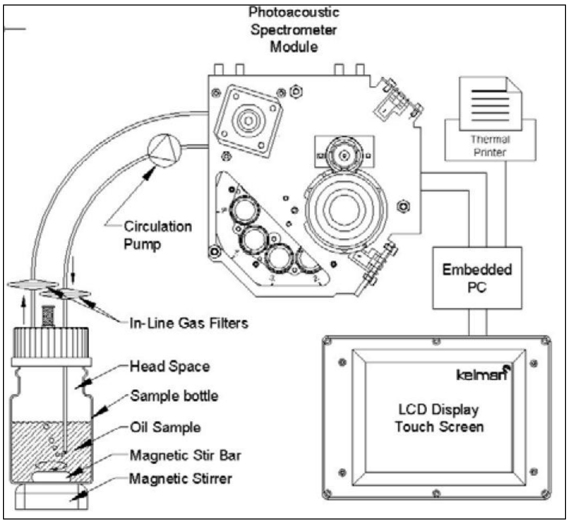

Figure 1. Photo acoustic spectroscopy

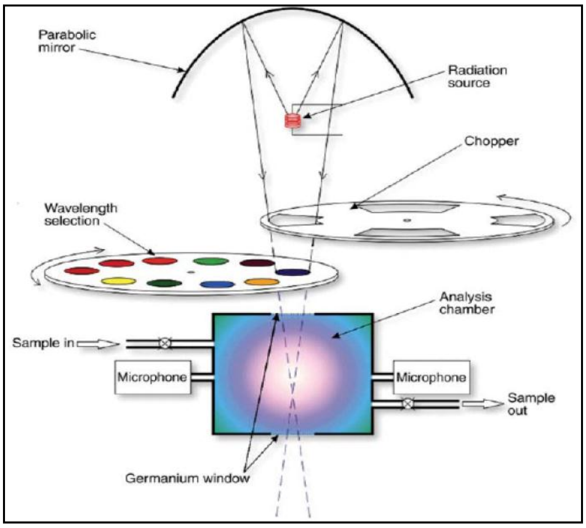

Figure 2. Principle of acoustic spectroscopy

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To use this instrument an oil sample must initially be drawn from the transformer using a syringe. The oil is then injected into the instrument's measurement container from the syringe as shown in Fig. 1. Teflon coated magnets contained within the container then proceed to stir the oil which extracts the dissolved gases into the headspace [3]. The gasses are then taken from the headspace and are circulated through the sampling loop of the photo acoustic spectroscopy moduleas shown in Fig. 2. When the gas concentration has reached a stable equilibrium, the photo acoustic spectroscopy module analysis the gases in the head space, and the results are presented on the integrated display.

B. Gas Chromatography

1) Gas sample injected into column

2) Gases are absorbed onto carrier walls at different rates, thus separating out different gases

3) Gas quantities are determined as gases exit the column into detector unit

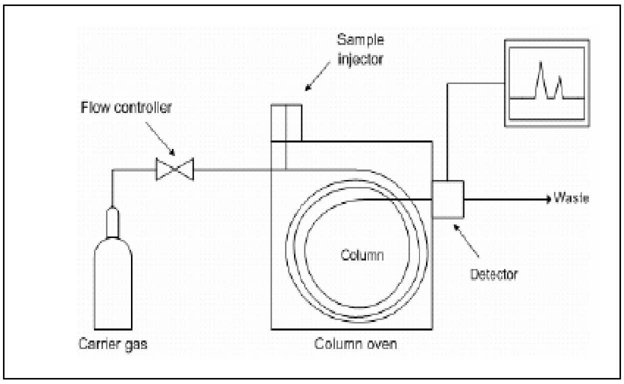

Figure 3. Gas chromatography

The module takes advantage of the photo acoustic effect which is when an infra-red light is transmitted through a gas, the pressure of the gas immediately increases and this pressure change is related to the concentration of the gas. How this module exactly works is an infrared source reflects off a parabolic mirror through a filter [4]. This filter allows only a specific frequency to pass through which will excite an individual gas. This allows you to measure the concentration of an individual gas. The device has a filter for each of the gases that it will analyze. The chopper cuts the signal up with a given frequency allowing the microphone to pick up this frequency. Gas sample is injected into a column along with a carrier gas. The carrier gas is basically a medium that is added to allow the gas sample to travel through the column. The column walls are coated with a stationary phase. As the gas sample passes through the column, the gas is absorbed onto the column walls. Since different gases within the sample gas are attacked to the column wall with different strengths, the gasses because separated as they pass through the column as shown in Fig. 3. A detector located at the end of the channel then looks at the different quantities of gas at the different arrival times to determine the gas concentration of each particular gas.

III. Evaluation of Gas in Transformer

Faults in a transformer sometimes lead to the degradation of insulation materials and oil. During this degradation, gaseous products are formed and dissolved in the oil, namely H_2, CO, CO_2, CH_4, C_2H_6, C_2H_4, C_2H_2, etc. If a certain level is exceeded, gas bubbles arise and oil-filled transformers are subject to electrical and thermal stresses, which may break down insulation materials and release gaseous decomposition products. Evaluation procedures for DGA have been implemented widely based upon the guidelines recommended by IEC [1], IEEE [5] and CIGRE [6]

The immediate effect of the breakdown of hydrocarbon molecules as a result of the energy of a fault is to create free radicals as indicated in Fig. 4

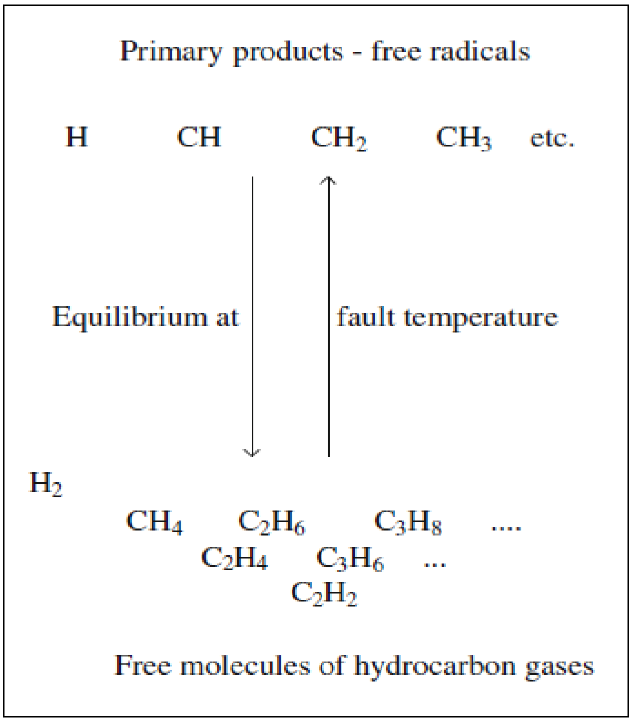

Figure 4. Breakdown of hydrocarbon

These subsequently recombine to produce low molecular weight hydrocarbon gases. This recombination process is largely determined by operation temperatures, but also influenced by other factors. The result is that the pattern of gases appearing in the oil has a form as shown in Fig. 4. For the lowest temperature faults both CH_4 and H_2 are generated, with CH_4 being predominant. As the temperature of a fault increases, C_2H_6 starts to be evolved and CH_4 is reduced, so that the C_2H_6/CH_4 ratio becomes predominant. At still higher temperatures the rate of C_2H_6 evolution is reduced and C_2H_4 production commences and soon outweighs the proportion of C_2H_6. Finally, at very high temperatures C_2H_4 puts in an appearance and as the temperature increases still further it becomes the most predominant gas. It is noted that no temperature scale is indicated along the temperature axis of Fig. 5, and the graph is subdivided into types of faults. The areas include normal operating temperatures go up to about 140 ℃, hot spots extend to around 250 ℃ and high temperature thermal faults to about 1000 ℃. Peak C_2H_4 evolution occurs at about 700 ℃ [1]

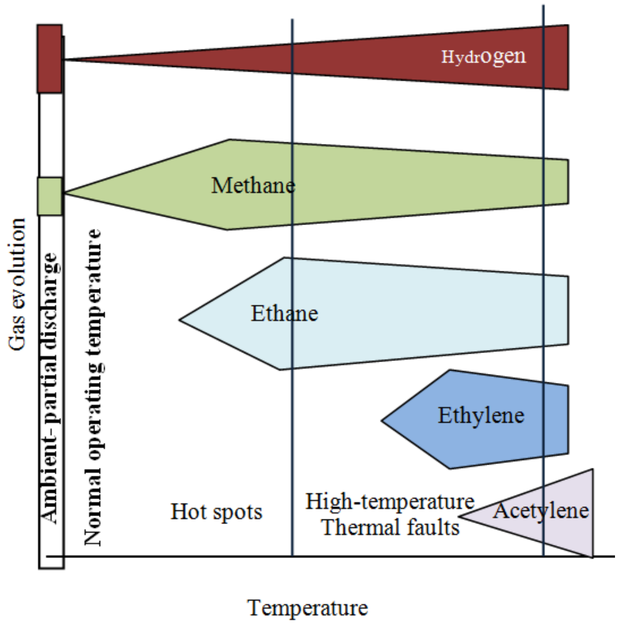

Figure 5. Hydrocarbon gas evolution in transformer

IV. Dissolved Gas Analysis Algorithms

The Gas module collects the gas information of different gases from sensors like, Hydran, Kelman etc. The module collects information of different gases like

- Hydrogen – H_2
- Carbon Monoxide – CO
- Carbon dioxide – CO_2
- Acetylene – C_2H_2
- Ethylene – C_2H_4
- Methane – CH_4
- Ethane – C_2H_6

The collected gas information will be stored for trending and different analytical methodologies were used to analyze the system state as per gas information

- IEEE C57 – 104 state estimation analysis
- IEC 60599 state estimation analysis
- Rogers's ratio state estimation analysis
- Dornenburg's state estimation analysis
- Duval's triangle state estimation analysis

A. *IEEE Analysis*

The IEEE analysis uses the Total Dissolved Combustible gases (TDCG), rate of rise of TDCG and trend data of individual gases to analyze the state of the gases in the transformer. The fault types were divided into 4 types as shown in Table I, normal condition, low decomposition, where individual gases has to be analyzed for their levels, High decomposition, where individual gases has to be analyzed and transformer has to be removed from service and excessive decomposition, danger to operate transformer.

TABLE I. Status Information of IEEE Analysis

Condition 1	TDCG below this level indicates Normal Operation, If any individual gas increases, additional investigation required. Then go for key gas and ratio methods.
Condition 2	TDCG in this limit indicates low level decomposition, requires individual gas Investigation, load dependency to be determined, If any individual gas increases, additional investigation required. Then go for key gas and ratio methods. TCG and TDCG to be determined Establish trend
Condition 3	TDCG in this limit indicates high level decomposition, requires individual gas investigation, Immediate trend needs to establish, Plan outage
Condition 4	TDCG above this limit indicates excessive decomposition, operation may result in failure, removal from service

$$TDCG = H_2 + CH_4 + C_2H_2 + C_2H_4 + C_2H_6 + CO \qquad (1)$$

where

TDCG – Total Dissolved Combustible gases, ppm
H_2 – Hydrogen, ppm
CH_4 – Methane, ppm
C_2H_2 – Acetylene, ppm
C_2H_4 – Ethylene, ppm
C_2H_6 – Ethane, ppm
CO - Carbon Monoxide, ppm

B. *Key Gas Analysis*

The IEEE key gas analysis will be used if individual gas analysis suggested or the rate of rise trend data available is less than one year. It uses the TDCG value and individual gas values to analyze the system state, detailed investigation will be done on particular gas which exceeded certain limits

TABLE II. Key Gas Analysis TDCG and Gases

TDCG	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO	CO_2	Status
<=720	<100	<120	<1	<50	<65	<350	<2500	Condition 1
721 – 1920	101 -700	121 - 400	2 – 9	51 - 100	66 - 100	351 - 570	2500 - 4000	Condition 2
1921 – 4630	701 - 1800	401 - 1000	10 – 35	101 - 200	101 - 150	571 - 1400	4001 - 10000	Condition 3
> 4630	>1800	> 1000	> 35	> 200	> 150	> 1400	> 10000	Condition 4

TABLE III. KEY GAS FAULT ANALYSIS

Sl No	Fault	Principle gas	CO	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2
1	Overheated oil	Ethylene C_2H_4	-	2%	16%	19%	63%	-
2	Overheated cellulose	Carbon monoxide CO	92%	-	-	-	-	-
3	Corona in oil	Hydrogen H_2	-	85%	13%	1%	1%	
4	Arcing in oil	Acetylene C_2H_2	-	60%	5%	2%	3%	30%

C. IEC Analysis

IEC analysis uses an advance scenario of fault matrix where faults were classified as 7 different types Partial discharge, Low energy discharge, high energy discharge, thermal fault <300 deg C, 300 to 700 deg C, > 700 deg C.

TABLE IV. STATUS INFORMATION OF IEC ANALYSIS

Type	Fault	Remarks
PD	Partial Discharge	Discharges in gas filled cavities resulting incomplete impregnation, high-humidity in paper, oil super saturation or cavitation's and leads to X-wax formation
D1	Low Energy Discharges	Sparking or arcing between bad connections of different or floating potential, from shielding rings, toroid's, adjacent disks or conductors of winding, broken brazing or closed loops in the core. Discharges between clamping parts, bushing and tank, high voltage and ground within windings, on tank walls. Tracking in wooden blocks, glue of insulating beam, winding spacers, Breakdown of oil, selector breaking current.
D2	High Energy Discharges	Flashover, tracking or arcing of high local energy or with power follow-through. Short circuits between low voltage and ground, connectors, windings, bushings and tank, copper bus and tank, windings and core, in oil duct, turret. Closed loops between two adjacent conductors around the main magnetic flux, insulated bolts of core, metal rings holding core legs.
T1	Thermal Fault < 300 deg C	Overloading of the transformer in emergency situations. Blocked item restricting oil flow in windings. Stray flux in damping beams of yokes.
T2	Thermal Fault 300 to 700 deg C	Defective contacts between bolted connections (particularly between aluminum bulbar), gliding contacts, contacts within selector switch (paralytic carbon formation), connections from cable and draw-rod of bushings. Circulating currents between yoke clamps and bolts, clamps and laminations, in ground wiring, defective welds or clamps in magnetic shields. Abraded insulation between adjacent parallel conductors in windings.
T3	Thermal Fault > 700 deg C	Large circulating currents in tank and core. Minor currents in tank walls created by a high uncompensated magnetic field. Shorting links in core steel laminations.

The IEC state estimation uses a boundary limits for different gases and 3 different gas ratios to analyze the system state. The boundary limits vary as per the OLTC design for internal and external OLTC as mentioned in Table V.

TABLE V. IEC LIMITS FOR INDIVIDUAL GASES

Gas	Limit (external OLTC)	Limit (Internal OLTC)
H_2	60 - 150	75 – 150
CH_4	40 - 110	35 – 130
C_2H_2	3 - 50	80 – 270
C_2H_4	60 - 280	110 – 250
C_2H_6	50 - 90	50 – 70
CO	540 - 900	400 – 850
CO_2	5100 - 13000	5300 – 12000

TABLE VI. IEC GAS RATIOS

Ratio	Gas
Ratio 2	C_2H_2/C_2H_4
Ratio 1	CH_4/H_2
Ratio 5	C_2H_4/C_2H_6

TABLE VII. IEC ANALYSIS RATIO LIMITS

Case	Characteristic fault	C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6
PD	Partial Discharge	-	< 0.1	< 0.2
D1	Low Energy Discharges	> 1	0.1 - 0.5	> 1
D2	High Energy Discharges	0.6 - 2.5	0.1 - 1	> 2
T1	Thermal Fault < 300 deg C	-	> 1	< 1
T2	Thermal Fault 300 to 700 deg C	< 0.1	> 1	1 - 4
T3	Thermal Fault > 700 deg C	< 0.2	> 1	> 4

D. Rogers's ratio state estimation analysis

Rogers's ratio uses three gas ratios to analyze the system state with 6 types of fault states[7].

TABLE VIII. ROGERS GAS RATIOS

Ratio	Gas
Ratio 2	C_2H_2/C_2H_4
Ratio 1	CH_4/H_2
Ratio 5	C_2H_4/C_2H_6

TABLE IX. ROGER'S RATIO LIMITS

Case	Fault diagnosis	C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6
0	Unit Normal	< 0.1	0.1 - 1.0	< 1.0
1	Low energy density arcing	< 0.1	< 0.1	< 1.0
2	High energy discharge arcing	0.1 - 3.0	0.1 - 1.0	> 3.0
3	low temperature thermal	< 0.1	0.1 - 1.0	1.0 - 3.0
4	thermal fault < 700 deg C	< 0.1	> 1.0	1.0 - 3.0
5	thermal fault > 700 deg C	< 0.1	> 1.0	> 3.0

E. Dornenburg's State Estimation Analysis

Dornenburg's analysis uses 4 different gas ratios to analyze 3 different faults in gases. This methodology sets boundary limits of individual gases, if any gas exceeds the limits, than fault diagnosis limits will be employed to gas ratios to diagnose the fault type

TABLE X. DORNENBURG'S LIMITS FOR INDIVIDUAL GASES

Gas	Limit
H_2	100
CH_4	120
C_2H_4	50
C_2H_2	35
C_2H_6	1
CO	350

TABLE XI. DORNENBURG'S GAS RATIOS

Ratio	Gas
Ratio 1	CH_4 / H_2
Ratio 2	C_2H_2 / C_2H_4
Ratio 3	C_2H_2 / CH_4
Ratio 4	C_2H_6 / C_2H_2

TABLE XII. DORNENBURG'S LIMITS FOR FAULT DIAGNOSIS

Fault diagnosis	CH_4/H_2	C_2H_2/C_2H_4	C_2H_2/CH_4	C_2H_6/C_2H_2
Thermal Decomposition	> 1.0	< 0.75	< 0.3	> 0.4
Corona (Low Intensity PD)	< 0.1	-	< 0.3	> 0.4
Arcing (High intensity PD)	0.1 - 1.0	> 0.75	> 0.3	< 0.4

F. *Duval's Triangle State Estimation Analysis*

Duval's triangle employs triangular phenomenon between 3 gases CH_4, C_2H_4, C_2H_2, uses % gas ratios of 3 gases to analyze system state. Duval's triangle analyzed the faults into 7 different types as shown in Fig 6. [8], [9].

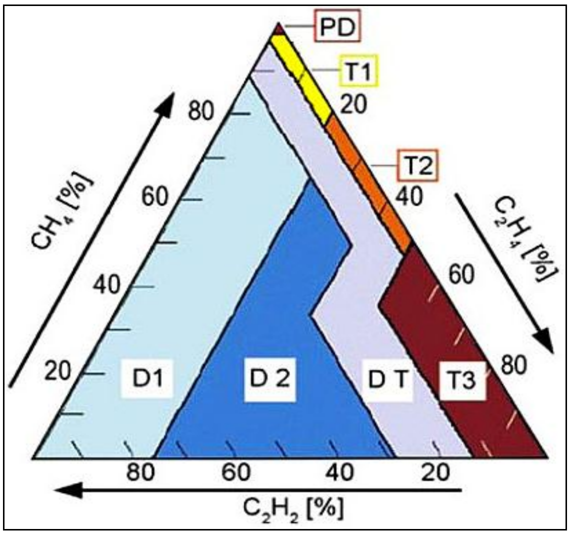

Figure 6. Duval's triangle

$$\%CH_4 = \frac{CH_4}{CH_4 + C_2H_2 + C_2H_4} \times 100 \quad (2)$$

$$\%C_2H_2 = \frac{C_2H_2}{CH_4 + C_2H_2 + C_2H_4} \times 100 \quad (3)$$

$$\%C_2H_4 = \frac{C_2H_4}{CH_4 + C_2H_2 + C_2H_4} \times 100 \quad (4)$$

TABLE XIII. DUVAL'S TRIANGLE FAULT ZONES

Case	Fault Diagnosis	$\%CH_4$	$\%C_2H_2$	$\%C_2H_4$
PD	Partial Discharge	98%		
D1	Low energy discharge		> 13%	< 23%
D2	High energy discharge		%13 - %29	23% - 38%
			> 29%	> 23%
T1	Thermal fault < 300 deg C		< 4%	< 20%
T2	Thermal fault 300 - 700 deg C		< 4%	20% - 50%
T3	Thermal fault > 700 deg C		< 15%	> 50%
DT	Thermal & electrical fault	rest area		

V. CONCLUSION

The interpretation of gases in the transformer helps in the early detection of the faults in transformer, due to which by taking appropriate action danger of bigger damage can be prevented. There are many algorithms by which the faults can be detected. Different algorithms are used to find the faults by using different gas combinations. So according to the requirement algorithm can be selected for detection.

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