Central Power Research Institute

Vol. 18(2)/113-120, December 2022
ISSN (Print) : 0973-0338
DOI : 10.33686/pwj.v18i2.1088

Power Research

Dissolved Gas Analysis is an Art of Testing and Analysis Method for the Incipient Faults in Power Equipment - Like Transformers and OLTCs

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Abstract

This paper describes the importance of Testing and Analysis of Dissolved Gases in oil-filled electrical power equipment like transformers and OLTCs and maintenance practices adopted based on DGA test results; the case studies wherein faults predictions and or confirmation of faults suggest for further maintenance or actions to be taken to remain the system functional for long life. The paper mentions the various methodology being adopted for the interpretation of DGA test results to conclude the type of faults in the equipment and a comparative study of DGA test results based on proficiency test results carried out by International laboratories concluding a similar type of fault indicating international acceptance of DGA testing of oil filled power equipment.

Keywords: DGA, Duvals Triangle Stray Gassing etc., Key gases, Proficiency Test

1. Introduction

Dissolved Gas Analysis popularly known as DGA provides insights into thermal and electrical stresses sustained by oil-immersed power transformers. It is a sensitive and reliable technique that can help to prevent further damage to power transformers since a test can detect incipient transformer faults. To protect the transformer from severe damage, DGA shall be performed. DGA test is advised to be performed- When we suspect a fault (e.g., abnormal sounds). In case of signals from gas or pressure relay in service conditions; and after obvious overloading of the transformers. Also- when a transformer essential to the network is taken into operation, followed by further tests after some months in operation i.e., directly after, and within some weeks of installation of power transformers. DGA is also done on power transformers before putting them into service new power transformers after factory tests like Temperature rise, Impulse tests and short circuit tests- to know their conditions and also to know the facts whether new oil is in use or not before putting in service- whether it has dissolved gases like air, hydrocarbons gases (i.e., in new or serviced oil)- as a Reference point for the presence of gases in power transformers and further rise of gases and its fault analysis.

2. Oil Properties and Generation of Dissolved Gases

The type of oil used affects the performance of power equipment. A satisfactory functioning and long service life are always expected which is dependent on many factors like the quality of material components and their compatibility, design and maintenance conditions of power transformers. There are various types of liquid Di-electrics like Mineral oil, Silicone Oil, and Natural and Synthetic esters that act as coolants and insulant media in power equipment. The mineral insulating oil is the most commonly used liquid di-electrics material even today. The quality check as per national and international test standard norms is done for its use for proper functioning in power equipment. Generally, IS 335-2018/IEC 60296-2013 is followed for new mineral Oil. IS 1866-2017/IEC 60422 is followed for testing on oil before energization of power transformer in-service check of oil conditions.

Mineral transformer oil generally paraffin-based and naphtha-based transformer oil are two common types of transformer oil in transformers. Naphtha-based oil is more easily oxidized than paraffin oil, but the oxidation product (i.e., sludge) in naphtha oil is more soluble than paraffin oil. The above oil is further classified as Type 1 transformer oil or Type 2 transformer oil for application use. These oils may contain solid or liquid impurities may contain some gases impurities and air/gases during the process of refining, filtration, transportation (containers) in the new oil stage itself or even in service condition (generated impurities) due to normal degradation of oil or abnormal prevailing conditions in the transformers under service.

A gaseous presence in oil is an unfavourable condition and oil should not contain gas in it; hence oil before use in a transformer is degassed. A typical air presence limit for different ratings of power transformers like large transformers>100 MVA is <0.5 %, for Medium power transformers (between 20 MVA to 100 MVA) is < 1% and for Small and distribution transformers; it is up to 2%. A new oil that has not gone under any thermal or electrical tests generally also has air dissolved in it and this air can be removed by degassing/filtration of the oil. DGA of fresh new oil shows the presence of air constituents like Oxygen and Nitrogen mainly and a very trace amount of Methane. This comes because air is dissolved in Oil and oil is not properly degassed. A properly filtered oil should have no or minimum air constituents.

Sometimes we also have found the presence of trace hydrocarbon gases in so-called or claimed new oil; which indicates the oil is not new or it is blended/leached with other used oil.

Stray gassing or Gassing the Tendency of oil also affects the gas formation in oil. The gas dissolution rate and temperature also affect the rate of gaseous presence in oil.

3. Effects of Dissolved Gases on the oil Properties

Transformer oil in service generates various types of key gases. The gases that are of interest for Dissolved Gas Analysis (DGA) are the following: H_2- hydrogen CH_4- methane C_2H_4- ethylene C_2H_6- ethane C_2H_2 – acetylene C_3H_6- propane C_3H_8- propane CO- carbon monoxide CO_2- carbon dioxide O_2 – oxygen N_2 – nitrogen. Some gas generation is expected from the normal ageing of the transformer insulation. Therefore, it is important to differentiate between normal and excessive gassing rates. The number of dissolved gases and the relative distribution of these gases affect mostly the Dielectric strength (BDV) of transformer oil. Decrease of the average breakdown voltage under the influence of air bubbles are well established and noticeable; an early flash-over is seen in presence of air bubble in oil. That is why as per IS 6792 and IEC 60157 an initial stand time of 5 minutes is given before testing the first breakdown. Whereas for natural ester oil, 15- 30 minutes of initial stand time is given so that dissolved air bubbles come to surfaces before the first BDV test. In any way, the gas's presence in oil is unwanted as it affects the Breakdown voltage of oil. The moist air with carbon or dust contaminants in oil acts as a catalyst and enhances the early Breakdown of oil value.

It is also to be mentioned that Gaseous presence brings down the flash point value of oil (as volatile hydrocarbon gases including hydrogen are combustible in nature). As per IS 1866/IEC 60422 a decrease of 10% of the Flashpoint value of oil is allowed for the safe working of oil. It may be noted that each sample may have a different initial flash point.

4. Methodology: Dissolved Gas Analysis of Power Transformer

Over time, electrical and thermal stresses on a transformer's insulating materials (arcing, corona discharge, sparking, and overheating) can result in incipient transformer faults. As these stresses accumulate, the insulating materials will break down and release several different gases. These gases can be detected in transformer insulating oil using sensitive and reliable Dissolved Gas Analysis (DGA) techniques for determining the type of pending or occurring fault. DGA is considered the best method for determining a transformer's overall condition and is now a universal practice.

Advantages of DGA include 1. Advanced warning of developing faults 2. Status checks on new and repaired units 3. Convenient scheduling of repairs 4. Monitoring of units under potential overload conditions. The use of appropriate DGA diagnostic methods can provide improved service reliability, avoidance of transformer failure, and deferred capital expenditures for new transformer assets. In this paper, we will discuss DGA case studies and tools available for DGA interpretation of test results.

In DGA testing and Analysis first aim should be to get the correct amount of gas content in oil using the latest gas extraction methodology and sensitive gas chromatographic equipment to analyze the qualitative and quantitative presence of gases. After that, a proper fault diagnosis is done based on warnings of any gases with concentrations, increments, rates of change, or ratios that exceed the standard limits, along with short interpretive remarks and recommendations.

The various guidelines and standards for testing and interpretations are referred to for correct diagnosis. The latest standards like IS 9434, IS 10593, IEC 60567, IEC 60599, IEC 61181, ASTM D 3612/IEEE C57.106, and CIGRE guidelines of DGA analysis are referred to for proper conclusion.

The chemistry behind gas formation has to be understood for the proper type of fault analysis. Decomposition of Oil lead formation of Hydrogen, Methane, Ethylene, and Acetylene as well as solid particles of carbon and hydrocarbon polymers (X-Waxes). Low energy discharge such as partial discharge will lead to the formation of H-H, C-H, and C-C bond molecules of Hydrogen, Methane and Ethane where as Hi temperature fault (Thermal or arcing) will lead C=C or C=C bond molecules of Ethylene and Acetylene. Oil may also oxidize leading CO and CO_2 formation and accumulation in large over the period.

Decomposition of Solid insulation- cellulose paper takes place at temp. higher than 105°C and complete decomposition and carbonization above 300°C leading formation of CO and CO_2 with Moisture. An increase in CO and CO_2 formation is seen not due to temperature only but also due to oxygen content in oil and Moisture content in the paper.

Stray Gassing of Oil: Gas formation in some oil takes place on moderate heating < 200°C or due to oxidation leading to the evolution of gases like H_2, CH_4 and C_2H_6. Thus oil having stray gas tendency is a non-damage fault indication.

Other Sources of Gas: Gases may also get formed due to rusting or other chemical reactions involving steel, metals, uncoated surfaces, protective paints and varnishes. H_2 may get generated due to the reaction of steel, galvanized steel, uncoated metal surfaces with water, and the reaction of water with special coatings on the metal surface. H_2 and C_2H_2 and other gases may also be formed from steel that got absorbed during the manufacturing process, and welding and slowly gets into the oil. Gases may also be produced and oxygen consumed due to exposure to sunlight. Thus such a phenomenon is not an indication of a fault in the transformer.

So there will be a typical presence of gases specific to each kind of transformer and as long as there is no significant increase, it should not be considered as fault indicative. Under normal operating conditions as well the gas rises will take place without fault. Each system equipment has a "Typical concentration value" of gases which are affected by the factors like operating time since commissioning, type of equipment, load factors etc. This is the value above which the rate of the gas formation may permit the detection of a probable fault.

5. Types of Faults in Transformer

After the physical inspection of hundreds of faulty transformers detectable by visual inspections and DGA results the faults as classified as

Partial Discharge (PD)- the corona type occurs, which can result in deposits of 'X-Wax' on paper insulation, or the sparking type occurs, which can induce pinholes (carbonized punctures) in the paper that may be difficult to find.

Discharges of Low Energy (D1)- occur in oil and/or paper, as indicated by large carbonized punctures in paper (pinholes), carbonization of the paper surface (tracking), or carbon particles in oil (as in an OLTC).

Discharges of High Energy (D2)- occur in oil and/or paper, as indicated by extensive destruction and carbonization of paper or metal fusion at the discharge extremes, extensive carbonization in oil, and some cases, tripping off the equipment confirming a large current follow-through.

Thermal Fault (T1)- occurs in oil and/or paper below 300°C, turning the paper "brownish".

Thermal Fault (T2)- occurs in oil and/or paper above 300°C and below 700°C, carbonizing the paper.

Thermal Fault (T3)- occurs in oil and/or paper above 700°C with strong evidence of carbonization of the oil, metal colouration (at 800°C), or metal fusion (below 1,000°C).

DGA Tools for Result Analysis: There are various methods adopted for the analysis and conclusion of test results. These are the Key Gas method, Gas Ratio Method, Rogers Gas Ratio Method, IEC Gas ratio method, Doernenburg Ratio method, Nanograph method, Duval's triangle Method, and TDCG IEEE guideline Methods. Each method has its level of accuracy in fault prediction and not cent per cent; hence from different methods, the fault has to be analysed before concluding.

6. Key Gas Methods

The amounts and types of gases found in the oil are indicative of the severity and type of fault occurring in the transformer.

ORIGIN OF GASES IN TRANSFORMER OIL Fault gases are caused by corona (partial discharge), thermal heating (pyrolysis) and arcing.

PARTIAL DISCHARGE is a fault of low-level energy which usually occurs in gas-filled voids surrounded by oil-impregnated material. The main cause of decomposition in partial discharges is an ionic bombardment of the oil molecules. The major gas produced is Hydrogen. The minor gas produced is Methane.

THERMAL FAULTS A small amount of decomposition occurs at normal operating temperatures. As the fault temperature rises, the formation of the degradation gases changes from Methane (CH_4) to Ethane (C_2H_6) to Ethylene (C_2H_4). A thermal fault at a low temperature (300°C) produces Ethylene. The higher the temperature becomes the greater the production of Ethylene.

ARCING is a fault caused by a high-energy discharge. The major gas produced during arcing is acetylene. Power arcing can cause temperatures of over 3000°C to be developed.

NOTE: If the cellulose material (insulating paper etc.,) is involved, carbon monoxide and carbon dioxide are generated. A normally ageing conservator-type transformer having a CO_2/CO ratio above 11 or below 3 should be regarded as perhaps indicating a fault involving cellulose, provided the other gas analysis results also indicate excessive oil degradation.

Dissolved O_2 and N_2 may be found in the oil. The O_2/N_2 ratio in oil reflects air composition and is close to 0.5. In service, this ratio may decrease as a result of oil oxidation and/or paper ageing. Factors such as the load and preservation system used may also affect the ratio, but a ratio less than 0.3 are generally considered to indicate excessive consumption of oxygen.

DGA Case Studies and Fault Analysis by Different Methods of Analysis (Gas Ratio And Duval's Triangle Method) based on *International DGA Proficiency Test Data:*

CASE 1

Independent studies have shown lab-to-lab DGA differences, with some results necessarily not accurate. There is a Difference in DGA lab results among Labs: This study consisted of Proficiency test samples (Transformer samples) analysed by Different International laboratories (9 labs) wherein the difference in test results have been noticed. The gas concentrations found are as follows:

Table 1. Gas concentration for DGA Labs

LAB	H2	O2	N2
L1	130	6419	19225
L2	338	7545	41457
L3	417	8877	41651
L4	430	10700	42895
L5	531	15498	56117
L6	634	17891	65828
L7	636	17991	71556
L8	668	18731	74158
L9	983	22249	82879

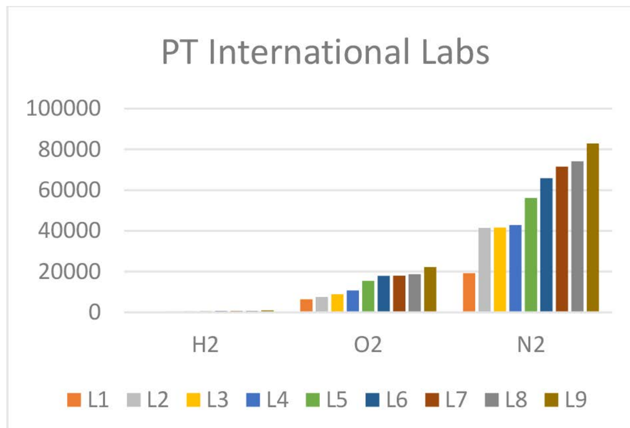

Figure 1. Gas concentration and proficiency test samples.

Table 2. Gas concentration for DGA labs

LAB	CO	CO2	CH4	C2H6
L1	199	203	220	266
L2	408	276	425	357
L3	409	335	428	391
L4	492	455	439	452
L5	512	556	518	535
L6	559	666	563	602
L7	586	701	566	613
L8	601	745	591	633
L9	618	1120	609	644

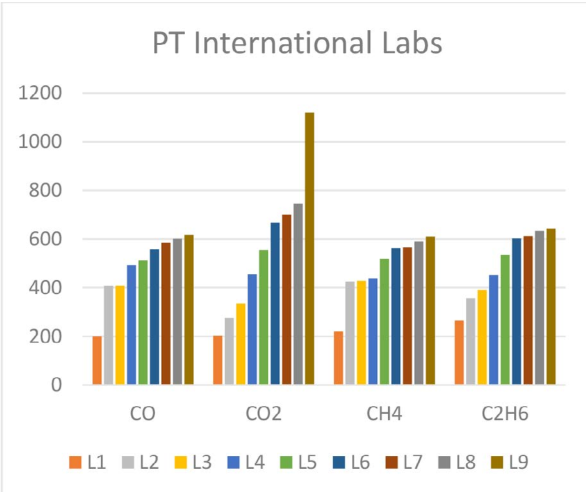

Figure 2. Gas concentration and proficiency test samples.

Table 3. Gas concentration for DGA labs

	C2H4	C2H2	C3H6	C3H8
L1	250	269	49	0
L2	376	372	474	1
L3	445	434	494	1
L4	450	442	560	2
L5	524	510	566	458
L6	580	583	581	540
L7	588	592	591	609
L8	594	624	633	625
L9	598	677	676	705

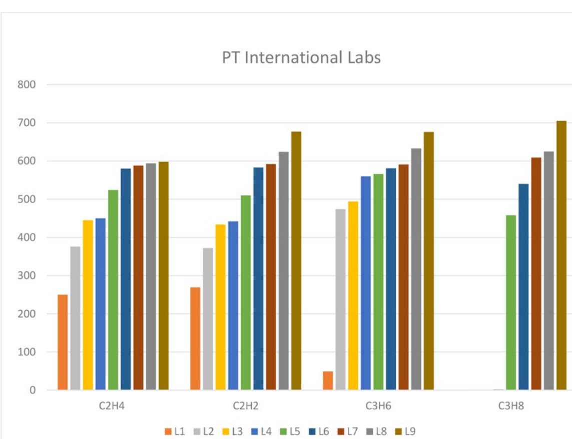

Figure 3. Gas concentration and proficiency test samples.

Possible causes of differences in test results are:

*Even with the same sampler and sample process, contamination could have occurred *Transportation may have affected the samples. In spite of variation in gas concentration results if the gas Ratio method and Duvals Triangle methods of analysis are applied; the outcome for the nature of the fault is the same. Let us see the Gas Ratio Calculation on the above lab results:

Table 4. Gas Ratio and Duval's triangle Result analysis

LAB	C_2H_2 / C_2H_4	CH_4 / C_2H_6	C_2H_4 / C_2H_6	Remark Fault	O_2 / N_2	CO_2 / CO	Duval's Triangle
L1	1.07	1.69	0.94	D1/D2	0.33	1.02	D2 Fault
L2	0.98	1.25	1.05	D1/D2	0.18	0.67	D2 Fault
L3	0.97	1.02	1.14	D1/D2	0.21	0.81	D2 Fault
L4	0.98	1.02	1.00	D1/D2	0.25	0.92	D2 Fault
L5	0.97	0.97	0.98	D1/D2	0.27	1.08	D2 Fault
L6	1.00	0.88	0.96	D1/D2	0.27	1.19	D2 Fault
L7	1.00	0.88	0.96	D1/D2	0.25	1.19	D2 Fault
L8	1.05	0.88	0.94	D1/D2	0.25	1.23	D2 Fault
L9	1.13	0.61	0.93	D1/D2	0.26	1.81	D2 Fault

Under Duval's triangle we consider % CH_4, % C_2H_4 and % C_2H_2 out of total of gas mixture and point of cross section that lies in the type of region denotes the nature of fault.

Remark: In above all the cases, irrespective of different concentrations found by the labs the nature of fault denoted as per IEC, Duval's method of analysis as per IEC 60599-2015 is "High Energy Discharge" leading cellulose paper Carbonization and Oxidation of oil.

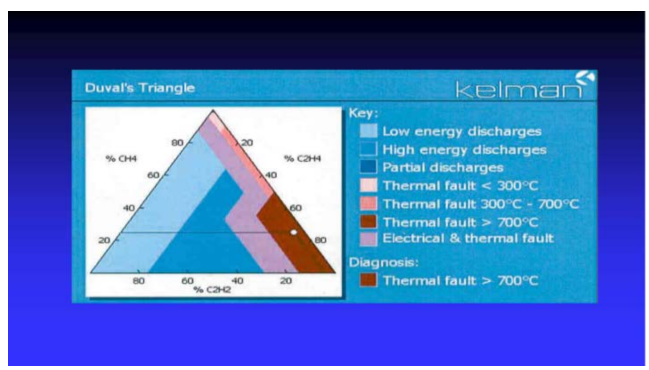

Figure 4. Duval's Triangle.

CASE 2

In a power transformer in the consequitive month of Feb 2019 has been tested and DGA results found are as follows:

From the above we see that only Acetylene is in the typical value range (2-20 PPM); the result above 2 PPM

Table 5. DGA results for Power Transformer

SN.	Gases	Date of Testing		
	PPM	1.2.19	15.2.19	5.4.19
1	CH_4	3	5	7
2	C_2H_6	0	0	2
3	C_2H_4	7	9	13
4	C_2H_2	5	9	13
5	CO	337	285	450
6	CO_2	37	42	75
7	H_2	0	0	4
8	O_2	8757	5985	12005
9	N_2	17105	13167	26835
	Commissioning of transformer	2014		
SN.	Gases	Date of Testing		
	PPM	17 .7.19	30.7.19	29.8.19
1	CH_4	5	3	6
2	C_2H_6	2	0	1
3	C_2H_4	10	7	9
4	C_2H_2	9	7	8
5	CO	432	387	495
6	CO_2	46	25	116
7	H_2	0	0	5
8	O_2	1928	7419	3425
9	N_2	6172	15996	10925

indicates fault (Arcing) that may or may not be; however, as this is not beyond the typical value exact presence of fault cannot be confirmed. Also, in this case there is no substantial increase in gas concentration over the last analysis to confirm the fault. This variation in values may be seen as due to diffusion loss of gases in samples and no active fault in the transformer. The presence of Acetylene is due to once transient arcing that might have taken and later it has subsided.

Also, to be noted that at low concentration gas content the DGA result accuracy varies a lot and is dependent on the type of gas extraction methods. As per standard, the accuracy of the gas extraction method is tabulated below:

7. Accuracy of Extraction Methods

The accuracy of DGA results of low gas content samples in oil (after gas extraction) further goes down. At a very low gas content level, DGA accuracy as per IEC 61181 (for 1-3 ppm of hydrocarbon, 2.5 ppm of H_2, 5 ppm of CO, 40 PPM of CO_2 level) is approx. +44%.

Table 6. Accuracy of Extraction Method

Extraction	Medium Conc.	Low Conc.
Procedure	**% Accuracy**	**% Accuracy**
Toepler:	13	35
Partial-Degassing:	13	30
Stripping:	18	23
Headspace:	18	37

Any analytical system consisting of degassing equipment, and gas chromatograph shall have adequate sensitivity for detection limits, repeatability and accuracy for results. The DGA results depend on many details of the overall procedure particularly the method of gas extraction, design, method of operation of equipment, ancillaries and calibration etc. A GC having Methanizer combined with TCD detector will give better sensitivity for carbon oxides rather than a thermal conductivity detector.

CASE 3

An example of the abnormal presence of gases in the OLTC transformer oil sample is found is given as follows:

From the above, we find that there is quite a substantial amount of presence of Hydrocarbon gases beyond typical value indicating fault that is occurring in oil. The carbon oxides are low in a concentration less than the typical value indicating that this amount has been generated from the oil component and not from cellulose as in the case of the transformer it would have happened. Also, substantial loss of air is seen that has been consumed in the degradation of oil. Let us find the type of fault by the Gas Ratio Method of Analysis.

The above Gas Ratio Method and Duval's Triangle Method of the analysis indicate fault of "High Energy Discharge/ Arcing" resulting in High Temperature in the equipment.

But OLTC has developed faults that can not be concluded from the above. The fault in OTLTC is determined by the STENSTAM GAS RATIO METHOD; which is as follows:

From the above if we see OLTC case 2, the damage is more severe in it as the arcing gas ins-spite of low concentration in comparison to other OLTCs, the heating

Table 7. OLTC Transformer oil sample results

SN	Gases	OLTC Samples (1 - 6)		
	PPM	OLTC 1	OLTC 2	OLTC 3
1	CH_4	687	1557	845
2	C_2H_6	533	2040	270
3	C_2H_4	3916	13209	3405
4	C_2H_2	8003	2305	10040
5	CO	48	23	79
6	CO_2	539	685	882
7	H_2	6286	9178	8538
8	O_2	3194	1484	4637
9	N_2	8046	6326	12530
	Commissioning of transformer	1984		

SN	Gases	OLTC Samples		
	PPM	**OLTC 4**	**OLTC 5**	**OLTC 6**
1	CH_4	1726	621	3337
2	C_2H_6	1005	246	1283
3	C_2H_4	10145	2921	16764
4	C_2H_2	2815	6263	22530
5	CO	103	93	815
6	CO_2	1249	629	923
7	H_2	9986	5567	9039
8	O_2	3193	3770	3187
9	N_2	15146	9921	8070
	Commissioning of transformer	1984		

Table 8. Gas Ratio & Duval's Triangle method analysis-Fault for High energy Discharge /Arcing

Sample	C_2H_2 / C_2H_4	CH_4 / H_2	C_2H_4 / C_2H_6	Remark Fault	Duval's Triangle
S1	2.20	0.69	6.78	D2	D2
S2	0.17	1.58	6.48	T3	D2
S3	2.94	0.85	12.61	D2	D2
S4	0.28	1.76	10.09	T3	D2/T3
S5	2.14	0.63	11.87	D2	D2/T3
S6	1.34	3.39	13.07	T3	D2

gases are formed more indicating the severe fault; where in other OLTCs in-spite of high C_2H_2 concentration has affected less for generating other heating hydrocarbon gases indicating less damage in OTLCs.

Table 9. Stenstam Gas Ratio method

Total Gas (CH_4, C_2H_4, C_2H_6)/ C_2H_2	Remark	ACTION	CASE(1-6) TG/C_2H_2
---------- **<0.5**	**Normal**	Continue normal	0.64
		Annual sampling	
0.5 to 1	**Heating Possible**	Sample every 3-6 month	**7.29**
1 to 3		Sample every 1-3 month	**3.42**
3 to 5		sample Weekly to Monthly	1.28
>5		Remove from service to inspect	0.90
			0.60

8. Conclusion

1. Data Analysis of Dissolved gases (DGA) is a significant and powerful tool for the diagnostic study of the nature of faults in electrical power equipment like Power transformers and OLTC.
2. DGA interpretation of fault in power transformers and OLTCs is different. Merely the presence of high Arcing gas does not confirm the fault always it has to be seen in a combination of other heating gases as well for the fault analysis.
3. Accuracy of the result depends on many factors like representative samples, Methodology of Gas extraction, GC system, and diagnostic techniques.
4. High-precision equipment like Gas Chromatograph is needed for DGA testing and analysis of gases in low gas content levels. of equipment.
5. The Gas concentration level, Gas Ratio are the significant methods that indicate the type of faults inside the transformer.

9. Acknowledgement

The author is thankful for the technical lab resources and management of CPRI for providing an opportunity to work and gain experience in the field. He is also thankful to his colleagues and staff for their valuable help and support.

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