DISSOLVE GAS ANALYSIS OF AGED TRANSFORMER OIL: A CASE STUDY

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Abstract: *Insulating oil of the transformer plays important role by serving several purposes like dielectric media, an insulator, helps to extinguish arcs as well as heat transfer agent between the conductors and cooling medium inside the transformer. During continuous long period of operation, transformers are subject to huge thermal and electrical stresses, which degrade the insulating oil and leads catastrophic failure of transformer, hence failure in power system network. The degradation of such transformer oil produces different kinds of gases as byproducts which entirely or partially dissolve in the transformer oil and the quality of dielectric strength of insulating oil is degrading. The dissolved gas analysis (DGA) is popularly recognized as most useful and predictive maintenance tool for condition monitoring of transformer health. In this work, an Infrared photo-acoustic spectroscopy (IPAS) and Fourier Transform Infrared Spectroscopy (FTIR) technique is used for dissolve gas analysis of three different distribution transformer oil sample for finding out the fault gas. Finally, observed practical results are tested with developed software in MATLAB environment for validation of fault gases representation using Duval Triangle method.*

Key words: *Dissolved gas analysis, High voltage transformer, Aged transformer, Insulating oil.*

1. Introduction

With the increase of population throughout the world, electrical power demand is also increasing rapidly to survive the modern civilization in a better fashion. To meet such increasing demand there are several interconnected power system networks are commissioning both in our country and as well as abroad. It is well known that each of the power system networks have several transformers are connected either in transmission or distribution side which plays an important role in it. At the same time these transformers are facing continuous thermal and electrical tress during their operation throughout their service period of life which can cause the degradation of the insulating materials presence inside the transformer [1-2]. The transformers are filled with a insulating liquids is so called transformer oil that serves several purposes like dielectric media, an insulator, helps to extinguish arcs as well as a heat transfer agent [3]. The degradation of such insulation due the thermal and electrical stresses leads catastrophic failure of transformer which leads to failure of power system network. The degradation of such insulation failure due to local electrical breakdown produces different kinds of gases as byproducts which entirely or partially dissolve within the transformer oil. The gases generally dissolved in the transformer oil are Hydrogen (H_2), Ethane (C_2H_6), Ethylene (C_2H_4), Acetylene (C_2H_2), Methane (CH_4), Carbon monoxide (CO), Carbon dioxide (CO_2), Oxygen (O_2) and Nitrogen (N_2). However, Oxygen and Nitrogen gas is consider as 'no-fault' gas which is produce due to leakage and changes in pressure and temperature in the transformer [3-4].The distribution of these gases can be related to the type of electrical fault, and the rate of gas generation can indicate the severity of the fault. The identity of the gases being generated by a particular unit can be very useful information in any preventative maintenance program. Moreover, quality of dielectric strength of this insulating oil is degrading.

As these transformers life time is more less 38-40 years from the date of its commissioning in the power system network, a periodic maintenance is utmost requirement for increasing the efficiency and reliable operation of such costly equipment [4]. Therefore, protection of such transformer is the prime task to each power engineer. There are several techniques commercially available for detection of such failure mechanism. One of the popular techniques to diagnosis the incipient fault inside the transformer by identifying the gases being generated in it is so called Dissolved Gas Analysis (DGA).

On the other hand various works has been done on the analysis of ageing of the transformer oil for determining the faults before any damage in the transformer. The ageing process has been explored and based on the spectral absorption characteristics a methodology for on-line transformer health assessment using ultraviolet absorption [5-8]. The effect of different ageing processes on the optical absorption properties of insulating oil of a model transformer using UV spectrophotometer is getting more importance for monitoring of high voltage power apparatus [8]. Further, to diagnosis the health condition of the high voltage power equipment another additional method called Fourier Transform Infrared Spectroscopy (FTIR) technique has been widely used. This method is based on the principle of multiple total reflection of radiation on the phase measured sample measuring crystal interference [9, 10].

In this work, an effort has been made for diagnosis the incipient fault inside the transformer using dissolve gas analysis (DGA) technique. The novel technique is known as Infrared photo-acoustic spectroscopy and FTIR technique which is used to detect the gases presence in the transformer oil sample and compare the both results. Moreover, for utility concern the transformer oil is under gone break down voltage test to ensure the dielectric strength of collected transformer oil sample specimen. Finally, computer based transformer oil insulation assessment software has been developed for analysis the detected dissolve gases from the oil sample and compared with the practical result found from the portable DGA analyzer.

2. Method of Transformer Fault Analysis

It is well studied that, partial discharge, arcing, overheating, winding circulation current and continuous sparking are the major factors for effecting the insulating oil and cellulose material of transformer. Finally, failure of such insulation produces certain combustible gases referred as fault gas inside the transformer which is higher than the normal permissible value. The most significant fault gases generated by oil decomposition includes Hydrogen (H_2), Ethane (C_2H_6), Ethylene (C_2H_4) and Acetylene (C_2H_2) as well as Carbon monoxide (CO) and Carbon dioxide (CO_2) which produce from decomposition of insulated paper (Cellulose). Over the past couple of decades, several diagnosis techniques have been developed to identify the nature of fault inside the transformer by detecting the dissolve gas in the transformer oil.

A. Key Gases Method

Key Gas method becomes applicable to transformer with developed faults where absolute values of key gases are considered. The key gases are acetylene (C_2H_2), hydrogen (H_2), ethylene (C_2H_4) and carbon monoxide (CO).Various faults produce certain gases and the percent of some gases have been found to indicate fault types, such as overheated oil and cellulose, corona in oil and arching in oil. For thermal fault occurring at a temperature of less than 300° C, the paper insulation of the transformer will turn brownish. For thermal fault occurring at temperatures between 300°C and 700° C, the paper insulation will carbonize. For thermal fault occurring at a temperature of more than 700° C, the oil will carbonize and metal will become coloured or will fuse. This method is described in IEEE C57.104 standard [11] and it gives four main faults which are depicted in Table 1.

Table 1: Key gas and their corresponding fault identification

Key Gas	Nature of Fault
Acetylene (C_2H_2)	Electrical Arc in Oil
Hydrogen (H_2)	Corona, Partial Discharge
Ethylene (C_2H_4)	Thermal Degradation of Oil
Carbon Monoxide (CO)	Thermal Ageing of Oil

B. Dornenburg Ratio Method

This method utilizes the gas concentration from four ratios of gases such as *Ratio 1*, *Ratio 2*, *Ratio 3* and *Ratio 5* (i.e., CH_4/H_2, C_2H_2/C_2H_4, C_2H_2/CH_4 and C_2H_6/C_2H_2) which is depicted in Table 2. In this method the value of the individual gas concentration must exceed the specified concentration given in Table 3 to ascertain whether there is really a problem with the transformer and further to ascertain whether there is sufficient generation of each gas for the ratio analysis to be applicable [12-13].

Table 2: IEEE and IEC 60599 proposed ratio to interpret fault in transformer

Ratio 1	Ratio 2	Ratio 3	Ratio 4	Ratio 5	Ratio 6	Ratio 7	Ratio 8
CH_4/H_2	C_2H_2/C_2H_4	C_2H_2/CH_4	C_2H_4/C_2H_6	C_2H_6/C_2H_4	C_2H_2/H_2	O_2/N_2	CO_2/CO

Table 3: Concentration for Doernenburg Ratio method

Key Gas	Concentration L1 (ppm)
Hydrogen (H_2)	100
Methane (CH_4)	120
Carbon Monoxide (CO)	350
Acetylene (C_2H_2)	35
Ethylene (C_2H_4)	50
Ethane (C_2H_6)	65

C. Roger's Ratio Method

In this Roger's ratio method mainly three gas ratios such as *Ratio 1*, *Ratio 2* and *Ratio 4* (i.e., CH_4/H_2, C_2H_2/C_2H_4 and C_2H_4/C_2H_6) are used for dissolve gas analysis. This method's flow chart along with key gas limits is elaborately discussed in the IEEE standard [13]. Table 4 shows the relationship between the fault type and the gas ratio. 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, such as, for example, the evolution of an existing T2 thermal fault into the more serious T3 thermal fault.

Table 4: DGA interpretation according to IEC ratios

Nature of the fault	C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6
Partial Discharge (PD)	NS	< 0.1	< 0.2
Discharges of low energy (D1)	>1	0.1– 0.5	> 1
Discharges of high energy (D2)	0.5– 2.5	0.1 - 1	> 2
Thermal fault of low T°C (T1)	NS	> 1	< 1
Thermal fault of medium T°C (T2)	<0.1	> 1	1 - 4
Thermal fault of high T°C (T3)	0.2	>1	>4

However, further three ratios to interpret fault in transformer is proposed in IEC60599 which is depicted in Table 2. According to IEC60599, *Ratio 6* is used to determine On Load Tap Changer (OLTC) contamination and taken in to consideration when it value is greater than 3. The *Ratio 7* is used to determine possible oxidation or abnormal oil heating in the transformer and taken the value less than 0.3 for consideration. Generally, concentration of Oxygen (O_2) is slightly more than twice the concentration of Nitrogen (N_2) in equilibrium condition. The O_2:N_2 ratio in transformers should be maintained at less than 1:10, in order to prolong the useful life of the fluid. On the other hand at lower temperature the carbon monoxide and the carbon dioxide are produced and the measurements are being done with the help of *Ratio 8* i.e., CO_2/CO which is used to determine the severity of the insulation paper degradation [13].

D. Duval Triangle Method

In the year of 1974, Duval Triangle diagnostic method for oil-insulated high-voltage equipment (mainly transformers), developed by Michel Duval is described in IEC 60599 [12-15]. Duval's triangle method employs graphical representation of three key gas ratios such as methane (CH_4), ethylene (C_2H_4), and acetylene (C_2H_2) in order to determine fault which is shown in Fig. 1. In this method the concentrations (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 (see Table 5) which has been subdivided into six fault zones. In addition of the six individual faults (PD, D1, DT2, T1, T2, T3), an intermediate zone 'DT' has been introduced to mixtures of electrical and thermal faults in the transformer. The fault zone in which the point is located designates the likely fault type which produced that combination of gas concentrations. The Duval Triangle method, like any other DGA diagnostic method, should be applied only when there is some suspicion of a fault, based on an increase in combustible gas or some other suspicious symptom. Because of the relative inaccuracy of gas-in-oil concentration measurements at low concentrations, DGA diagnostic methods, including the Duval Triangle, should not be applied unless the gas concentrations are well above the detection limit.

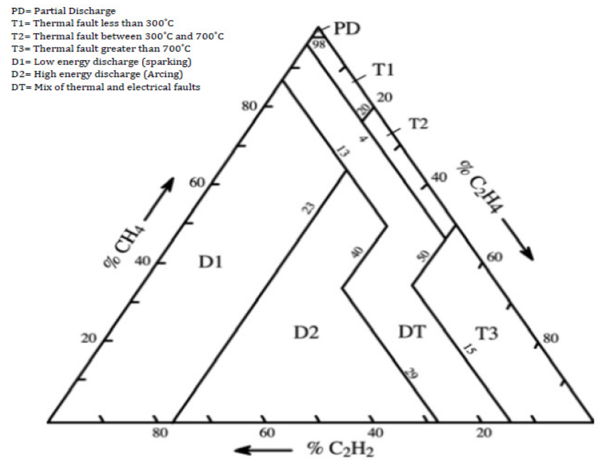

Fig. 1. Duval triangle for dissolve gas analysis of transformer oil.

3. Computer Simulation Based DGA for Transformer Fault

Now a days, computer simulation before performing a practical experiment is one of the most important tool to analysis the data, verify and improvement of a modern technology. With the application of such modern technique several diagnosis methods has been developed for monitoring of high voltage power transformer. Dissolved gas analysis is one of the most popular methods for diagnosis the health condition of high voltage power transformer. Moreover, several techniques are developed using soft computing technique such as Artificial Intelligence (AI), Artificial Neural Network (ANN), Fuzzy logic etc [16-22] for proper analysis and prediction of insulation condition of high voltage power transformer. Many researchers are explored these technique with many dimension considering different dependable parameter of condition monitoring of such HV power transformer [23-25]. The basic technique of such computational diagnostic method is to determine the different evolve gases in transformer oil and their analysis during long operation service period of high voltage power transformer.

In this study, a computer simulation technique has been developed for detecting the transformer fault at an early stage using dissolve gas analysis. The technique is capable to identify the incipient fault of transformer with the help of graphical representation of 'Duval Triangle' using MATLAB platform. The technique is also provides the necessary remedies with an alarm indication and present condition of the transformer oil depending upon the input parameter. The detail mechanism for identify the dissolve gases in the transformer is given in the flow chart which is shown in Fig. 2.

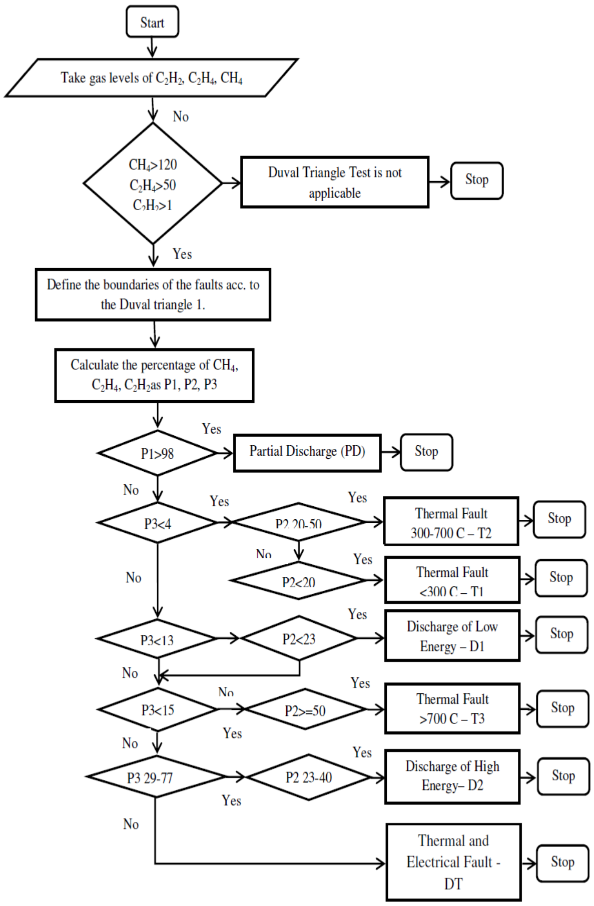

Fig. 2 Flow chart for Computer based dissolve gas analysis of transformer oil.

4. Experimental Setup for Dissolve Gas Analysis

To analysis the presence of dissolve fault gases and moisture in the transformer oil sample an Infrared photo-acoustic spectroscopy (Model: Kelman TRANSPORT X, GE Energy make) is used for this study. The TRANSPORT X consists of sample bottle with connections and pipes and a syringe for extracting oil sample from the equipment and injecting it into the bottle. It contains an embedded PC with touch screen facility and a thermal printer is also provided to take the hard copy of the records. Moreover, the whole measurement system is within a rugged, impact resistant, carrying case. In this study, the gases are extracted from the oil sample using highly stable proprietary dynamic headspace equilibrium and then measured using Infrared photo-acoustic spectroscopy. With this facility an extremely high performance standards and genuine portability, giving measurement of all fault gases along with moisture contains in the transformer oil [26].

The technique design of a practical Infrared photo-acoustic spectroscopy measurement module is shown in Fig.3 (a). The photograph of the DGA system is shown in Fig. 3 (b). In this technique a simple hot wire source produces broadband radiation across the Infrared range that is focused into the measurement cell using a parabolic mirror.

Table 5: Triangular coordinates for Graphical representation of Duval triangle zones

When a species absorbs some of the incoming light, one of several mechanisms of de-excitation is intermolecular colliding, which ultimately leads to increases in translation energy of the gas particles i.e., heating.

Area	Points	CH_4(%)	C_2H_4(%)	C_2H_2(%)
PD	PD1	98	2	00
	PD2	100	00	00
	PD3	98	00	2
D1	D11	0	0	100
	D12	0	23	77
	D13	64	23	13
	D14	87	00	13
D2	D21	00	23	77
	D22	0	71	29
	D23	31	40	29
	D24	47	40	13
	D25	64	23	13
DT	DT1	00	71	29
	DT2	00	85	15
	DT3	35	50	15
	DT4	46	50	4
	DT5	96	00	4
	DT6	87	00	13
	DT7	47	40	13
	DT8	31	40	29
T1	T11	76	20	4
	T12	80	20	00
	T13	98	2	00
	T14	98	00	2
	T15	96	00	4
T2	T21	46	50	4
	T22	50	50	00
	T23	80	20	00
	T24	76	20	4
T3	T31	00	85	15
	T32	00	100	00
	T33	50	50	00
	T34	35	50	15

According to the various gas laws, an increase in the temperature of the gas leads to an increase in the pressure of an isochoric (constant- volume) sample. The chopper wheel rotates at a constant speed to give a modulated frequency light signal from single to several thousand hertz. Before reaching the measurement cell the radiation is passed through one of a number of optical filters.

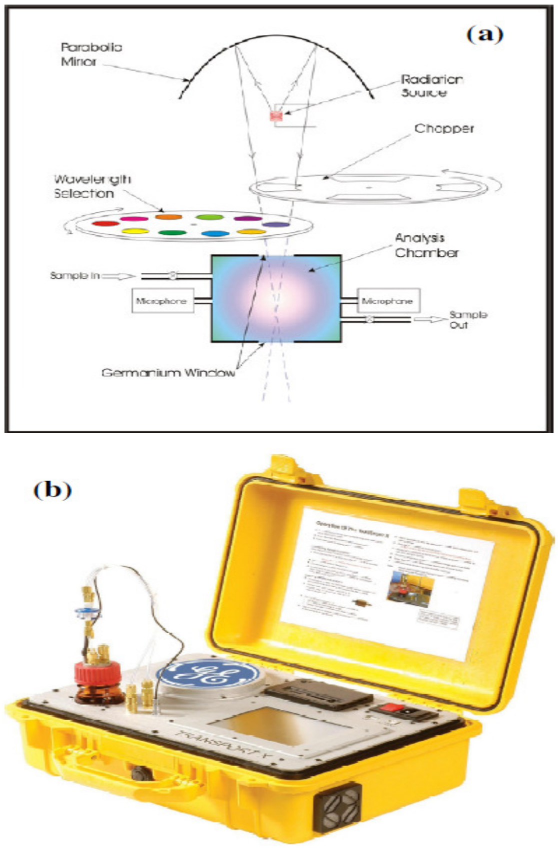

Fig. 3: Experimental setup for detecting the fault gas in the transformer oil sample (a) Schematic diagram of Infrared photo-acoustic spectroscopy measurement module (b) portable DGA system

These filters are designed to transmit the specific wavelengths chosen to excite one of the compounds under investigation. The sample is introduced into the measurement cell and the acoustic signal level is recorded at the chopper frequency from the microphones as each optical filter is indexed into the light path. Incoming light of varying wavelength will change the amount of light absorbed, the amount of pressure changes occurring and hence the amount of sound or the acoustic signal produced. The series of readings produced then gives the concentration of the desired compounds in the sample.
To carry out this work three transformer oil sample is collected and the details of the same distribution transformer are depicted in Table 6.

Table 6: Information of the transformer for DGA test

Transformer	Power (MVA)	Input Voltage (kV)	Output Voltage (kV)
TR-1	16	33	7.1
TR-2	2.75	33	0.745
TR-3	63/50/40	132	32.5

5. Results and Discussion

To conduct the DGA test three different distribution transformers are chosen for collection of transformer oil. The sample oils are kept in a test chamber after collection of oil from the service transformer. The individual gas concentrations of the sample oil for three transformers are found after performing the DGA test for five consecutive years and which depicted in Table 7. It is also observed from the same table that the water content of the each transformer is calculated which gives an additional information about the current status of the moisture presence in the transformer. The carbon dioxide, carbon monoxide and moisture of all three samples are significantly changes its concentration during its operating service period.

The ratios of the key gases of three different samples (TR-1, TR-2 and TR-3) are calculated with the help of individual gas concentration which is depicted in Table 8. The ratios of five gases C_2H_2/C_2H_4, CH_4/H_2 and C_2H_4/C_2H_6 for five consecutive years starting from 2010 and mainly calculated for electric discharge of high density of energy, partial discharge or overheating of transformer oil and presence of high and prolong temperature respectively. The ratio of C_2H_2/C_2H_4 is increasing with increase of time of transformer oil sample TR-3 compared to other sample TR-1 and TR-2 which indicates the electric discharge of high density of energy takes place. The ratio of CH_4/H_2 is not much change with the time for all the transformer oil sample which indicates the presence of partial discharge is not significantly changes for all transformers. It is also observed that the ratio C_2H_4/C_2H_6 is significantly increases with the time in case of transformer oil sample TR-2 compare to other transformer oil sample which indicates the presence of high and prolong temperature.

Analysis of Transformer oil Sample

The analysis of the three different transformer oil samples (TR-1, TR-2 and TR-3) has been carried out and their output results are shown in Fig. 4 - Fig. 7. The first transformer oil sample (TR-1) gives the output results and analysis of all gases concentration which is shown in Fig. 4 (a) and Fig. 4 (b) respectively. It is found that the transformer oil contains significant amount of carbon dioxide (7982 ppm), carbon monoxide 552 ppm and the moisture content of this sample is 75 ppm. Further it is observed that carbon dioxide and carbon monoxide concentrations are crossed its normal limit of 2500 ppm and 350 ppm respectively [4] which is indicated with red colour as '*warning'* and yellow colour as '*caution'* symbol. Figure 5 shows the graphical representation of the fault gases in 'Duval Triangle'. Due to higher concentration value of carbon dioxide T_2 region of the Duval triangle is indicated which further indicates thermal fault (300^o C - 700^o C) took place during the operating service period of the transformer which is shown in Fig. 5 (a).
Table 7: Individual gas concentration of transformer oil sample found from different year

The similar result is obtained by using same concentration value of the carbon dioxide to confirm the in-house developed software for graphical representation

Transformer oil sample	Key gases	2010	2011	2012	2013	2014
TR-1	Hydrogen	35	<5	35	26	25
	Water	89	42	53	75	89
	Carbon-Dioxide	7616	1181	8553	7982	9161
	Carbon monoxide	640	40	663	552	608
	Ethylene	60	5	43	34	38
	Ethane	89	3	46	33	34
	Methane	77	7	51	39	44
	Acetylene	<0.5	<0.5	<0.5	<0.5	<0.5
	TDCG	901	57	836	685	738
TR-2	Hydrogen	<5	<5	<5	<5	24
	Water	72	36	38	56	94
	Carbon-Dioxide	7013	4257	5520	5925	8695
	Carbon monoxide	469	319	577	420	456
	Ethylene	25	13	17	37	43
	Ethane	18	8	9	12	41
	Methane	9	6	7	8	64
	Acetylene	0.5	<0.5	<0.5	<0.5	<0.5
	TDCG	524	348	514	482	807
TR-3	Hydrogen	<5	<5	15	17	21
	Water	81	19	24	57	96
	Carbon-Dioxide	1288	2002	1261	1386	1965
	Carbon monoxide	61	247	133	133	178
	Ethylene	12	9	7	8	12
	Ethane	17	5	5	3	5
	Methane	3	9	5	12	16
	Acetylene	<0.5	<0.5	14.5	25.5	28.5
	TDCG		275	179	199	267

of the Duval triangle which is shown in Fig. 5 (b). The fault T_2 has been inactive since 2010. For the second transformer oil sample (TR-2) results and analysis is carried out and found the all fault gases concentration which is shown in Fig. 6 (a) and Fig. 6 (b) respectively. It is found that the transformer oil contains significant amount of carbon dioxide (5925 ppm), carbon monoxide (420 ppm) and the moisture content (56 ppm) which is comparatively less than the transformer oil sample TR-1 and TR-3. Further, it is observed that carbon dioxide and carbon monoxide concentrations are crossed its normal limit of 2500 ppm and 350 ppm respectively [4] which is shown in Fig. 6(b).

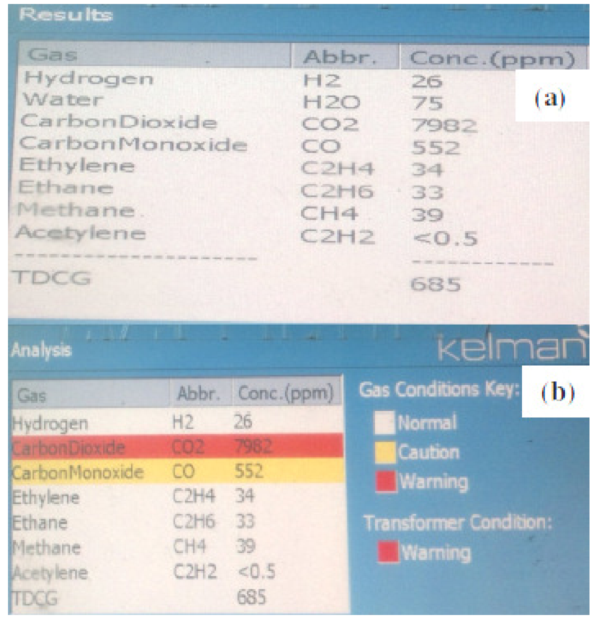

Fig. 4: Experimental observations for detecting the fault gas in the transformer oil sample 1 (TR-1) (a) different gas concentration observed in ppm (b) analysis of different gases found with portable DGA system.

Table 8: Gas ratio of three different transformer oil samples calculated in four different consecutive years

Transformer oil sample	Gas Ratios	Ratio of the gases observed in different year				
		2010	2011	2012	2013	2014
TR- 1	C_2H_2/C_2H_4	0.001	0.10	0.012	0.014	0.001
	CH_4/H_2	2.20	1.40	1.457	1.50	1.760
	C_2H_4/C_2H_6	0.674	1.667	0.934	1.03	1.120
TR- 2	C_2H_2/C_2H_4	0.02	0.038	0.029	0.014	0.011
	CH_4/H_2	1.80	1.20	1.40	1.60	2.670
	C_2H_4/C_2H_6	1.389	1.625	1.89	3.083	1.050
TR- 3	C_2H_2/C_2H_4	0.034	0.056	2.071	3.187	0.041
	CH_4/H_2	0.60	1.80	0.34	0.71	0.761
	C_2H_4/C_2H_6	0.706	1.80	1.40	1.67	2.40

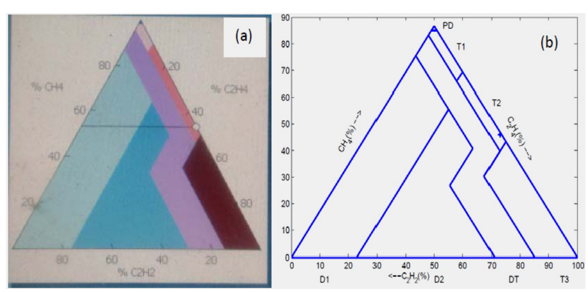

Fig. 5: Comparison of result for detecting the fault gas in the transformer oil sample 1 (TR-1) (a) experimental result for detecting fault gas (b) simulation result for detecting fault gas

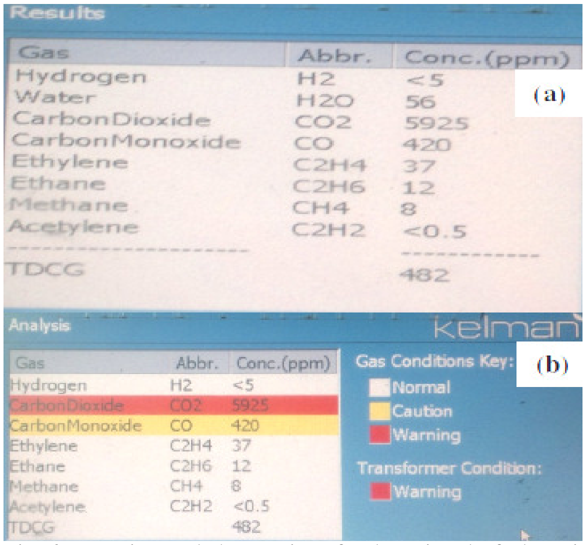

Fig. 6: Experimental observations for detecting the fault gas in the transformer oil sample 2 (TR-2) (a) different gas concentration observed in ppm (b) analysis of different gases found with portable DGA system

Due to higher concentration value of carbon dioxide T_3 region of the Duval triangle is indicated which further indicates thermal fault > 700° C took place during the operating service period of the transformer which is shown in Fig. 7 (a). The similar result is obtained by using same concentration value of all fault gases to confirm the in-house developed software for graphical representation of the Duval triangle which is shown in Fig. 7 (b).

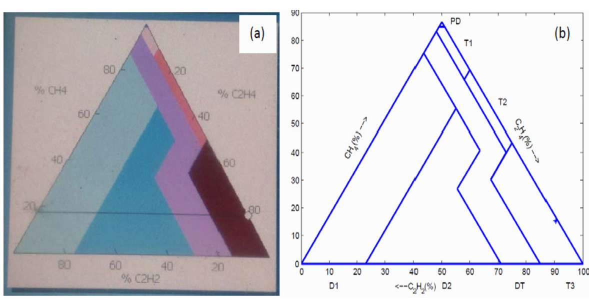

Fig. 7: Comparison of result for detecting the fault gas in the transformer oil sample 2 (TR-2) (a) experimental result for detecting fault gas (b) simulation result for detecting fault gas

Similar type of observation has been also carried out for the third sample (TR-3) and found that the transformer oil contains significant amount of carbon dioxide (1386 ppm), carbon monoxide (133 ppm) and the moisture content of this sample is 57 ppm which is depicted in Table 8. It is also observed that carbon dioxide and carbon monoxide gas concentrations are within its normal limit. However, due to higher concentration value of carbon dioxide, D_1 region of the Duval triangle is indicated which is further validated with developed software as done in case of sample TR-1 and TR-2 and indicates discharges of low energy took place during the operating service period of the transformer. It is also found that the rate of acetylene formation in oil sample (TR-3) is increasing in nature compare to other two sample which further indicates the thermal fault > 700° C took place during the operating service period of the transformer.

Further, the moisture content three individual transformer oil samples is plotted for a specified time period of every year starting from the year of 2010 which is shown in Fig. 8. The moisture content of each sample is significantly reduces in the year of 2011 because all the three transformer oils are filtrated in order to remove the presence of high level of water content. It is also found that the moisture content in the transformer oil is gradually increases which further decrease the dielectric strength of the transformer oil during the year of 2011-14. As per record from the year of 2013, it is observed that the first transformer oil sample (TR-1) has a high value of moisture concentration of 75 ppm compare to other two transformer oil sample TR-2 and TR-3. In order to know the dielectric strength of the each transformer oil samples are undergone with breakdown voltage test and found that transformer oil sample (TR-1) has lower dielectric strength because of higher level of water content which is depicted in Table 8. Further with the increase of moisture content with time period (in the year 2014) and to keep the dielectric strength of the transformer oil is reasonably high which again indicating the requirement of filtration process.

On the other hand, the ratios of the carbon monoxide to carbon dioxide are also significant and these ratios should be in the range of 1:10 for normal operation of the transformer [11]. The ratio of the carbon dioxide (CO_2) and the carbon monoxide (CO) is not included in Rogers Ratios method of analysis but is useful to determine if a fault affecting the cellulose insulation.

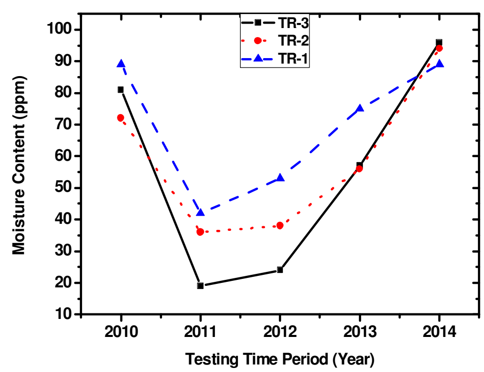

Fig. 8: Observed Moisture content in three transformer oil sample in four consecutive years

The ratio of the CO_2 and CO of each transformer oil samples are changing rapidly with the time which is depicted in Table 9. It is found from the first transformer oil sample (TR-1) has ratio of carbon dioxide and carbon monoxide is greater than 10. According to IEEE standard which is again indicating the operating condition of this transformer is in 'good' [11]. Figure 10 shows the concentration of carbon dioxide (CO_2) and the carbon monoxide (CO) gas present in dissolve condition in the second transformer oil sample (TR-2). It is found that the ratio of CO_2 and CO of each transformer oil samples is changing rapidly with the time. For the second transformer oil sample (TR-2), it is found the ratio of CO_2 and CO is below 10 but within the range of 6-10 in the year 2012. According to IEEE standard which is again indicating the operating condition of this transformer is in 'fair' which further denoted acceptable marginal operating condition of the transformer [11].

Similarly, the concentration of carbon dioxide (CO_2) and the carbon monoxide (CO) gas present in dissolve condition in the third transformer oil sample (TR-3) is calculated and found that the ratio of CO_2 and CO of each transformer oil samples is changing rapidly with the time. However, the result in the year of 2011 and 2012 the CO_2 and CO ratio is below 10 but within the range of 6-10 which indicating the operating condition of this transformer is in 'fair' [11] which is further denoted acceptable marginal operating condition of the transformer during this time period. Further, it is observed that from the three transformers oil sample (TR-1, TR-2 and TR-3) the fault T_2 has been inactive since 2010, transformer oil sample (TR-2) the fault T_3 is very small and not a concern and transformer oil sample (TR-3) the rate of acetylene formation is potentially a concern.

Table 9: Ratio of the CO_2 and CO in three transformer oil samples

Transformer oil sample	Gas Ratios		Ratio of the gases observed in different year			
		2010	2011	2012	2013	2014
TR- 1	CO_2/CO	11.9	29.53	12.90	14.46	15.07
TR- 2	CO_2/CO	14.95	13.35	9.56	18.86	19.07
TR- 3	CO_2/CO	21.12	8.11	9.48	10.42	11.04

Further it is observed that the ratio of the carbon dioxide (CO_2) and the carbon monoxide (CO) of each transformer oil sample is changing rapidly with the time which is shown in Fig. 9. In the transformer oil sample TR-1 and TR-2 the amount of CO_2 gas concentrations is increases significantly but at the same time the ratio of CO2 and CO are also significantly changes and the magnitude of this ratio is much higher than the specified value [11]. This ratio has increased in the year of 2013 & 2014 and which is greater than the 10 and the transformers are in safe zone as per IEC standard.

Breakdown voltage test of transformer oil sample

Apart from the DGA test, dielectric test for the transformer has been carried out for extract additional information of the breakdown voltage (BDV) of the transformer oil sample. Table 10 is showing the breakdown voltage of three different transformer oil samples. The reading of the breakdown voltage is taken as mean value after five consecutive BDV test on the each transformer oil samples which is depicted in Table 10.

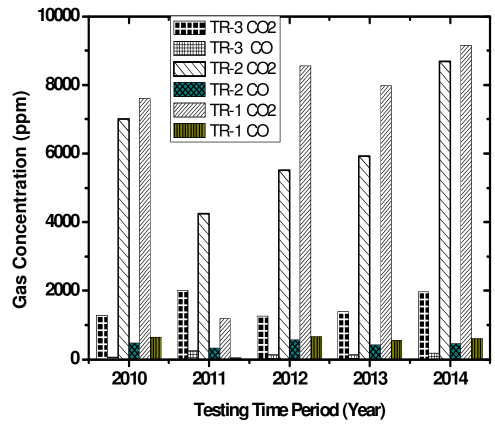

Fig. 9: Dissolved Carbon Monoxide (CO) and Carbon dioxide (CO_2) gas concentration obtains from transformer oil sample (TR-1, TR-2 and TR-3) in different time period.

Table 10: Breakdown voltage of three different transformer oil samples

Transformer Oil Sample	Mean BDV (kV)
TR-1	8.9
TR-2	23.5
TR-3	28.2

The BDV value of the transformer oil sample TR-2 and TR-3 is reasonably good and suggested that to continue the operation with a periodically check up of BDV test. It is also found that the transformer oil sample (TR-1) having less BDV value of 8.9 kV which means that its crosses the critical limit of dielectric strength of transformer oil. It is also observed that the reason behind getting the less value of BDV is moisture content of this sample much higher compare to other sample which is 75 ppm as of 2013.

Figure 10 shows that FTIR spectra obtained for transformer oil samples TR-1, TR-2 and TR-3. For sample TR-1 the peaks observed are at 2920,2851,1459,1375 and 721 wavenumbers. These peaks represent interaction of light with the various functional groups at different wavelengths. Whereas in the case of sample TR-2 and TR-3 peaks are almost at same wavenumbers, amplitude of the peaks are higher which indicates these oils are degraded as transformer is affected by various stresses during transformer operation. It is observed for sample TR-2 and TR-3 that, the peaks at 2920 and 2851 wavenumber indicate alkyl C-H bend stretch, in fact it is CH_2 bond. Gases identified at 2920 and 2851 are CH_4, C_2H_6, and H_2O. Subsequently peaks at 1459 and 1375 wavenumber reveals that these are CH_3 carbon Hydrogen bending vibration. Also between 860-680, the peaks observed are found to be CH_2 bonds. Exactly at 721 peak acetylene (C_2H_2) gas is identified.

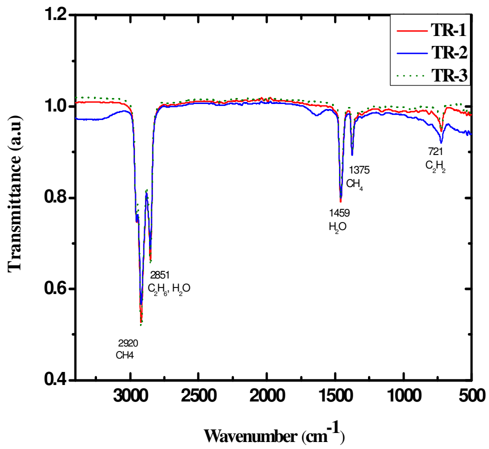

Fig. 10: FTIR spectra of diagnostic gases obtain from transformer oil sample (TR-1, TR-2 and TR-3).

Infrared photo-acoustic spectroscopy (IPAS) and the Fourier Transform Infrared Spectroscopy (FTIR) technique have been compared for diagnosis of the transformer health condition. It is observed that all the dissolve gases are not identified by the FTIR method. However, IPAS technique has potential to identify all the nine gases and the moisture content in the transformer oil with higher accuracy.

6. Conclusions

In this work, an effort has been made for diagnosis the incipient fault inside the transformer using novel technique is known as Infrared photo-acoustic spectroscopy. The technique which is used to detect the fault gases (H_2, C_2H_6, C_2H_4, C_2H_2, CH_4, CO, CO_2, O_2 and N_2) presence in the transformer oil sample. The identities of the gases being generated are very useful information in any preventive maintenance program. Moreover, it does not suffer from electrical interference and can be done without de-energisation of the transformer. The cost of each DGA is relatively inexpensive. All these factors make this Infrared photo-acoustic spectroscopy technique, a powerful tool in the preventive maintenance of transformers. With this facility an extremely high performance standards and genuine portability, giving measurement of all fault gases along with moisture contains in the transformer oil. In addition, computer based transformer oil insulation assessment software using Duval Triangle method has been developed for analysis the detected dissolve gases from the oil sample and verified the test result with commercially available portable dissolve gas analyzer. It is found that the developed software is quite suitable for identify dissolve gases inside the transformer oil. Finally, the Infrared photo-acoustic spectroscopy (IPAS) and the Fourier Transform Infrared Spectroscopy (FTIR) results are compared and found the superiority of IPAS technique for diagnosis of the transformer health condition.

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