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An Experimental Approach: Condition Monitoring of Transformer Liquid Insulation

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Abstract*— Power transformer is the only device in electrical sector which costs about 30% of the total cost involved in power system network .Any fault in this device leads to unplanned outages, thus, creating problem to end user and huge loss to electrical as well as industrial sectors. 70-75% faults occur in insulating parts of transformer i.e. insulating oil, 20% faults in winding and bushing parts and 5% others. Various diagnostic tests are carried out such as Breakdown voltage test (BDV), Dissipation Factor (DDF), Sweep Frequency Response Analysis (SFRA), Spectrophotometer to avoid failure of the system, but they do not give information regarding incipient faults, which result in liberation of gases .These gases may increase with temperature rise (ACCELERATED AGEING) and distribution of these gases is related to particular type of electrical fault. At a certain temperature, these gases react with paper insulation which reduces the dielectric strength of paper i.e. Degree of polymerization (DP). This paper mainly explains how dissolved gas analysis is carried out for a practical transformer and a particular fault is determined and degree of polymerization value is obtained through Experimental approach.

***Index Terms*— Degree of polymerization (DP), Dissolved gas analysis, Furanic compounds, Transformer mineral oil.**

I. INTRODUCTION

The transformer is a static device, which transfers power from one circuit to another circuit without change in frequency. In many plants, these transformers are bulky in size because of greater capacity. As its efficiency is 99% its lifespan is more, but its life depends on the rate of faults occurring and rate at which moisture enters the transformer tank. We need to check the heath of transformer regularly by means of testing the transformer oil so that we can detect incipient faults and can provide predictive maintenance. The quality of the transformer oil greatly affects the insulation and cooling properties of the transformer. Performing tests to evaluate the quality of the transformer oil constitutes an important part of the condition monitoring of transformers. The major causes of oil deterioration are moisture and oxygen which cause the paper insulation to degrade at higher rate than normal. When the oil oxidizes acid, sludge and water are produced. The sludge settles on the windings and reduce the heat transfer from the windings to the oil .The oil oxidation begins as soon as the transformer is energized and cannot be stopped but can be slowed down by preventive maintenance actions. This is carried out by two methods namely Dissolved Gas Analysis & Furan Analysis.

II. DISSOLVED GAS ANALYSIS

By DGA, we can test and predict the gases evolved and dissolved in gases, with that we can analyse the particular fault in transformer, where as in furan analysis we can test, which compounds are formed in oil and corresponding fault is predicted. The health of a transformer can be monitored without taking a shutdown by analyzing the dissolved combustible gases which are formed due to electrical and thermal stresses. Both oil and cellulose breakdown due to electrical and thermal stresses to release Hydrogen, Hydrocarbon Gases and Oxides of Carbon [1-2]. It is possible to detect faults in transformers at the incipient stage by proper gas analysis. The gas chromatograph is the most practical method available to identify and quantify combustible gases.

Oil consisting of high molecular weight hydrocarbon molecules can suffer degradation due to decomposition of these molecules in to lighter and more volatile fractions. This process is also accelerated by temperature and it cannot be prevented at higher temperatures generated by fault conditions. The composition of the gas produced in a fault is decided by many factors. In addition the gases which are seen in any sample taken for analysis are further influenced by factors other than those relating to the fault. The previous history of the transformer, the loading regime, and the amount of insulation that it contains and the dryness of this insulation as well as the precise location of the fault are just some of these. Nevertheless, it is possible to relate certain patterns of gas evolution to temperatures existing at the fault and from knowledge of these, along with a careful assessment of all other relevant factors, to obtain some appreciation of the nature and seriousness of the fault.
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. The important gases produced from the transformer operation can be listed as follows:

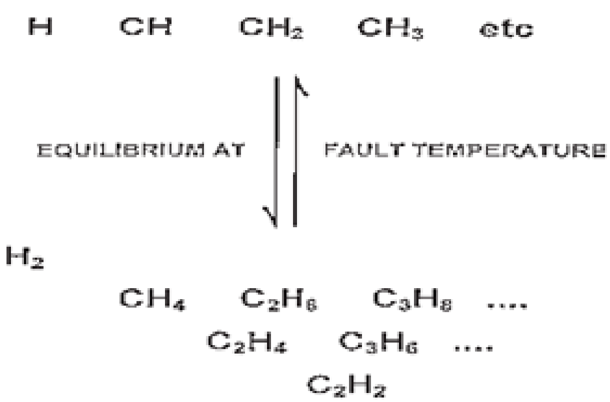

Fig. 1 Free Molecules of hydrocarbon gases

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-*Hydrocarbon gases and hydrogen*: methane, ethane, ethylene, acetylene, and hydrogen.
-*Carbon oxides*: carbon monoxide and carbon dioxide.
-*Nonfault gases*: nitrogen and oxygen

A healthy transformer should have less than 0.05 ml of combustible gases (hydrogen and short chain hydrocarbons: methane, ethane, ethylene, acetylene) per 100 ml of oil and insignificant levels of higher hydrocarbon gases. Measurements on free breathing transformers show average CO+CO(2) levels of 0.4 ml/100 ml of oil after15years.

Normally causes of fault gases are classified into three categories:
-*Corona or partial discharge*
-*Thermal heating*
-*Arcing.*

It is commonly accepted that hydrogen gas is produced from the corona effect on oil and cellulose. Methane and ethane are produced from low temperature thermal heating of oil and high temperature thermal heating produces ethylene and hydrogen as well as methane and ethane. Acetylene is only produced at very high temperatures that occur in the presence of an arc. Low temperature thermal degradation of cellulose produces CO(2) and high temperature produces CO. Low energy electrical discharges produce hydrogen and methane, with small quantities of ethane and ethylene. Electrical arcing produces large amounts of hydrogen and acetylene with minor quantities of methane and ethylene.

The solubility's of these gases in oil as well as temperature dependence are also important factors for consideration in fault gas analyses [2]. It should be noted that there is almost two orders of magnitude difference, least soluble HYDROGEN and most soluble is ACETYLENE gas.

[1] Permissible limits at normal operating conditions

The majority of the gases that are indicative of faults are also those that are in general the more soluble in oil. Refer Fig. 2.

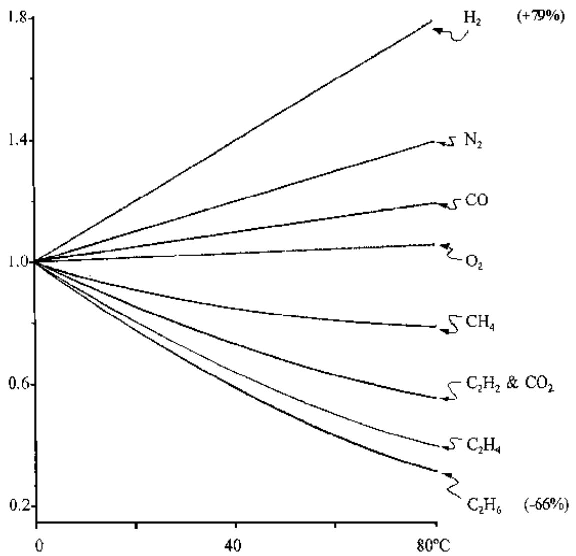

Fig. 2 Permissible limits at normal operating temperature

TABLE I Normal values of dissolved gases in transformer oil

Gas	H2	CH4	C2H4	C2H2	CO2	CO
Ppm	100	50	50	5	5000	200

[2] Temperture dependence of these gases

When rates of gas generation are being followed it is important to take in to account the solubilities of these gases as a function of oil temperature Over a temperature of 0 to 80 ◦C some gases increase in solubility up to79% while other decrease up to solubility 66◦C. Refer Table II.

[3] Solubilty of gases by volume

The health of paper insulation can be determined by measuring the concentration of furanic degradation products in the transformer oil. The state of degradation of the paper determines its mechanical properties and its ability to effectively act as insulator. Furanic compounds from the paper can be quantified in the oil by HPLC. The origin of Furans comes from thermal degradation of cellulose to release by-product levo-glucosan (LG) which is rich in polysaccharide compounds. The Kraft pulping process employed to manufacture electrical winding insulation paper reduces the lignin and hemicelluloses content of wood by approximately 80 and 90%, respectively. The resultant paper, however, still contains about 3 to 7% lignin and 2 to 4% hemi-cellulose. In addition to these residues, are metallications along with absorbed moisture content in the range of 2–4 percent by weight? The amount and type of hemicelluloses may be an important factor in the production of furanic compounds from Cellulosic paper.

TABLE II. Solubility of Gases by Volume

Solubility Of These Gases In Transformer Oil At 760mm of Hg @25◦C	
Hydrogen	7% by volume
Nitrogen	8.6%
Carbon monoxide	9%
oxygen	16%
Methane	30%
Carbon dioxide	120%
Ethane	280%
Ethylene	280%
Acetylene	400%

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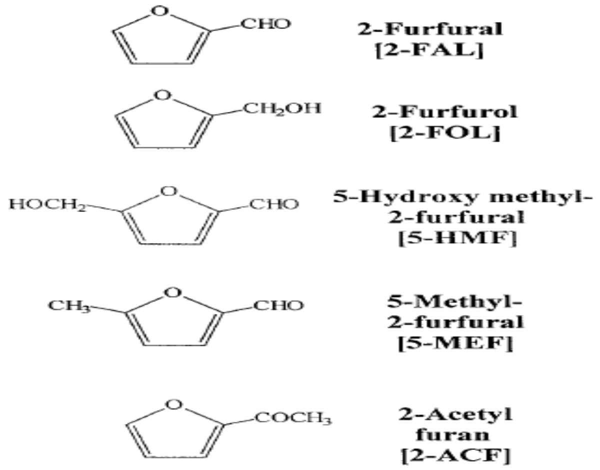

Fig 3. Furanic Compounds

Another factor that complicates the investigation of the formation and mechanism of furanic compounds from cellulosic insulation is the influence of water. It has been known for some time that the hydrolytic degradation of cellulose can lead to the formation of furanic compounds, particularly 2-FAL. It has been observed in operating transformers that highest rates of furfural hydrolysis reactions are important for the production of furanics at low temperatures. Indeed, has been identified 2-FAL, 5-HMF, and 5-methyl-2-furfural (5-MEF) as major products of the hydrolytic degradation of cellulose in the temperature rangeof100–200 C. Although water clearly promotes furanic formation, the mechanism by which this occurs is unclear. A mechanism for hydrolytic formation of 5-HMF and 2-FAL from cellulose.

[4] Production of 2-FAL hydrolytic thermal degradation Degree of polymerization

Another possibility is that there is paper insulation which is provided wrapped over windings and its aging is irreversible, tensile strength decreases making the unit susceptible to vibration, through faults, & short Circuit When it is mixed with oil there is a possibility of natural and steady breakdown of polymer chains i.e., degradation of cellulose material leads to formation of furanic compounds referring fig. 4.The mechanical properties of insulating paper can be established by direct measurement of its tensile strength or degree of polymerization (DP). These properties are used to evaluate the end of reliable life of paper insulation. It is generally suggested that DP values of 150-250 represent the lower limits for end-of-life [3].

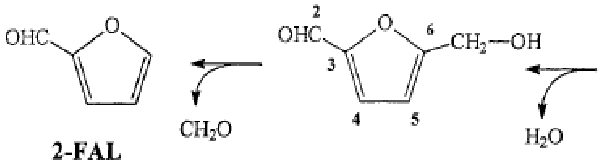

Fig 4. Thermal Degradation To 2-FAL

The solid insulation used in transformer gets degraded at higher temperatures in presence of oxygen and moisture .The furan test is recommended when the ratio of carbon dioxide/carbon monoxide > 7 ,it means the solid insulation dielectric strength is no more capable of sustaining high temperature heating and other through faults. The following are the furanic compounds that arises in transformer under abnormal conditions (Fig. 3):

1. 2-Furaldehyde(2-Fal)
2. 2-acetyl furan(2-ACF)
3. 2-Furfuryl alcohol(2-FOL)
4. 5-methul-2-furaldenhyde(5-MEF)
5. 5-hydroxylemethy-2-furaldehyde(5-HMF)

III. EXPERIMENTAL PROCEDURE

A. Dissolved Gas Analysis

Sampling: Utmost care should be taken while collecting sample because moisture and oxygen influences and results obtained will be inaccurate. The oil is collected in a metallic cylindrical vessel made of Aluminum, glass or stainless steel and tightly sealed after sampling.

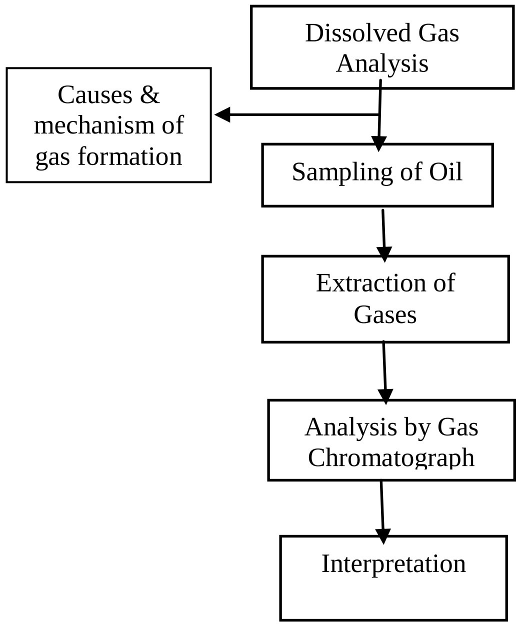

Fig. 5 Flowchart for DGA process

Fig. 6 Sampling at Anoo substation, Hamirpur, HP, India

Extraction of Gases: Extraction of gases from oil is carried out through 2 methods:

TORRICELLI PUMP METHOD----- used to extract single gas from oil;

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TOEPLER PUMP ----used to extract multiple gases.

CPRI has developed the toepler pump and it has been passed to M/S *Dakshin lab agencies, Bangalore* for manufacture and supply and it can extract minimum 98% gases from dissolved oil.

Analysis of Gases: The Kelman TRANSPORT X is a compact portable dissolved gas analysis (DGA) system which analyses transformer oil samples for all dissolved fault gases by gas chromatography. The accessories include Sample bottle with connection and pipes and a syringe for extracting oil sample from the equipment and injecting it into bottle. The embedded pc and touch screen display step by step instruction, thermal printer gives display of output in hard copy

Interpretation: There are several interpretation techniques proposed by different researches and they are prominently used to identify type of fault and severity of fault in most of the practical applications .Different techniques are as listed:

1. Key Gas Method
2. Rogers Ratio Method
3. Dual Triangle method
4. Dorenberg Method
5. IEC Ratio Method 60599

Fig. 7 Kelman Transport X DGA Analyser

In this paper IEC Method is used to diagnose fault based on "*Guide for Interpretation of the Analysis of Gases in Transformer and Other oil Filled Equipment in Service"[4]*

B. Furan Analysis

To measure furans is to estimate the degree of polymerization which indirectly estimates health of transformer is carried by *High Performance Liquid Chromatography (HPLC).*A sample of oil is extracted with either another liquid such as aceto -nitrile or with solid extraction (SPE) device. The extract is analyzed by *HPLC.*

The five compounds mentioned above are separated on an appropriate column and each is detected by use of an ultraviolet detector that is adjusted to the appropriate wavelength for each of its five compounds. Degradation of cellulose materials produce carbon monoxide and carbon dioxide gases. By extracting these gases and analyzing them, the paper insulation degradation can be accessed. Furan level in a transformer can be correlated with the paper DP, and therefore an in-service assessment of the mechanical strength of the paper insulation can be made. De Pablo reported the following relation between the furfural and DP based on viscosity (DPv)

$$DP_V = \frac{7100}{8.88 + 2FAL}$$

Where 2FAL is the 2-furfural concentration in mg/kg of oil

Fig. 8 High performance liquid chromatograph

IV. CASE STUDY

0.5 MVA, 5MVA and 50 MVA transformers installed in Himachal Pradesh, Hamirpur region 66/33 kV substation have different ageing aspects. Oil samples are taken and tests were conducted in TIFAC-CORE NIT Hamirpur laboratory. The following tests (DGA AND FURAN) and their corresponding results are shown below:

TABLE III DGA Results for Different Samples

Gas	Sample 1	Sample 2	Sample3
H2	8	12	7
CO2	3940	4210	4662
CO	393	480	510
C2H4	12	11	8
C2H6	10	13	6
CH4	11	10	8
C2H2	0.1	0.2	0.2
TDCG	434	526	537

DGA for Different Samples

Referring Table III, Sample data 3 is analyzed to interpret type of fault and whether furan test is recommended for further analysis or not.

$C_2H_2 / C_2H_4 = 0.025 < 0.5$ $CH_4/H_2 = 1.14 > 1$

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C_2H_4/C_2H_6 = 1.33 >1 CO_2/CO = 9.14 > 7
Code obtained from above analysis is 1 1 0 implies fault is PARTIAL DISCHARGE of high energy density
CO_2/CO Ratio is > 7 implies thermal fault. It also recommends furan test to check the degree of polymerization state

HPLC Result

In Fig. 9, 3 samples are used to understand the ageing characteristics from the wavelength and DP value. This DP indicates insulation condition which don not have linear variation, it depends on Different parameters such as moisture content, operating Temperature of oil, Rate of change of Fault gases present etc., It was Observed that as wavelength increases its corresponding absorbance area increases from reference value and this causes Furan concentration to be appreciably not acceptable level, DP value goes down indicates

TABLE IV HPLC Result

Sample	Wavelength (nm)	Absorbance (nm)	Furan (ppm)	Dp value
1.	311.80	1.320	0.30	640
2.	333.20	1.412	0.89	580
3.	390.20	1.635	1.22	430

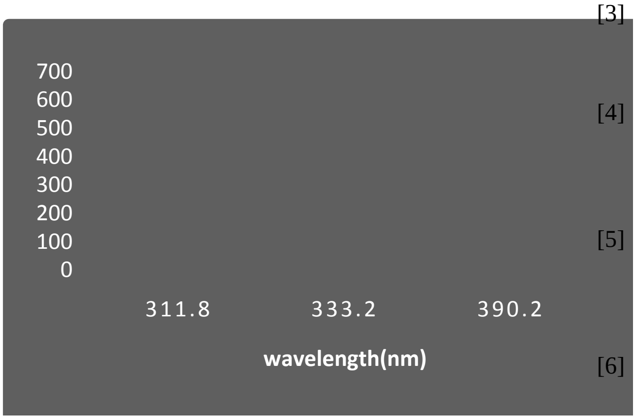

Fig. 9 Variation of DP versus Wavelength

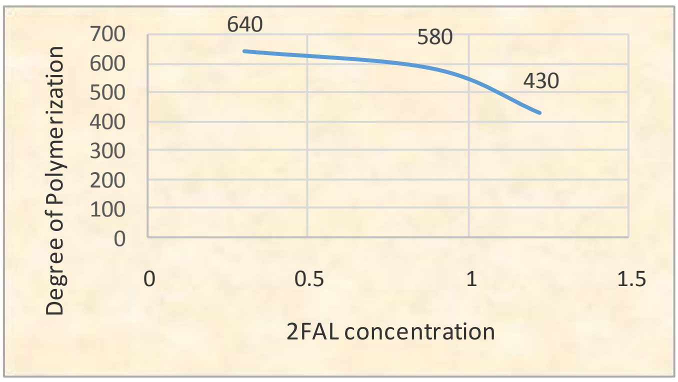

Fig. 10 Variation in DP versus 2FAL Concentration

the state of solid insulation. If DP < 300 it is recommended to change the solid insulation to avoid failure of transformer.

IV. CONCLUSION

IEC Method is good at interpretation of one type of fault mostly preferred in industrial as well as laboratory research works. It was observed that fault is partial discharge which is not severe since gases are with in permissible limits, but variation of CO gas at other than normal temperatures causes deterioration of solid insulation. Hence it is recommended to change the solid insulation if DP value reaches below 300 to avoid failure of transformer.

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