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Assessment of Solid Insulationof Power Transformers through Dissolved Gas Analysis

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Power Transformers are the most vital equipment in a sub-station / Receiving station. Failure of a transformer leads to loss of revenue besides affecting reliability of power supply to consumers and also on cost. Hence assessment of transformers plays crucial role in the overall integrity of power system which includes remaining life of the equipment. In order to ensure that Power Transformers provide long and trouble-free service, several diagnostic tests are carried out and remedial actions initiated throughout their operational lifetime. It can be done by assessing the extent of degradation of the cellulosic paper & oil insulation through furan content in oil, degree of polymerization of paper insulation and dissolved gas analysis (DGA) in oil. This can help the utilities in making optimum use of the Transformers and also taking timely decisions regarding refurbishment / replacement of Transformers. Therefore, attempts are being made to discuss the details of furan analysis, degree of polymerization and DGA with few case studies in assessment of power transformers.

Keywords: *Power Transformers, Degree of Polymerization, Furan content, Dissolved Gas Analysis.*

1.0 INTRODUCTION

Reliable electrical supply has become one of the basic needs for development of society. Gap between demand and supply of electrical power has increased considerably in recent years. Therefore in the present circumstances it is essential to utilize the existing power network to its optimum design capability. Power transformers performance implies power system efficiency and transfer capability. Due to deregulation of electrical utilities, they are under pressure of reducing the generation cost of electricity. Hence, left with the option of overloading of transformers. Overloading introduces transformers to thermal and electrical stresses and health deteriorates [1]. The power transformer design, operation and maintenance are very complicated and hence it is very difficult to predict the expected life of a transformer. Various power transformer failures lead to minor/severe power supply interruptions, raising need of different preventive, predictive and spontaneous repair techniques to eliminate or at least minimize them. Hence, assessment is essential for checking the health of transformers. Assessment tests include IR, Tan delta, Mag. balance, Turn ratio, Furan tests and Dissolved gas analysis. SFRA is also conducted these days. Assessment enables utilities to take appropriate decision on renovation or replacement [2].

Assessment of older transformer is more relevant in recurring problem or met with a major failure. Age of a transformer is decided by life of cellulosic materials. A composite insulation system comprising of Insulating liquid and solid (paper, press board, cotton tape) insulation of any power transformers. This is not only provides the required insulating media, also performs the function of providing strength to the windings

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and also acts as the heat transformer media (Insulating liquid). During the service period of the power transformer, insulation system deteriorates and completely loses its dielectric properties.Presently special importance is given to condition based maintenance which includes assessment of remaining life. The transformer is said to reach end of its life when the insulation system deteriorates and completely loses its dielectric properties.

Insulation age of a transformer is exclusively decided by life of cellulosic materials. In this study an effort has been made to measure all three ageing indicating parameters (namely ratio of CO_2/CO using DGA, degree of polymerization (using models) and furan content) with few case studies in determining the assessment of solid insulation in maintenance of power transformers.

2.0 EXPERMENTAL

Furan analysis and dissolved gas tests were carried out as the samples received for this study.

Degree of Polymerization (DP) test is also known as Viscometric degree of polymerization (DP_v). The DP test provides information on the integrity of the cellulose chains, i.e. the average number of glucose units in the cellulose molecules of a paper sample. This is a physico–chemical test and the test method is as per ASTM D 4243 and it involves measurement of moisture content of the paper and intrinsic viscosity of solution of paper in cupric ethylene diamine solvent.

Several relations between Degree of polymerization and 2-Furaldehyde (FAL) content in Transformer oil have been postulated by researchers. The models are Chendong model, Stebbings model, De Pablo model and Modified De Pablo's equation by Phalvavanpour. DP values were calculated using Modified De Pablo's equation by Phalvavanpour for this study [3].

Modified De Pablo's equation by Phalvavanpour is given as

$$DP=800/ (0.18682FAL)+1 \quad \ldots(1)$$

Where DP is the Degree of Polymerization

FAL is the 2-Furaldehyde in ppm

Thermal degradation of paper leads to formation of Furanic compounds in transformer. The Furanic compounds generated exists in dynamic equilibrium between solid and liquid insulation.The main furanic compounds are a) 2-Furfuraldehyde (Furfural -2FAL); b) 2-Furfuryl alcohol (2 FOL); c) 5-Hydroxymethyl-2-furfuraldehyde (5HMF); d) Acetyl Furan (ACF) and e) 5 Methyl-2-furfuraldehyde (5MEF). Among these compounds,2-Furfuraldehyde (Furfural -2FAL) is major furan and the other furans (minor furans) are scarce.

The types and concentrations of furans in an oil sample can also indicate abnormal stress in a transformer, whether intense, short duration overheating or prolonged, general overheating. Table 1 shows types of furans with type of stresses in the transformers [4].

TABLE 1

TYPES OF FURANS WITH TYPE OF STRESSES IN THE TRANSFORMER

5-Hydroxymethyl-2-furaldehyde	5H2F	Oxidation
Furfuryl alcohol	2FOL	High Moisture
2-Furaldehyde	2FAL	Overheating, old faults
2-Furyl methyl ketone	2ACF	Rare, lighting
5-Methyl-2-furaldehyde	5M2F	Local, severe overheating

Paper in a transformer does not age uniformly and variations are expected with temperature, moisture distribution, oxygen levels and other operating conditions. The levels of 2-furaldehyde in oil relate to the average deterioration of the insulating paper. Consequently, the extent of paper deterioration resulting from a "hot spot" will be greater than indicated by levels of 2-furaldehyde in the oil.

Similar to Dissolved gas analysis which gives indications of incipient faults in the transformer, Furanic compound analysis is useful in ascertaining

the condition of solid insulation in the transformer and thereby one can take preventive measures to avoid failure of transformer.

Furanic compounds were measured using high performance liquid chromatography (HPLC), Make : Shimadzu, Model : SPD-M20A as per IEC 61198 /ASTM D 5837 [5,6]. The furanic compounds from transformer oil were extracted by liquid – liquid extraction and injected into the UHPLC System having isocratic conditions and eluent – Mixture of water and methanol or acetonitrile in the ratio 80:20 at flow rate of 1 ml/ min. The column for separation of components is the C18 column and the detector used is the Photo Array diode detector. The absorbance at wavelengths 220 nm for FOL and 276 nm for FAL, 5MEF, HMF and ACF were recorded and analyzed. HPLC grade chemicals were used. The results are expressed in ppb.

Factors affecting Furan concentration:

The furanic compounds exists in equilibrium with solid insulation and liquid insulation depending on the operating temperature and moisture saturation of the oil. Furan content in oil is having an inverse relationship with moisture content of the oil. As the moisture content in oil increases, furan content decreases. Myers has given a relation between the two as-

Total furan (ppb) = 2.170 – (20.3 x % moisture saturation). --- (2)

Reclaiming of oil with fullers earth seriously disturbs the furan content in thetransformer. Fuller's earth will remove furan content down to few ppb level in oil. But reclamation will not remove furans from the paper insulation. Furanic compounds reside on the paper and they will migrate back to the oil during operation and this may take few months.

The main advantages of minor furans are their sensitivity and specificity and are the first indicators of trouble.

It has been reported in the literature that

a) thermally upgraded paper generated substantially lower furanic compounds concentration
b) Furanic compounds demonstrated lower stability in insulating liquids spiked with dicyandiamide and
c) Furanic compounds, on average, were substantially higher in operating transformers that were not manufactured using thermally upgraded paper.

Dissolved Gas Analysis

DGA was measured using gas chromatography (GC), Make :Mayura, Model : 2001 as per IS : 9434 [7]. The power transformer oil sample constitutes various gases which are significant in deciding the transformer behavior and life. The main gases that are collected include: a) Hydrogen b) Methane c) Ethane d) Acetylene and e) Ethylene. These gases are generally isolated from the sample and analyzed quantitatively using Gas Chromatography process. This technique enables proper diagnosis of the transformer condition in service and can also suggest preventive measures. Elevated concentrations of gases may signal corona, discharge, overheating, arcing or cellulose insulation pyrolysis. Also, the relative quantities of all these gases give the oil decomposition energy during a particular fault. The results are expressed in ppm.

3. 0 Results and Discussions

The Mechanism of cellulose degradation is shown Figure 1.

Case Study 1

Oil samples were monitored for three consecutive years from 20 MVA, 132/6.6 kV, SS Transformer of a utility with 20 years of service and evaluated for furan analysis and dissolved gas analysis. D.P* values were calculated using modified De Pable equation by Phalvavanpour. The trends analysis results are indicated in Table 2.

TABLE 2			
TREND ANALYSIS OF TOTAL FURANS, DP & DGA			
Duration	Total Furans, ppb	D.P *	DGA, CO_2/CO
1st year	ND	800	4
2nd year	30	796	6
3rd year	ND	800	4

From the values of total furans, DP and DGA (CO_2/CO ratio) showed that the condition of insulation is normal.

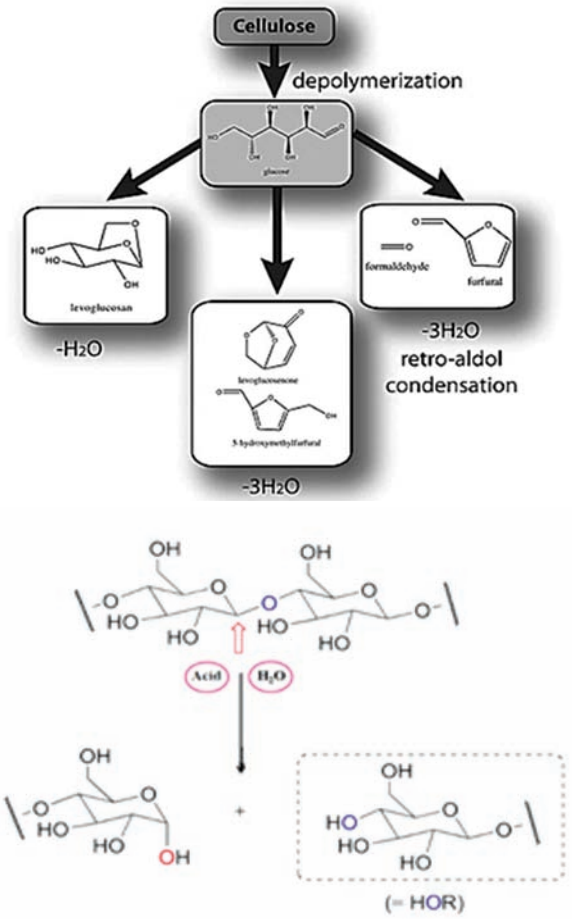

FIG 1 MECHANISM- CELLULOSE MOLECULE DEGRADATION

Case Study 2

Oil samples were monitored for three consecutive years from 16 MVA, 10.5/6.9 kV, UAT Transformer of a utility with 20 years of service and evaluated for furan analysis and dissolved gas analysis. D.P* values were calculated using modified De Pable equation by Phalvavanpour. The trends analysis results are indicated in Table 3.

TABLE 3			
TREND ANALYSIS OF TOTAL FURANS, DP & DGA			
Duration	Total Furans, ppb	D.P *	DGA, CO_2/CO
1st year	710	703	15
2nd year	830	693	15
3rd year	850	690	12

From the results of total furans, the insulation is normally deteriorated and the same has been confirmed with DP as well as DGA.

Case Study 3

Oil samples were monitored for three consecutive years from80 MVA, 132/10.5 kV, GT Transformer of a utility with 35 years of service and evaluated for furan analysis and dissolved gas analysis. D.P* values were calculated using modified De Pable equation by Phalvavanpour. The trends analysis results are indicated in Table 4.

TABLE 4			
TREND ANALYSIS OF TOTAL FURANS, DP & DGA			
Duration	Total Furans, ppb	D.P *	DGA, CO_2/CO
1st year	890	686	5
2nd year	1100	664	10
3rd year	1350	639	15

The first two years results of total furans, the insulation is normally deteriorated and the same has been confirmed with DP as well as DGA. The third year result of total furans along with DP and DGA shows the low reliability of solid insulation.

Case Study 4

Oil samples were monitored for three consecutive years from140 MVA, 220/10.5 kV, GT Transformer of a utility more than 30 years of service and evaluated for furan analysis and dissolved gas analysis. D.P* values were calculated using modified De Pable equation by Phalvavanpour. The trends analysis results are indicated in Table 5.

TABLE 5			
TREND ANALYSIS OF TOTAL FURANS, DP & DGA			
Duration	Total Furans, ppb	D.P *	DGA, CO_2/CO
1st year	2810	525	18
2nd year	3010	512	17
3rd year	3530	482	19

The values of total furans during 1st year show that the solid insulation is critical and the trend for consecutive years is uniform. It has been confirmed from the values of DP as well as DGA.

Case Study 5

TABLE 6			
TREND ANALYSIS OF TOTAL FURANS, DP & DGA			
Duration	Total Furans, ppb	D.P *	DGA, CO_2/CO
1st year	1600	616	5
2nd year	1600	616	7
3rd year	1580	618	5

TABLE 7	
INTERPRETATION OF RESULTS FROM D.P VALUE	
D.P Range	**Remarks**
< 200	Test indicates extensive paper degradation exceeding the critical point. Strongly recommend that the transformer be taken out of service immediately and visually inspected.
200-250	The paper is near or at the critical condition. Recommend that the transformer be taken out of service as soon as possible and thoroughly inspected. Paper samples can be taken for direct DP testing
260-350	The paper is approaching the critical condition. Suggest inspection be scheduled and/or resample within 1 year to reassess condition.
360-450	The paper is starting to approach the critical condition. Suggest a re-sample in 1-2 years time.
460-600	Significant paper deterioration but still well away from the critical point.
610-900	Mild to minimal paper ageing.
>900	No detectable paper degradation

Oil samples were monitoredfor three consecutive years from85 MVA, 132/13.8kV, GT Transformer of a utility with 35 years of service and evaluated for furan analysis and dissolved gas analysis. D.P* values were calculated using modified De Pable equation by Phalvavanpour.The trends analysis results are indicated in Table 6.

The values of total furans during 1st year show that the solid insulation is highly deteriorated and the trend for consecutive years is uniform. But DP and DGA results show that the condition of insulation is normal.

Limiting values/ interpretation of Degree of polymerization and Furan analysis are shown in Tables 7&8 [8].

TABLE 8	
INTERPRETATION OF RESULTS FROM FURAN ANALYSIS	
Total Furans, ppb	**Condition**
0 – 100	Normal
101 – 250	Questionable
251 – 1000	Deteriorated
1001 – 2500	Low reliability
>2500	Rewind / Replace solid insulation

4.0 CONCLUSIONS

Dissolved gas analysis and furan analysis are non invasive tests and it does not require shutdown of the transformer for conducting the tests. Hence DGA (ratio of CO_2/CO) and Furan analysis testsare to be used as preliminary tests to ascertain the condition of the solid insulation of the transformer / fault involving cellulose.

Furan analysis, DGA (CO_2/CO ratio) and Degree of Polymerization (DP) are the three complementary tests to find out whether solid insulation is healthy or needs replacement / refurbishment.

Furan analysis and DP tests were to be conducted along with DGA, when the transformer under energisation condition.

It has beenobservedthat monitoring of the health of paper insulation of the transformer by monitoring concentration of furfural in oil along with DGA periodically.

The use of furan in oil analysis has a significant cost benefit in planning and maintenance of power transformer. This data needs to be viewed in conjunction with fluid insulation tests and the maintenance history.

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