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Assessment of agedInsulating Oil of Transformer in Service for Ranking of Health Condition

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Power transformers are the most critical machinery in power transmission and distribution system. Failure of a transformer causes huge loss of revenue and also affects the reliability of power supply to the consumers. With the increasing population of transformers in service and their extended operating duration, extensive care is being paid on their reliability and availability. The health status of transformer is needed to be ascertained in order to avoid any possible outage and decide a suitable maintenance schedule. Insulating oil is one of the most important components of a transformer. There is a need for continuous monitoring and assessing ageing tendency of insulating oil as an essential part for estimating remaining life of a power transformer. This paper presents the concept of Ageing Index through relative scoring of various oil parameters like Acidity, Interfacial tension, Breakdown voltage, Water content and Tan delta through a scheme that combines theses results of routine oil tests. A simplified software program is used for analyzing the results of routine oil parameter testing. This paper includes a case study on several power transformers that are in continuous service with commissioning period ranging from year 1956 to 2016.

Key words: *Transformer oil, Mineral oil, ageing, degradation, lifetime of oil, health ranking.*

1.0 INTRODUCTION

Power transformer are the most critical and expensive machinery in electric power system[1-2]. They play important role in maintaining reliable and continuous electric power supply. As the transformers are in continuous service, their internal condition deteriorates due to thermal, mechanical, electrical and chemical stresses during their operation [3], increasing risk of failure. It is very crucial task of the utilities to maintain the transformer with minimum possible failure [4-5]. There are several diagnostic and monitoring methods that are being in practice for preventing catastrophic failure and minimizing the duration of outage from service. The most common diagnostic and monitoring techniques used are Dissolved Gas Analysis, Oil Parameter Analysis, Furan Analysis, Dielectric Response Measurement, Partial Discharge analysis, Winding Displacement and Deformation assessment, Infrared Thermography etc. [4-6]. It is universally accepted that the life of a power transformer largely depends on the condition of the paper – oil insulation system[8-9].

Petroleum based mineral oil is extensively used as liquid insulation in transformer. Other liquids used as insulating oil are silicone oil, synthetic ester and natural ester [10-16]. Silicone oil is synthetic in nature with better thermal stability and flash point. It has high viscosity at higher temperatures and lower lubrication properties. Synthetic esters are prepared through chemical processes. It has very high viscosity compare to mineral oil. The flash and fire points of synthetic

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esters are also found to be at higher side compare to mineral oil.

As per literature, the synthetic esters belong to chemical groups like diester, phthalate, trimellitate, pyromellitate, dimer acid ester, polyols, and polyoleates[17]. Pentaerythritol ester is a commercially available synthetic ester insulating oil that having four fatty acid groups connected to a central polyol backbone[17-18]. Due to presence of these saturated fatty acids group, it possesses excellent oxidation stability compared to both mineral and natural ester. IEC 61099 deals with technical specifications of new synthetic ester insulating oil [19] and the guideline for in-service maintenance is detailed in IEC 61203[20].

Natural esters are extracted from seeds and are also categorized as vegetable insulating oil. Various types of natural esters like saturated, single, double and triple unsaturated fatty acids are tried for using as alternate liquid insulation in power transformers. Degradation of both mineral and ester insulating oils in transformers occurs mainly due to oxidation. Operating temperature and dissolved oxygen along with metals are the factors that control the rate of oxidative degradation of oil[21-27]. The rate of deterioration of various insulating oils reported to be as Natural ester > Mineral oil > Synthetic ester. The chemical compositions of Natural esters differ to a significant extent depending on their sources. Hence the degradation processes are more complicated with a large number of intermediate oxidative by products[24]. Due to these reasons, the available literature is still inadequate to understand the behavior of natural ester as insulator and coolant.

Inspite of having option of large number of liquid insulating materials, mineral oil is most widely used. Considering the requirement of reliability of the performance of the power transformer and cost of the insulating oil, routine condition monitoring is conducted as per guidelines of IS 1866 or IEC 60296. The condition monitoring is useful for assessing health status and ageing of liquid insulation in service. Extensive research works are dedicated for finding ageing characteristic of mineral insulating oil[28-31].

Fuzzy logic model is a computational tool that uses the data collected from various diagnostic tests to assess the overall health index of power transformers. This method is applicable to determine the individual health index of transformer oil and solid insulations. It can also analyze the incipient faults in a transformer and assess multiple faults. The fuzzy models are found advantageous over conventional fault diagnostic methods [32-34]. Asset management and decision making activities can be faster and comprehensive through the use of fuzzy logic approach. Fuzzy logic computation on data obtained through real time condition monitoring, maintenance along with data input from management activities and financial activities is beneficial in increasing reliability of power transformer [35].

Data obtained from condition monitoring and ageing characteristic analysis finds application in establishing health indicators through a scoring expert system. As the scoring system is very helpful to manage trouble free uninterrupted service of transformer, a significant amount of research findings are reported [36-39]. This paper presents the concept of Ageing Index through relative scoring of various oil parameters like Acidity, Interfacial tension, Breakdown voltage, Water content and Tan delta through a scheme that combines theses results of routine oil tests. A simplified software program is used for analyzing the results of routine oil parameter testing. This paper includes a case study on several power transformers that are in continuous service with commissioning period ranging from year 1956 to 2016.

2.0 EXPERIMENTS SETUP AND MEASUREMENTS

The experimental tests are conducted on transformers oil in service as per guidelines of IS 1866 – 2015 for their electrical, physical and chemical properties such as Interfacial Tension, Neutralization number, Tan delta, Resistivity, Breakdown voltage and Water content following test procedure of IS 6104, IS 1448 [P : 2], IS 6262, IS 6103, IS 6792 & IS 13567 respectively. The tests are carried out on used oil collected from about 200 power transformers of age ranging from 1 to 60 years.

Breakdown voltage tests were conducted on oil samples using a standard cell having two uniform copper electrodes 25 mm diameter with a gap spacing of 2.5 mm according to IS 6792 standard. The apparatus used to carry out the tests was Megger make model FOSTER OTS100AF/2 with automatic voltage rising up to 2kv/s. IFT of oil indicates the of presence of polar components. IFT value of a new and good oil is about 50 mN/m. It decreases with ageing of oil. IFT was measured following the procedure of IS 6104 using a Tentiometer model SEO/ DST 30 M, South Korea. The total acid or Neutralization number (TAN) or Neutralization number of the oil provides information about the acidic compounds produced due to aging of the insulation. It is estimated through pH titration and is reported as milligrams of KOH solution required to neutralize the acid in 1 gram of oil. New oils can have a TAN of 0.01 whereas for aged oil it can be as high as 0.25 or more. TAN of oil samples were measured as per IS 1448 [P : 2] using Autotitrator, Kyoto AT510, Japan. The water content in oil is a very useful property as it is directly linked to dielectric strength or BDV of oil and hence it is considered as one of the key factors for the safe operation of a transformer. It also indicates the extent of ageing of insulation system and remaining lifetime of the transformer. KF Moisture meter, Metrohm, Switzerland was used for measurement of water content in oil samples. To measure dissipation factor (loss tangent, tanδ) and specific resistance (ρ), Eltel make ADTR 2K apparatus was used. The three terminal oil cell and the test procedure follows was as per IS 6262 and IS 6103. The oil sample was warmed at 90°C for measurement of resistivity and dissipation factor.

3.0 RESULTS AND DISCUSSION

The results of all the oil analyses covering low, medium and high voltage power transformers with different age are determined. The transformers considered for oil analysis were of the age of 1 year to 60 years. Approximately the population of transformers was equal for all the three voltage range, 69 numbers of low voltage, 73 numbers of medium voltage and 64 numbers of high voltage.

The variation of the properties of the oil samples versus the real age of the transformers is depicted in Figure 1-5. Interfacial tension is a measure of overall oil degradation as it represents the increase in concentration of polar compounds generated as degraded products over the period of service. Figure 1 shows the variation in IFT of oil with the increasing age of transformers. A steep decrease is observed in transformer ageing upto 15 year and after this the gradient is found to be very low.

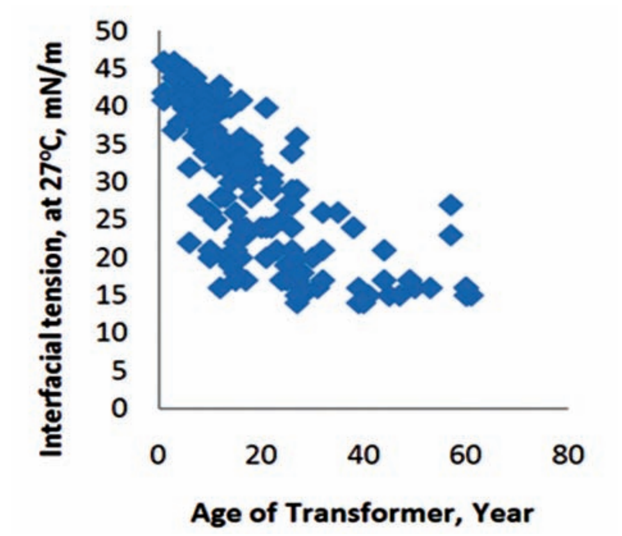

FIG 1. VARIATION IN IFT OF OIL WITH THE INCREASING AGE OF TRANSFORMERS

The insulating oil in a transformer in service is subjected to various types of stresses. Among these, the main force for ageing is oxidation. Oxidation of oil occurs in presence of air and heat. Presence of catalytic species like metal further accelerates the process of oxidation. Mineral insulating oil in service undergoes a number of degradations and finally converted to an acid. Figure 2 shows the extent of acid produced due to oxidative degradation of oil in ageing transformers. It is seen from the figure that the neutralization number is within 0.05 during the beginning stages upto an average age of about 10 years. The trend in increase in acid number with age of the transformers can be better visualized by plotting a logarithmic graph of acid numbers verses age of transformer as depicted in Figure 3.

Figure 4 demonstrates that dissipation factor of the oil increases during the service time. Hence increase in tan delta of insulating oil can be considered as a sign of ageing. Figure 5 shows that the specific resistivity of oil drops down with ageing and estimation of it can also be considered as a sign of the aging.

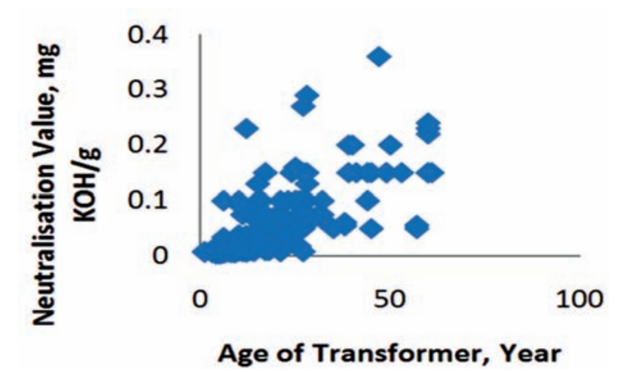

FIG 2. NEUTRALIZATION VALUE VS AGE OF TRANSFORMERS

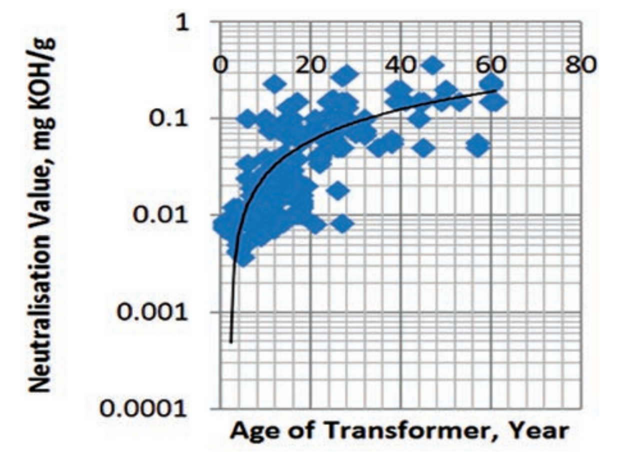

FIG 3. LOGARITHMIC PLOT OF ACID NUMBERS VERSES AGE OF TRANSFORMER

It well known that Tan delta and specific resistance also depend extensively on the water content, suspended particles and dirt in oil. Among the parameters that gauges the ageing of oil, acid number is the one that has a greater significance as it is not influenced by any contaminations like water, particle etc. Hence correlation of acid number with age of transformer can be considered as most important criterion for evaluating ageing of insulating oil.

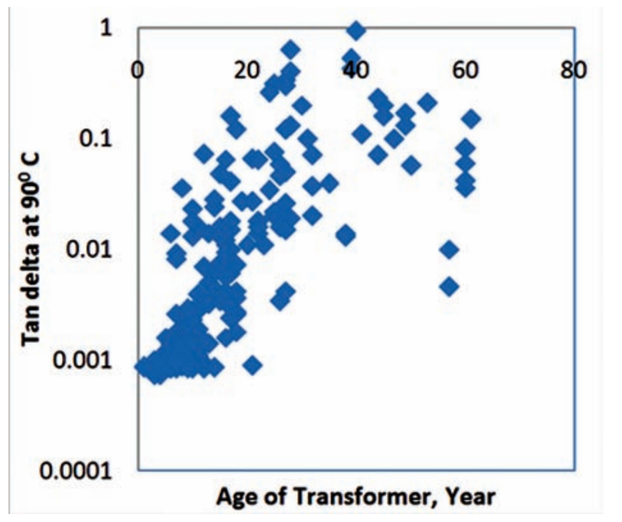

FIG 4. INCREASE OF TAN DELTA OF OIL WITH AGE OF TRANSFORMER

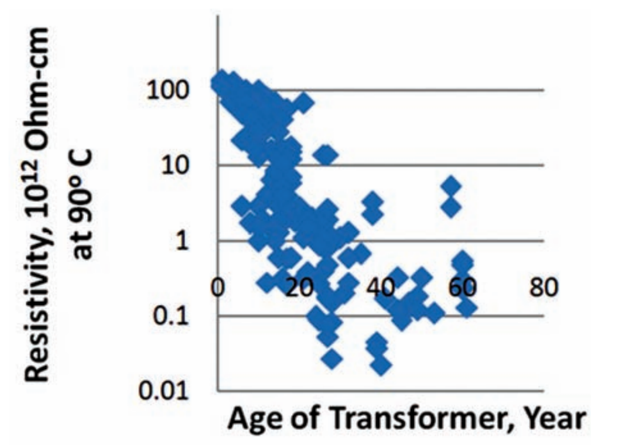

FIG 5. LOGARITHMIC PLOT OF SPECIFIC RESISTIVITY OF OIL WITH TRANSFORMER AGEING

4.0 ESTIMATION OF HEALTH INDEX

Transformer oil in service gradually deteriorates due to electrical, thermal and chemical stress. Hence it is needed to combine electrical, physical and chemical tests results to establish condition monitoring methodologies. In the present study oil properties like BDV, acidity, water content, interface tension (IFT) and tan delta are selected in line with recommendation of IEEE C57.106 to be as critical factors for oil quality determination. Table 1 describes the scoring method adopted for assessing heath of transformer oil.

The ranking procedure shown in Table 1 based on IEEE and IEC standards and in line with recommendation made by CIGRE. As per the methodology, the oil quality analysis factor F_o is calculated using equation (1), where n_i = 1…4 is the score assigned to the diagnostic factor i and p_i – being its weight factor.

$$F_0 = \sum_{(i=1)}^{6} ni*pi \;/\; \sum_{(i=1)}^{6} pi \quad ...(1)$$

The score n_i corresponding to factor i is selected based on each value of the diagnostic factor in Table 1 [39].The quality analysis factor F_o is calculated using values of n_i and p_i. Rating grade like A,B,C,D or E are assigned depending of the derived values of F_0. Grade A is assigned to the oil that is having best quality with $F_o < 1.2$ and grade E for the worst oil with $F_o \geq 3$. In order to incorporate these grading in computation number scoring were assigned from 4 to 0 for A to E grade respectively. This computational procedure was applied to the results obtained from testing of about 200 oil samples comprising 4 zones. The final outcome of the computational procedure is shown in Figure 6 – 9. The overall grading considering all the samples together is shown in Figure 6. Rankings of individual zones are shown in Figure 6 – 9.

TABLE 1

RATIOS FOR OIL TESTS PARAMETERS BASED ON IEEE C57.106 [39]

U_n	$U_n \leq 69$ kV	69 kV < U_n < 220 kV	220 kV ≤ U_n	n_i	p_i
BDV, kV	≥ 45	≥ 52	≥ 60	1	3
	35 - 45	47 - 52	50 - 60	2	
	30 - 35	35 - 47	40 - 50	3	
	≤ 30	≤ 35	≤ 40	4	
IFT, mN/m	≥ 25	≥ 30	≥ 32	1	2
	20 - 25	23 – 30	25 – 32	2	
	15 - 20	18 – 23	20 – 25	3	
	≤ 15	≤ 18	≤ 20	4	
Acid Number	≤ 0.05	≤ 0.04	≤ 0.03	1	1
	0.05 – 0.1	0.04 – 0.1	0.03 – 0.07	2	
	0.1 – 0.2	0.1 – 0.15	0.07 – 0.1	3	
	≥ 0.2	≥ 0.15	≥ 0.10	4	
Water content, ppm	≤ 30	≤ 20	≤ 15	1	4
	30 - 35	20 – 25	15 – 20	2	
	35 – 40	25 – 30	20 – 25	3	
	≥ 40	≥ 30	≥ 25	4	
Tan delta at 50 Hz	≤ 0.1			1	3
	0.1 – 0.5			2	
	0.5 – 1.0			3	
	≥ 1.0			4	

TABLE 2

TRANSFORMER CONDITION ASSESSMENT USING F_0 [39]

Description	State	State score	Diagnostic index DI_o
$F_0 < 1.2$	Good	A	4
$1.2 \leq F_0 < 1.5$	Satisfactory	B	3
$1.5 \leq F_0 < 2$	Poor	C	2
$2 \leq F_0 < 3$	Very Poor	D	1
$F_0 \geq 3$	Dangerous	E	0

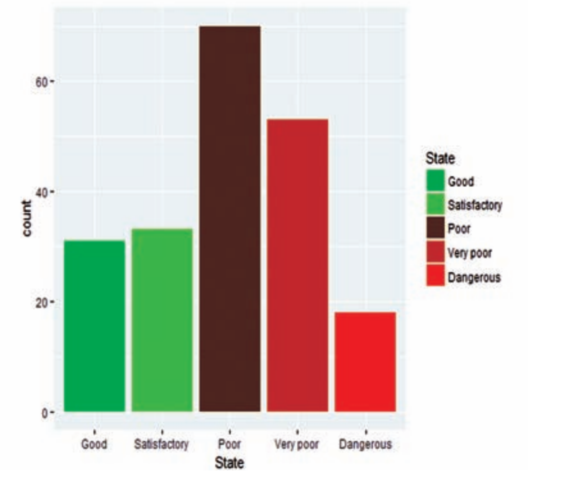

FIG 6. OVERALL GRADING CONSIDERING ALL THE SAMPLES TOGETHER.

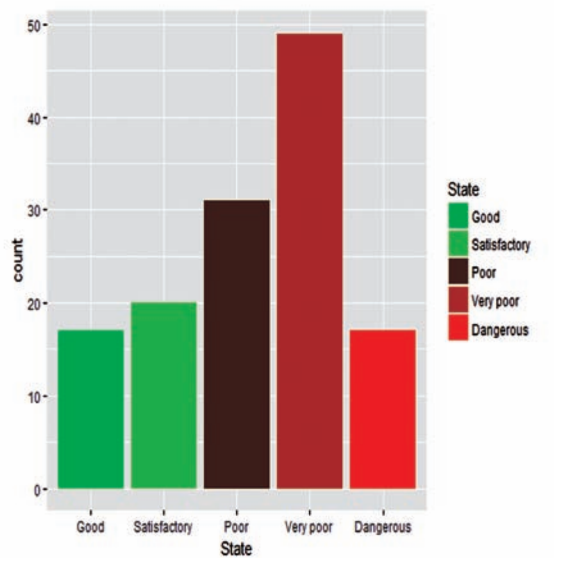

FIG 7. RANKINGS ZONE A SAMPLES

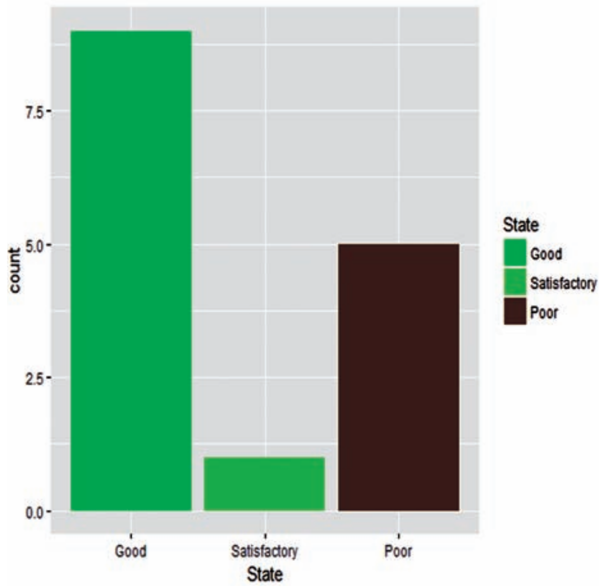

FIG 8. RANKINGS ZONE B SAMPLES

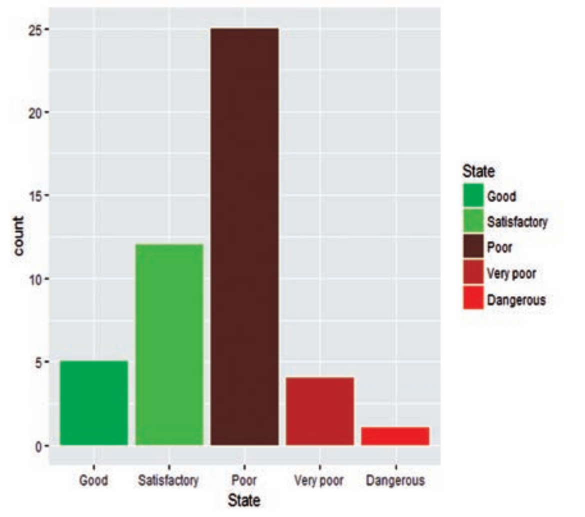

FIG 9. RANKINGS ZONE D SAMPLES

5.0 CONCLUSIONS

In this study, transformer oil analysis results of about 200 power transformers of various ages were taken for assessing ageing behavior of transformer oil. Tan delta, resistivity, IFT and acidity are the properties that are found to be useful to correlate ageing behavior of oil. Increase in tan delta of insulating oil with age of transformers observed to follow logarithmic trend. The trend in increase of acid number may be judged as more significant character for assessing ageing as it is not influenced by contaminants like water, suspended particles etc. A considerable number of oil samples were found to be substantially better than average value of the specific age, indicating proper maintenance of those transformers. It is attempted to estimate ageing condition of transformer oil through multi-parameter ageing index methodology. Oil samples studied are tried to classify in grades like good, satisfactory, poor etc. It was also attempted to assign grading of oil of various zones that are considered in this study. This methodology may find application in scheduling overall maintenance activities or zone wise activities. This methodology can also be helpful for asset management especially with the increasing population of power transformers.

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