Degradation studies of electrical, physical and chemical properties of aged transformer oil

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Abstract: Transformer is crucial equipment in the transmission of electric power. Various types of insulating materials used in the transformer among those mineral oil or transformer oil is used for the insulation. To reduce the failure percentage of transformer it is necessary to maintain the purity of oil. This paper investigates work on different properties of aged transformer oils and pure transformer oil. The aged oils are taken as filtered and unfiltered after using in the transformer. The electrical, physical and chemical properties are investigated for pure and aged transformer oils. UV-spectroscopy is used to test the quality of oil based on the absorbance value and FTIR analysis is performed to determine the functional groups existing in the pure and aged transformer oils. The results showed that breakdown strength is less for used transformer oil due to formation of acidic functional groups. The absorption peak is high for unfiltered oil followed by filtered oil and pure oil.

1. INTRODUCTION

Transformer plays a vital role in the power system. Transformer is used for stepping up, stepping down and isolation purpose. The mineral oil plays a dual role viz., cooling and insulation. It is also used in circuit breakers for arc quenching, capacitors as a dielectric medium. Mineral oils are used as transformer oil. It consists of hydrocarbons [1]. The hydrocarbons present in mineral oils are classified as paraffinic, naphthenic and aromatic compounds. Paraffinic compounds are saturated compounds whereas naphthenic and aromatic are unsaturated compounds. Paraffinic components have high oxidation stability but less pour point, naphthenic has less oxidation stability but high pour point. Aromatic compounds have high volatility. Based upon the content present, the mineral oil can be called as a paraffinic/naphthenic/aromatic[2]. To monitor the transformer condition, it is not necessary to monitor the entire transformer. The condition of transformer can resolute by the condition of insulation. Due to the continuous operation of transformer oil is exposed to various stresses like mechanical, electrical and thermal stresses. Because of the presence of oxygen the oxidation process will occur and transformer oil gradually degrades[3]. While aging of oil the physical, chemical and electrical properties get reorganized[4]. Due to ageing of oil, not only the dielectric strength is affected but also tan δ,
interfacial tension, acidity, etc [5]. The less value of Breakdown voltage (BDV) indicates the existence of foreign particles and other impurities in the transformer oil[6], the tan δ will increase, if impurities and oxidation present in the oil[7], acidity and moisture content will increase, interfacial tension will decays as oil ageing day to day. The quality of mineral oil can be studied using UV spectroscopy and functional groups in molecules present in the oil can be assessed using FTIR analysis[8]. In this paper three different oils are collected. Pure oil, used filtered oil and used unfiltered oil. Used filtered and unfiltered oils are collected from the SPM (Special primitive maintenance), APSPDCL, Rajampet, Andhra Pradesh, India. In this treatise the properties of pure oil, used filtered oil, used unfiltered oil are compared and how the oil properties are affected due to deterioration is studied. The collected transformer oil is being in service for more than 2 years and the analysis is done with filtering and without filtering.

2. AGEING OF TRANSFORMER OIL

Transformer oil is subjected to the reaction of oxygen, acidity and moisture, also the thermal, electrical stress loading, decomposing of cellulose and other materials, present in the transformer leads to the transformer oil deterioration or ageing during the operation. Ageing of oil reduces the life span of transformer [9]. This ageing can be identified by performing tests for oil like breakdown test, flash & fire point, acidity, tan δ, interfacial tension, FTIR analysis, UV spectrometric analysis etc.

3. PROPERTIES OF TRANSFORMER OIL

- Electrical properties: Dielectric strength, Dielectric Dissipation Factor.
- Physical properties: Appearance, Viscosity, Density.
- Chemical properties: Moisture content, Neutralization value or acidity [9].

4. DIAGNOSIS OF TRANSFORMER OIL

The condition of transformer can be easily identified by diagnosing or analyzing the condition of transformer oil. Diagnosis of transformer oil can be done according to the electrical, physical and chemical properties.

4.1. Electrical Properties of Transformer oil

4.1.1 Break Voltage of Transformer oil. The breakdown voltage of oil is the voltage at which the oil becomes conductive [10]. The transformer oil placed in test cell containing hemispherical electrodes to which AC electric field is applied according to the IS standard 6792 and sampling is done according to standard IS 6855. Table 1 shows that used unfiltered oil having less breakdown strength compared to other oils. This is due to the presence of impurities, oxidation, over heating of oil, presence of moisture will affect the breakdown strength of the oil. The moisture present in the transformer oil increases the gaseous content and presence of dirt particles or impurities leads to initiation of streamers in the gases which will disseminate under the electric field. The mechanism behind breakdown consists of three phases [11]. At initial phase, due to the applying of electric field, thermal agitations take place in the oil and leads to the formation of microscopic cavities. At the second phase, continuous applying of electric field the electron passes through the oil permeated by micro-cavities will capture energy and gas development takes place then microbubble will form. At third phase, continuous application of voltage then gas production exceeds the formation of bubbles leads to breakdown.
Figure 1. Test cell used for BDV.

Table 1. BDV for three different aged oils.

| Transformer oil          | BDV(kV) |
|--------------------------|---------|
| Pure oil                 | 72      |
| Used and filtered oil    | 49      |
| Used and unfiltered oil  | 35      |

4.1.2 Dielectric Dissipation Factor (DDF) or tan δ. Dielectric Dissipation Factor (DDF) is also called as loss angle or tan δ. The tan δ is measured by using the Automatic Dissipation Factor Megger group. It consist of test cell having range 45ml and display panel. The test is performed according to the standard IEC 60247: 2004. From the Table 2, tan δ increases as pure oil getting deteriorated and its value decreased when it is filtered. For pure and used filtered oil tan δ value is acceptable range, whereas for used unfiltered oil the tan δ is very high. It is due to the presence of moisture, overheating and other impurities in oil. If impurities are more, then tan δ will increase and also if temperature increases then tan δ increases. When the voltage is applied to the transformer oil it will act as a dielectric material. If the dielectric material is ideal without any lossy component then current leads voltage by an angle 90°. If oil contains impurities then the angle slightly lags behind 90°. If voltage V is applied to the oil containing impurities loss current I, will be produced as shown in figure 2[11].

\[
\tan \delta = \frac{I_1}{I_c}
\]  

(1)

Table 2. Tanδ for different aged Transformer oils.

| Transformer oil        | DDF or Tanδ at 32°C |
|------------------------|---------------------|
| Pure Oil               | 0.001424            |
| Used filtered oil      | 0.012228            |
| Used unfiltered oil    | 0.115026            |
4.2. **Physical Properties of Transformer oil**

4.2.1. **Appearance.** The colour of transformer oil is changed as oil ages due to effect of different conditions in transformer. As can be seen in the figure 3 for the pure oil colour is clear and transparent and if it aged the colour is turns to yellow, brown and black. The colour is black then it is not useful further for insulation and coolant for transformer even after filtration is done. The change in the colour is due to oxidation, overheating, acidity content. In addition to these the colour is changed due to decomposing of materials present in transformer like metals, cellulose, plastic materials etc. and other impurities formation. At certain operating temperature of transformer, the materials will degrade and decomposed in transformer oil. These dissolved and decomposed materials will chemical reaction takes place and forms new bonds, changing colour in transformer oil and leads to deterioration of transformer oil.

![Figure 3. Appearance of different aged oils.](image)

4.2.2. **Density.** The quality of transformer oil does not depend on the density value but can be identified the suitability of required application [12]. Density depends upon the chemical composition of oil. The density varies if temperature varies. If temperature decreases, density of oil increases and temperature increases, density of oil decreases.

\[
\text{Density of oil} = \frac{\text{mass of oil}}{\text{volume of oil}}
\]

(2)

| Transformer oil | Density (g/cm\(^3\)) |
|-----------------|----------------------|
| Pure Oil        | 0.7919               |
| Used filtered oil| 0.746               |
| Used unfiltered oil | 0.746          |

From the table 3 it is found that density of oil at 34\(^\circ\)C for pure oil value is high and for filtered and unfiltered oil it is reduced. It is due to the overheating of oil.

4.2.3. **Viscosity.**
Viscosity is the foremost property of transformer oil for eviction of heat from the transformer. A small degree change in viscosity leads to large effect on the heat transfer. Viscosity is a resistance to the flow of liquid under force of gravity. The pressure is proportionate to density (\(\rho\)) and the kinematic viscosity is proportionate to rate of oil flow. Dynamic viscosity is associated to kinematic viscosity (\(\eta\)) and related as \(v=\eta/\rho\), where \(\eta\) is the proportion between the shear stress and the rate of shear. If the proportion is same for all shear rates then the fluid is called as a Newtonian fluid else non-Newtonian fluid. Kinematic viscosity represents in centistokes (cSt) and dynamic viscosity represents as centipoises (cP) [13]. The viscosity is measured according to IS 1448: 2002. Apparatus taken to measure using Ostwald’s viscometer.

![Figure 4. Ostwald’s Viscometer.](image)
Table 4. Viscosity of Various oils at room temperature.

| Transformer oil     | Kinematic viscosity(cSt) |
|---------------------|--------------------------|
| Pure Oil            | 6.44                     |
| Used filtered oil   | 7.35                     |
| Used unfiltered oil | 7.47                     |

\[ \eta_2 = \frac{\eta_1 d_2 t_2}{d_1 t_1} \]  

(3)

Where:
- \( \eta_1 \) = viscosity of water = 0.0091 poise
- \( \eta_2 \) = viscosity of oil
- \( d_1 \) = density of water = 1 g/cm\(^3\)
- \( d_2 \) = density of oil = 0.7919 g/cm\(^3\)
- \( t_1 \) = time for water
- \( t_2 \) = time for oil

From the table 5 it is found that pure oil has less viscosity and it gives good heat evacuation, whereas used transformer oil having high viscosity compared to pure oil because in used oils sludge formation and other dust particles will increase the viscosity. So, to reduce the viscosity value it is necessity to filter the oil.

4.2.4. Interfacial Tension.

Interfacial tension is the value measured between attraction of molecular force between oil and water. It is used to determine the existence of polar molecules and other contaminants present in the oil. Pure oil exhibits high IFT value \[14\]. IFT is determined using Kruss tensiometer. The pure oil will float on the surface of water and cannot miscible with water. Whereas, the contaminated oils will miscible with water.

Table 5. Interfacial tension of various transformer oils.

| Transformer oil     | Interfacial tension (mN/m) |
|---------------------|----------------------------|
| Pure Oil            | 36.74                      |
| Used filtered oil   | 32.28                      |
| Used unfiltered oil | 27.22                      |

Presence of polar molecules in oil reduces the surface tension between the oil and water. The oil and water are miscible each other, then IFT value will be reduced. Due to less IFT the water molecules will get dissolved in oil and reduce the dielectric strength of oil. From the table it can be seen that for pure oil has high interfacial tension, whereas for aged has less interfacial tension.

4.2.5. Flash & Fire Point.

The flash point is the transformer oil’s safety property and it can give information concerning to the risk of fire. At certain point of temperature the oil will ignites, it is called as flash point and at the certain temperature the oil continuously burn is called as fire point. The quality of oil cannot asset based on the flash and fire point but it is to determine safety of the transformer. High value of flash point and fire point can safe for transformer operation even at high temperature locations. Flash and fire point can vary the concentration of aromatic component present in the oil. More the aromatic concentration leads to less value of flash and fire point. Flash & fire point is done according to the standard IEC 2719: Pensky - Martens closed cup method.
Table 6. Flash & fire point of various transformer oils.

| Transformer oil          | Flash point (°C) | Fire point (°C) |
|--------------------------|-----------------|-----------------|
| Pure Oil                 | 140             | 155             |
| Used filtered oil        | 135             | 151             |
| Used unfiltered oil      | 133             | 145             |

From the table it is found that if the oil is aged the flash and fire point decreases it is due to formation of acidic and aromatic compounds during aging period. The pure oil have high flash & fire point, filtered oil and unfiltered oil flash and fire point is slightly reduced due presence of acidity and other impurities. The less flash and fire point is harmful to the transformer and leads to the fire accidents. So, it is necessity to maintain specific flash & fire point by purifying the transformer oil.

4.3. Chemical Properties of Transformer oil

4.3.1. Moisture Content. Transformer oil affinity is low for water. To saturate one litre of pure oil, one drop of water is enough at room temperature. Oil having some polar components like aromatic compounds, water attracted to these aromatic components. Acidity in transformer oils will increase due to thermal ageing of cellulose insulation and leads solubility of moisture in oil. Paper insulation is one of cause to enhancing moisture content in oil [15]. Moisture content is determined according to the standard ASTM D 1533: 2012 and values are given in table 7.

Table 7. Moisture content of various transformer oils.

| Transformer oil          | Moisture content (ppm) |
|--------------------------|------------------------|
| Pure Oil                 | 27.22                  |
| Used filtered oil        | 29.28                  |
| Used unfiltered oil      | 36.74                  |

Presence of water molecules will react with oil molecules then oxygen atom add to the hydrocarbon atoms leads to oxidation process will increases, sludge formation increases. It causes obstruction for heat transfer in transformer. Degradation of cellulose material in transformer reacts with aromatic hydrocarbons that causes formation of furans. Maximum limit of moisture content in transformer oil is 30 ppm.

4.3.2. Acidity.

Mineral oil are three different types hydrocarbons namely naphthene, paraffin and aromatic with 18 as average carbon number. The oxygen present in the oil will react with oil molecules then leads formation of carboxylic acids, aldehydes and ketones. These carboxylic acids have rapport with water and cellulose, ability to bond with hydroxyl group [16]. The acid number can identified by manual titration by preparing some solvents. Here 25ml of ethanol and diethyl ether is mixed and 10g of oil is added to the prepared composition. To know the acid value by neutralizing the acid by adding NaOH solution to prepared composition. 1g of NaOH is dissolved in the 250ml of distilled water. For identification of neutralization one drop of phenolphthalein is added into the oil mixture. The NaOH solution is thoroughly added into the oil mixture. The oil mixture turns to the pale pink, based on volume of NaOH solution can calculate acidity value. Acidity value is calculated using following formula:

\[
\text{Acidity} = \frac{\text{Vol of NaOH} \times 5.61}{\text{wt of oil}} \tag{4}
\]

For contaminated oil the colour is dark and with normal titration cannot able observe the pale pink. So, to determine it is neutralized by using pH value. The titration is done as usually with observing the pH value every time after addition of NaOH solution. Here for filtered oil neutralized at one point and unfiltered oils is neutralized at two times. In figure 5 shows the neutralization point of oils.
Table 8. Acidity of various transformer oils.

| Transformer Oil       | Acidity |
|-----------------------|---------|
| Pure Oil              | 0.7     |
| Used filtered oil     | 1       |
| Used unfiltered oil   | 1 & 3   |

Table 8 shows acidity for different aged transformer oils. The pure oil have less acidity compared to the other transformer aged oils. The used unfiltered oil have high acidity value due to it contains aromatic compounds and other impurities. The impurities are identified using the FTIR analysis.

Figure 5. Neutralization for aged oils or dark coloured oils.

The unfiltered oil is neutralized two times because it contains pure hydrocarbons and also contaminated hydrocarbons. So, to neutralize the unfiltered oil it requires two steps as shown in the fig 5.

4.3.3. UV-Spectroscopy Analysis. The spectrometer used having wavelength spectrum range between 190 to 900nm consisting of a visible spectrum range between 280 to 900nm and UV spectrum range between 190 to 380 nm. Here three different aged oils are used for determining the quality of oil using UV-spectroscopy. The UV meter measures the propagated light intensity through the sample cell (I) coming from the UV source and then compares that light before propagating through the sample cell (I₀). Transmittance is determined as the ratio of I/I₀. The absorbance can be given as:

\[ A = -\log(T) \] (5)

Where,  
\( A = \) Absorbance  
\( T = \) Transmittance

Figure 6. Absorbance of pure and aged oils.

The absorbance of different aged oils are shown in figure 6. From the figure 6, pure oil has less absorbance followed by filtered oil and unfiltered oil. The absorbance is high when the impurities or
other functional groups present in the oil other than required functional groups[17].

4.3.4 FTIR Analysis. FTIR Analysis is used to determine various functional groups present in the pure and aged oils (used filtered oil & used unfiltered oil) [18]. Atoms present in the oils vibrate each other with certain frequency, each atom frequency is different from other atom. Whenever IR frequency match with the atom frequency then peaks will form based on the peaks we can find functional group present in the oil. Pure oil has only hydrocarbon bonds and other compounds. But used filtered and used unfiltered oils has hydrocarbon and aromatic compounds that also have ketone compound with small changes in wave number of filtered and unfiltered oils due to the decomposition of hydrocarbon atoms, presence of moisture, acidity. These functional groups are determined using the IR interpretation table and pure and aged oils functional groups are shown in figure 7-figure 9.

Table 9 shows the wave number and its functional group for pure oil. From the table, the pure oil does not have any contaminants in it and it only have hydrocarbon bonds.

| Wave number (cm⁻¹) | Functional group                      |
|-------------------|--------------------------------------|
| 2920.0978         | C-H(Alkane & Stretching)             |
| 2853.314          | C-H(Alkane & Stretching)             |
| 1458.232          | C-H(Methylene & Bending)             |
| 1376.44           | O-H(Alcohol & Bending)               |
| 722.309           | C-C(Methyne &Skeletal vibration)     |

Table 10 shows the wave number and its functional group for used filtered oil. From the table, the used oil have some contaminants but it is not harmful to the transformer.

![Figure 7. FTIR Analysis for Pure oil.](image)

![Figure 8. FTIR for used filtered transformer oil.](image)
Table 10. FTIR analysis of used filtered oil.

| Wave number (cm\(^{-1}\)) | Functional group                          |
|---------------------------|------------------------------------------|
| 2918                      | C-H(Alkane & Stretching)                 |
| 2851.824                  | C-H(Alkane & Stretching)                 |
| 1716.8                    | C=O(Stretching & Aliphatic ketone)       |
| 1459                      | C-H(Methylene & Bending)                 |
| 1375.82                   | O-H(Alcohol & Bending)                   |
| 722                       | C-C(Methyne & Skeletal vibration)        |

Figure 9. FTIR for unfiltered Transformer oil.

Table 11 shows the wave number and its functional group for used unfiltered oil. From the table, the used oil have some contaminants and these functional groups are harmful to the transformer and it is necessity to filter the oil.

Table 11. FTIR analysis of used unfiltered oil.

| Wave number (cm\(^{-1}\)) | Functional group                      |
|---------------------------|---------------------------------------|
| 2918                      | C-H(Alkane & Stretching)              |
| 2851.824                  | C-H(Alkane & Stretching)              |
| 1718                      | C=O(Stretching & Aliphatic ketone)     |
| 1458                      | C=C Aromatic                           |
| 1375                      | O-H(Alcohol & Bending)                 |
| 722                       | C-C(Methyne & Skeletal vibration)      |

5. CONCLUSION

In this paper, an experimental study was conducted on the pure and used oils which are used in distribution transformers in India to study the quality of pure and aged oils and asses the life of the transformer. By diagnosing different properties of the pure and aged oils, pure oil has good properties whereas the filtered and unfiltered used oils are degraded. The degradation is due to the extraction of various gases due to decomposition of hydrocarbons present in the oil, cellulose material and other materials present in the transformer. The decomposition is mainly occurred due to the temperature, acidity, moisture. Due to degradation of oil, most affected property is breakdown strength of oil compared to other properties and dissipation factor. Interfacial tension is also affected severely. Filtered oil has better properties than unfiltered oil. Even though filtered oil and unfiltered oil both have same functional group analysed using FTIR spectroscopy but various functional groups effect is less in filtered oil, because the absorbance of light is less for filtered oil compared to the unfiltered oil by analysing using UV-spectroscopy and all properties are better for filtered oil compared to unfiltered oil.
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