Influence of Temperature and Accelerated Aging Factors on Dielectric Properties of Transformer Insulating Oil

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Abstract—This paper deals with the experimental analysis to measure the influence of temperature and accelerated aging factors such as accelerated thermal aging factor (ATAF) and accelerated electrical aging factor (AEAF) on dielectric properties such as resistivity and dielectric dissipation factor (DDF) or tan delta (tan δ) of transformer oil. A number of vital decisions such as oil reconditioning, oil replacement etc. are based on these parameters. These parameters were determined experimentally for fresh oil samples as well as for samples subjected to accelerated ageing.

Index Terms — Power Transformer, Insulation oil, dielectric dissipation factor, resistivity, accelerated thermal aging factor, accelerated electrical aging factor.

I. INTRODUCTION

The reliability of a power transformer (PT) is largely determined by its insulation condition. The transformer insulating oil gets degraded under a combination of thermal, electrical, chemical, mechanical and environmental stresses during its operation. These stresses reduce the dielectric capability of a transformer and increase the probability of failure. In transformer, thermal and electrical stresses are the most influential parameters which cause aging of oil insulation. The thermal and electrical stresses on the insulation system may occur due to discharge, dielectric heating, operation under high temperature environment, due to the current flowing through the conductors etc. The combined effect of thermal and electrical stresses is available in literature but the contribution of individual thermal and electrical stresses on the insulating oil are not well known. So our main aim is to determine experimentally the effect of individual stresses on transformer oil.

The dielectric diagnostic methods such as DDF, resistivity etc. is required to understand the effect of thermal and electrical stresses on the insulating oil. These methods give an early indication of the change in the dielectric properties of insulating oil, thereby providing the useful information about the insulation quality [1]. A high value of DDF and low value of resistivity is an indication of presence of contaminants or deterioration products such as water, oxidation products, metals, etc [2].

The accelerated ageing experiments were performed in oil test cells to predict the long term insulation behavior and to provide information on the life expectancy of insulation system for different operating conditions. The accelerated aging experiments were performed to replicate the degradation processes observed in the insulation oil of actual aged transformers due to both thermal and electrical stresses [3].

Basically, insulating oil is a combination of hydrocarbon compounds. When an alternating voltage is applied to insulation, dielectric hysteresis and electric conduction take place which cause dielectric losses. The electric conduction is caused by aging or presence of impurities in the oil produced by colloidal particles [4], by the by-products or catalysts (such as moisture and acid) [5], because of non-uniform distribution of microbes in the insulation oil [6] etc. According to Ma. Weiping et al, there are many kind of microbes in the transformer oil, the microbes have certain effect on the oil tan δ. There is strong biological oxidation in transformer oil, the microbes can use transformer oil as their only carbon supply to live and reproduce. The microbes and its metabolic product are both polarized compounds. When an alternating voltage is applied to transformer oil, the microbes have certain effect on the oil tan δ. There is strong biological oxidation in transformer oil, the microbes can use transformer oil as their only carbon supply to live and reproduce. The microbes and its metabolic product are both polarized materials and the continuous rise of the oil tan δ owes to their metabolism and reproduction. The oil tan δ changed irregularly because of the non-uniform existence of the microbes in the insulation oil [6].

II. ACCELERATED AGING FACTORS

The aging of insulation is intimately connected with the magnitude and duration of stresses on the insulation. The stresses may be electrical or thermal. The accelerated thermal aging factor (ATAF) is defined as

\[ \text{ATAF} = T \times D \]

where T is temperature in °C at which the thermal stress is applied to the sample of transformer oil

D is duration of thermal stresses

So, the unit of ATAF is degree C-hours (°C-hr). ATAF represents a quantitative index of aging due to accelerated thermal degradation.

Similarly the accelerated electrical aging factor (AEAF) is defined as
AEAF = E x D

where E is voltage in kV at which the electrical stress is applied to the sample of transformer oil
D is duration of above-mentioned electrical stresses
The unit of AEAF is kV-hours (kV-hr).

III. DIELECTRIC DISSIPATION FACTOR OR TAN DELTA

When an ac voltage is applied to insulation, the leakage current flows, and this leakage current has two components, resistive and capacitive, as shown in figure 1. A resistive component (I_R) is in phase with voltage (V) and capacitive component (I_C) is 90° out of phase with the voltage. The power factor (PF) is the dimensionless ratio of resistive current (I_R) to total current (I_T) flowing through the insulation, and is given by cos θ [7].

\[ \text{PF} = \cos \theta = \frac{I_R}{I_T} \]  

(3)

The dielectric dissipation factor (DDF), also known as tan delta, is also a dimensionless ratio of the resistive current (I_R) to capacitive current (I_C) flowing through the insulation and hence it is the tangent of angle δ, known as loss angle.

\[ \text{DDF} = \tan \delta = \frac{I_R}{I_C} \]  

(4)

Figure 1. Phasor diagram of dielectric dissipation factor

As per ASTM D 924, DDF or PF is a measure of the dielectric losses (dissipated as heat) in an electrical insulating liquid when used in an alternating electric field. A low DDF or PF indicates low ac dielectric losses. It may be useful as a means of quality control, and as an indication of changes in quality resulting from contamination and deterioration in service.

The exact relationship between DDF and PF is given by the following equations [8]:

\[ \text{PF} = \frac{\text{DDF}}{\sqrt{1 + \text{DDF}^2}} \]  

(5)

\[ \text{DDF} = \frac{\text{PF}}{\sqrt{1 - \text{PF}^2}} \]  

(6)

The loss characteristic is commonly measured in terms of DDF or PF and may be expressed in decimal or in percentage. For decimal values up to 0.05, DDF and PF values are equal to each other within about one part in one thousand. In general, since the DDF or PF of insulating oils in good condition have decimal values below 0.005, the two terms may be considered interchangeable [8]. The term has got different references worldwide among the field engineers. This factor is referred as Power Factor in North America and as Dissipation Factor in Europe [9].

Standard values of DDF as per Indian standard (IS) 335 [10] for new oil is 0.002 (max) at 90°C. In table 1, DDF of power transformer (PT) at different voltage rating is given as per IS 1866:2000 [11]. The smaller is the value of DDF, the better is the quality of oil.

<table>
<thead>
<tr>
<th>S.No</th>
<th>IS No.</th>
<th>DDF</th>
<th>Voltage rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1866:2000</td>
<td>0.015 (max) at 90°C</td>
<td>&lt;7.25kV</td>
</tr>
<tr>
<td>2</td>
<td>1866:2000</td>
<td>0.015 (max) at 90°C</td>
<td>Voltage rating between 72.5 to 170 kV</td>
</tr>
<tr>
<td>3</td>
<td>1866:2000</td>
<td>0.010 (max) at 90°C</td>
<td>Voltage rating &gt;170kV</td>
</tr>
</tbody>
</table>

IV. RESISTIVITY

Resistivity or specific resistance is the most sensitive property of oil, it varies with temperature. It is desirable to have as high resistivity of oil as possible. Resistivity of oil reduces considerably due to presence of moisture, acidity, solid contaminants etc [12]. High resistivity reflects low content of free ions and ion-forming particles, and indicates a low concentration of conductive contaminants [13].

Standard values of resistivity as per Indian standard (IS) 335 [10] for new oil it is 1500 TOhm-cm (min) at 27°C and 35 TOhm-cm (min) at 90°C. In table 2, resistivity of power transformer (PT) at different voltage rating is given as per IS 1866:2000 [11].
Table 2.
Resistivity as per Indian Standard (IS)

<table>
<thead>
<tr>
<th>S.No</th>
<th>IS No.</th>
<th>Resistivity (Ω-cm)</th>
<th>Voltage rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>1866:2000</td>
<td>06 (min) at 90°C</td>
<td>&lt;72.5kV</td>
</tr>
<tr>
<td>2.</td>
<td>1866:2000</td>
<td>06 (min) at 90°C</td>
<td>72.5 to 170 kV</td>
</tr>
<tr>
<td>3.</td>
<td>1866:2000</td>
<td>06 (min) at 90°C</td>
<td>&gt;170kV</td>
</tr>
</tbody>
</table>

V. EQUIPMENT AND PROCEDURE

The ADTR-2K is an instrument used for measuring the electrical characteristics like DDF, resistivity, capacitance, dielectric constant, resistance of transformer oil.

The resistance measurement is accomplished by using semiconductor junctions that convert the current from the sample into a voltage. In this way one circuit can easily cover a range of six decades of current, or resistance without using any range changing.

In order to make the measuring circuit self checking and self calibrating two reference resistors are used in identical logarithmic circuits. Thus by comparing the output of two logarithm circuits and the output of a voltage divider, the measuring circuit can be calibrated and the unknown resistance determined. The resistivity of the measured sample is calculated from knowledge of the test cell and the measured resistance.

The capacitance measuring circuit uses a transformer ratio-arm bridge to compare the unknown capacitance to a reference capacitor. The inherent characteristics of the transformer ratio-arm bridge allow convenient three terminal measurements. The capacitance is primarily measured by changing the ratio of the comparator transformer, while the losses in the circuit are read as unbalance signal of the bridge. The bridge measuring circuitry measures the voltage (V), frequency (f), Capacitance (C) and power loss (P).

From these four measurements and knowledge of the test cell, DDF for the test specimen is determined by following calculation.

\[
DDF = \frac{P}{\omega CV^2} \quad (7)
\]

A high frequency induction heater is used to heat the oil in the cell to the required temperature from 20°C to 110°C. Figure 2 shows test chamber with a three electrode cell and test cables connected.
The average stress to which the specimen is subjected shall not be less than 200 V (rms)/mm. Tests at higher stresses are desirable but shall not reach such values that electrical discharges arise across the cell insulating surfaces. Stress ranges in normal usage are 200 to 1200 V (rms)/mm. Tests should be carried out in the frequency range 45–65 Hz [8]. The temperature difference in the test cell between any part of the inner electrode and the outer electrode does not exceed 2°C. In general, the use of a forced-draft air test chamber or automatic thermo-regulator cell is preferable.

After initial set-up, the oil measuring cell is filled with the sample and the test procedure is initiated. The test set performs all the selected measurements and the results are displayed. The test results can be printed or stored in a non-volatile memory.

VI. EXPERIMENTATION FOR ACCELERATED STRESSES

To understand the effect of accelerated thermal and electrical stresses on the transformer insulating oil, the special test cell shown in figure 4 has been fabricated.

![Test cell](image)

**Figure 4. Test cell**

The capacity of the test cell is 3 liters. The mild steel plate of 3.5mm thick is used. The inner surface of the cell has been painted with high temperature resistant enameled paint. The silicon sealing has been provided in between the top cover plate to prevent the leakage of gases at high temperature and at high voltage. The two copper strips covered with paper joined together were placed in the cell.

The test cell is filled with insulating oil and heated at 110°C for 12 hrs in an air circulating oven, so that the moisture gets removed from the oil.

To study the effect of individual thermal stress on transformer insulation oil, the fabricated test cell was kept in the air circulating oven at various durations as mentioned in table 3.

<table>
<thead>
<tr>
<th>S.No</th>
<th>Duration (hr)</th>
<th>Temperature (°C)</th>
<th>ATAF in °C-hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>150</td>
<td>190</td>
<td>ATAF₁ = 28500</td>
</tr>
<tr>
<td>2</td>
<td>300</td>
<td>190</td>
<td>ATAF₂ = 57000</td>
</tr>
<tr>
<td>3</td>
<td>300</td>
<td>210</td>
<td>ATAF₃ = 63000</td>
</tr>
<tr>
<td>4</td>
<td>450</td>
<td>200</td>
<td>ATAF₄ = 90000</td>
</tr>
<tr>
<td>5</td>
<td>600</td>
<td>200</td>
<td>ATAF₅ = 120000</td>
</tr>
<tr>
<td>6</td>
<td>600</td>
<td>210</td>
<td>ATAF₆ = 126000</td>
</tr>
<tr>
<td>7</td>
<td>750</td>
<td>210</td>
<td>ATAF₇ = 157500</td>
</tr>
</tbody>
</table>

The other test cells are subjected to electrical stresses by connecting them to HV electrical source at different voltage (kV) and for various durations as shown in table 4.

The ATAF and AEAIF are calculated using equation (1) and (2) and results are shown in table 3 and 4.

<table>
<thead>
<tr>
<th>S.No</th>
<th>Duration (hr)</th>
<th>Electrical stress (kV)</th>
<th>AEAIF in kV-hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>300</td>
<td>2</td>
<td>AEAIF₁ = 600</td>
</tr>
<tr>
<td>2</td>
<td>600</td>
<td>2</td>
<td>AEAIF₂ = 1200</td>
</tr>
<tr>
<td>3</td>
<td>600</td>
<td>4</td>
<td>AEAIF₃ = 2400</td>
</tr>
<tr>
<td>4</td>
<td>750</td>
<td>4</td>
<td>AEAIF₄ = 3000</td>
</tr>
</tbody>
</table>

![Influence of temperature on DDF for fresh oil and thermal stressed sample](image)

**Figure 5. Influence of temperature on DDF for fresh oil and thermal stressed sample**
VII. RESULTS AND DISCUSSIONS

A. DDF under thermal stressed condition

The variation of DDF with temperature for fresh oil as well as for thermally stressed oil, stressed at different ATAF is plotted in figure 5.

It can be observed from this figure that the increase in DDF with temperature for thermally stressed oil samples is exponential. Ln [DDF] has also been plotted in figure 6 against temperature for fresh oil and thermal stressed oil samples.

\[ T = T_0 e^{\alpha (T - T_0)} \]  \hspace{1cm} (8)

\[ \alpha = \frac{(\ln[DDF_T] - \ln[DDF_{T_0}])}{(T - T_0)} \]  \hspace{1cm} (9)

where \( \alpha \) = Temperature coefficient
T is temperature of oil sample in °C
T_o is initial temperature of oil sample

The temperature coefficient may be defined as relative change of Ln [DDF] with per °C change in temperature.

The relationship between DDF and temperature can be written as per equation (8) and (9).

\[ \alpha_T = (-1 \times 10^{-12}) \text{ATAF}^2 + (5 \times 10^{-7}) \text{ATAF} + 0.005 \]  \hspace{1cm} (10)

<table>
<thead>
<tr>
<th>S.No</th>
<th>ATAF</th>
<th>Temperature coefficient (( \alpha_T ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fresh Oil</td>
<td>0.004</td>
</tr>
<tr>
<td>2</td>
<td>28500</td>
<td>0.018</td>
</tr>
<tr>
<td>3</td>
<td>37000</td>
<td>0.026</td>
</tr>
<tr>
<td>4</td>
<td>63000</td>
<td>0.038</td>
</tr>
<tr>
<td>5</td>
<td>90000</td>
<td>0.025</td>
</tr>
<tr>
<td>6</td>
<td>120000</td>
<td>0.04</td>
</tr>
<tr>
<td>7</td>
<td>126000</td>
<td>0.047</td>
</tr>
<tr>
<td>8</td>
<td>157500</td>
<td>0.043</td>
</tr>
</tbody>
</table>

In statistics, the coefficient of determination, \( R^2 \) is used in the context of statistical models whose main purpose is the prediction of future outcomes on the basis of other related information. It is the proportion of variability in a data set that is accounted for by the statistical model. It provides a measure of how well future outcomes are likely to be predicted by the model.

The experimental relation between temperature coefficient (\( \alpha_T \)) for thermal stressed transformer oil and ATAF is given below:

\[ \alpha_T = (-1 \times 10^{-12}) \text{ATAF}^2 + (5 \times 10^{-7}) \text{ATAF} + 0.005 \]  \hspace{1cm} (10)
Figure 8. Variation of DDF (measured at 90°C) with ATAF

The figure 8 indicates the variation of DDF (measured at 90°C) with ATAF. This figure shows the increase in DDF with ATAF. The $R^2$ value is 0.96. The rate of change of DDF (measured at 90°C) is in accordance with results available in literature [15, 16].

The increase of the temperature is accompanied by an increase of the dissipation factor. This can be observed for both the fresh and stressed samples. This statement is caused by the increase of charge carrier mobility and the increase of the number of charge carriers due to the greater thermal dissociation as per ionic conduction mechanism [17].

Figure 9. Influence of temperature on DDF for fresh oil and electrically stressed sample

B. DDF under electrically stressed condition

The variation of DDF with temperature for fresh oil as well as for electrically stressed oil stressed at different AEAF is shown in figure 9.

Figure 10. Relation between Ln [DDF] and temperature for fresh oil and electrically stressed sample

It can be observed from figure 9 that increases in DDF with temperature for electrically stressed oil is exponential. The Ln [DDF] has been plotted in figure 10 against temperature for electrically stressed oil as well as for fresh oil.

The value of temperature coefficient ($\alpha$) calculated from figure 10 using equation (9); the relevant values are given in table 6 and plotted in figure 11.

<table>
<thead>
<tr>
<th>S.No</th>
<th>AEAF</th>
<th>Temperature coefficient ($\alpha_E$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fresh Oil</td>
<td>0.004</td>
</tr>
<tr>
<td>2</td>
<td>600</td>
<td>0.0025</td>
</tr>
<tr>
<td>3</td>
<td>1200</td>
<td>0.02533</td>
</tr>
<tr>
<td>4</td>
<td>2400</td>
<td>0.07167</td>
</tr>
<tr>
<td>5</td>
<td>3000</td>
<td>0.06833</td>
</tr>
</tbody>
</table>

The figure 11 indicates the temperature coefficient increases polynomial with ATAF. The $R^2$ value is 0.922.

The experimental relation between temperature coefficient ($\alpha_E$) for electrically stressed transformer oil and ATAF is given below:

$$\alpha_E = (7 \times 10^{-10})AEAF^2 + (2 \times 10^{-5})AEAF - 0.002$$  \hspace{1cm} (11)
The figure 12 indicates the variation of DDF (measured at 90°C) with AEAF. The figure indicates the DDF increases with AEAF. The R^2 value is 0.97.

C. Resistivity under thermal stressed condition

The variation of resistivity with temperature for thermally stressed oil stressed at different ATAF is shown in figure 13.

It can be observed from figure 13 that the decrease in resistivity with temperature for thermally stressed oil is exponential. Moreover, resistivity of fresh oil is much more as compared with thermally stressed oil so we neglect it in graphical representation.

The figure 14 indicates the variation of resistivity (measured at 90°C) with ATAF. The figure indicates the resistivity decreases with ATAF. The R^2 value is 0.93.
D. Resistivity under electrically stressed condition

The variation of resistivity with temperature for fresh oil and electrically stressed oil stressed at different AEAF is shown in figure 15. It can be observed from figure 15 that resistivity decreases exponentially with temperature for electrically stressed oil.

The figure 16 indicates the variation of resistivity (measured at 90°C) with AEAF. The figure indicates the resistivity decreases with AEAF. The R² value is 0.92.

E. Variation of DDF and resistivity under thermal & electrically stressed condition

The variation of DDF and resistivity with temperature for thermally stressed oil stressed at different ATAF is shown in figure 17. It indicates that with the change in temperature of oil the DDF increases but the resistivity of the oil decreases as both being affected by same contaminates [6]. It has been observed that the resistivity decreases with temperature at the same rate at which DDF increases with temperature.

Similar characteristics are observed for electrically stressed oil.
VIII. CONCLUSION

The transformer insulating oil gets degraded under a combination of thermal, electrical, chemical, mechanical and environmental stresses during its operation. These stresses reduce the dielectric capability of a transformer and increase the probability of failure. The effect on insulation of thermal and electrical stresses is predominant. In this paper, the effect of thermal and electrical stresses on the insulation has been experimentally investigated by some of the important properties of insulation such as resistivity and tan δ. The term accelerated thermal aging factor (ATALF) and accelerated electrical aging factor (AEAF) have been introduced in order to quantify the thermal and electrical stresses.

The graphical representation between DDF and temperature for different ATAF and AEAF has been presented; it indicates that with change in temperature DDF increases with temperature. The DDF changes more frequently with change in ATAF as compared to AEAF. The temperature coefficient for thermal (αT) and electrical (αE) have been calculated and correlated with ATAF and AEAF respectively. It changes polynomial with ATAF and AEAF. The variation of DDF (measured at 90°C) with ATAF and AEAF was also presented, which presents that DDF increases with ATAF and AEAF. In another graphical representation, graphs have been plotted between resistivity and temperature for different ATAF and AEAF respectively. The resistivity decreases with temperature.

The correlation between resistivity and accelerated aging factor have been introduced which decreases with ATAF and AEAF. Finally, DDF and resistivity have been compared for ATAF and AEAF respectively with temperature.

It is concluded that both thermal and electrical stresses have contributed in the degradation of the transformer insulation. The properties such as resistivity, tan δ, moisture, breakdown voltage etc. are very sensitive to thermal and electrical stresses. It changes with change in the accelerated stresses.

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Figure 18. Comparison of DDF and resistivity of electrically stressed sample

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