Impact of Accelerated Stresses on Power Transformer Insulation

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Abstract

The paper is based on the experimental investigation of accelerated stresses on insulation of power transformer. The effects of individual thermal and electrical stresses have been graphically presented. The factors accelerated thermal aging factor (ATAF) and accelerated electrical aging factor (AEAF) have been introduced, it helps to understand the contribution of thermal and electrical stresses and degradation trends of insulating properties. The accelerated aging factors have been mathematically correlated with different properties of insulation such as moisture, breakdown voltage (BDV), tan delta and resistivity. These parameters were determined experimentally for fresh oil samples and for samples subjected to accelerated aging.

Keywords

Accelerated Thermal Aging Factor (ATAF), Accelerated Electrical Aging Factor (AEAF), Moisture, Breakdown Voltage (BDV), Resistivity, Tan Delta

1. Introduction

The insulation of power transformer degraded under a combination of various stresses. The stresses reduce the dielectric capability of a transformer and increase the probability of failure. In this paper, the impact of accelerated stresses of power transformer insulation is presented. The various parameters used to measure these impacts are moisture, breakdown voltage (BDV), tan δ and resistivity [1].

2. Experimentation

To measure the impact of accelerated thermal and electrical stresses on the transformer insulating oil, the special test cell shown in **Figure 1** has been fabricated. The capacity of the test cell was 3 liters. The description of test cell is given in **Table 1** [2].
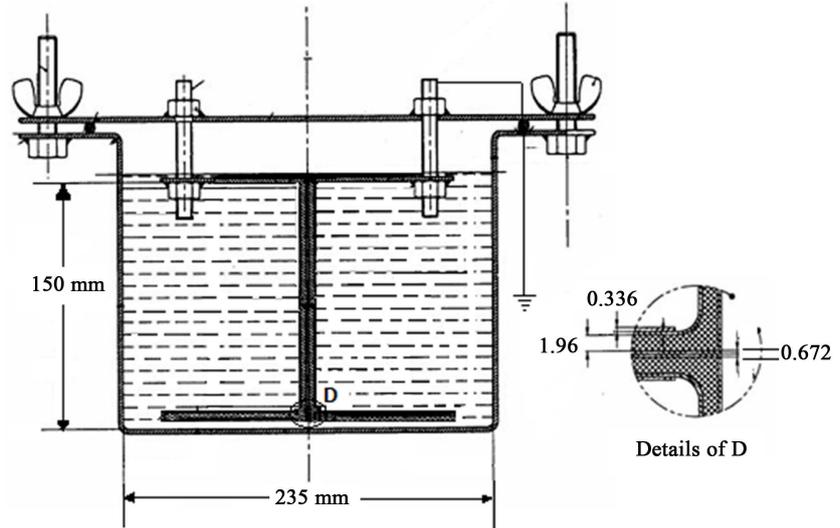
Figure 1. Test cell set up.

Table 1. Description of test cell.

Description	Material	Dimension
Cover plate	Mica sheet	5 mm
Sealing ring	Silicone rubber	5 mm
Tank	Mild steel (Coated with enamel paint)	235 mm × 100 mm × 150 mm
Round stud and nut	Copper	
Bolt	Mild steel	
Transformer oil	As per IS: 335 - 1993 (2005)	3 liter/cell
Copper strip without paper wrapped	Copper	205 mm × 12.5 mm × 1.96 mm
Insulating paper	Electrical grade paper, as per IS 9335-1993	

3. Accelerated Aging Factors

The aging of transformer insulation is intimately connected with the magnitude and duration of stresses. To understand the effect of thermal and electrical stresses on transformer insulation, accelerated thermal aging factor (ATAF) and accelerated electrical aging factor (AEAF) have been introduced:

$$\text{ATAF} = T \times D, \text{ unit is degree C-hours (°C-hr)} \tag{5}$$

$$\text{AEAF} = E \times D, \text{ unit is kV/mm-hours (kV/mm·hr)} \tag{6}$$

where T is temperature in °C, D is the duration of stresses in hours and E is electrical stresses in kV/mm.

Both factors help in generating the mathematical equation which helps in differentiate the degradation trends. The thermal stresses of 190°C, 200°C and 210°C and electrical stresses of 2 kV/mm, 4 kV/mm and 6 kV/mm were used. The electrical stresses have been performed at room temperature. The ATAF and AEAF were calculated using Equations (1) and (2) and results are shown in **Table 2** and **Table 3** [2].

Table 2. Accelerated Thermal Aging Factor (ATAF).

Temperature (˚C)	Aging (hours)	ATAF (˚C-hr)
190	150	ATAF1 = 28,500
200	150	ATAF2 = 30,000
210	150	ATAF3 = 31,500
190	300	ATAF4 = 57,000
200	300	ATAF5 = 60,000
210	300	ATAF6 = 63,000
190	450	ATAF7 = 85,500
200	450	ATAF8 = 90,000
210	450	ATAF9 = 94,500
190	600	ATAF10 = 114,000
200	600	ATAF11 = 120,000
210	600	ATAF12 = 126,000
190	750	ATAF13 = 142,500
200	750	ATAF14 = 150,000
210	750	ATAF15 = 157,500

Table 3. Accelerated Electrical Aging Factor (AEAF).

Electrical stress (kV/mm)	Aging (hours)	AEAF (kV/mm-hr)
2	150	AEAF1 = 300
2	300	AEAF2 = 600
4	150	
2	450	AEAF3 = 900
6	150	
2	600	AEAF4 = 1200
4	300	
2	750	AEAF5 = 1500
4	450	AEAF6 = 1800
6	300	
4	600	AEAF7 = 2400
6	450	AEAF8 = 2700
4	750	AEAF9 = 3000
6	600	AEAF10 = 3600
6	750	AEAF11 = 4500

4. Moisture Content

The virgin insulating oil and paper have moisture content of 50 ppm and about 0.5% by weight respectively. Moisture in the transformer reduces the insulation strength. The main reasons for moisture content changes over the life cycle are:

moisture interactivity with environment due to leakage, additional moisture generation due to chemical reactions [3], transformer breathing, decomposing the cellulosic materials under stresses, aging phenomena, exposure to atmospheric moisture during maintenance, failure to dry out the insulation during manufacturing [4]. The moisture content is a life-shortening parameter. It can weakens the withstand breakdown voltage of the insulation system [5], promotes local heating, reduces the overload capability of transformers in emergency conditions [6], accelerates the process of insulation deterioration [5], decreasing the electrical and mechanical strength [7]. Electrical or partial discharges can occur in a high voltage region due to a disturbance of the moisture equilibrium [8] [9] increase the electrical conductivity and dissipation factor. According to Fabre [10], the rate of thermal aging of paper is proportional to its moisture content. Moisture in transformer oil can also lead to partial discharge, bubble formation when high temperatures are attained in the winding and an abrupt desorption of moisture takes place from the paper toward the oil [9]. Moisture is a polar liquid having high permittivity and therefore is attracted to areas of strong electrical field [11]. As the transformer warms up, moisture migrates from the solid insulation into the fluid. The rate of migration depends on the conductor temperature and the rate-of-change of conductor temperature. The moisture moving between the cellulose and oil are different for each direction as the moisture in the cellulose is not evenly distributed. The migration of small amounts of moisture from paper to oil has been associated with the phenomenon of static electrification appearing when there is a charge accumulation on the interfaces between dry and humid zones [12] [13]. Moisture transfer can be activated by moisture concentration gradient, temperature gradient and pressure gradient [13]. In addition dissolved moisture in oil can precipitate out during rapid cool down periods and become free water which may or may not re-dissolve [14]. Excessive amounts of moisture can accelerate the degradation process of the cellulose and prematurely aged the transformers insulation system [14].

The moisture in cellulosic insulation may be determined from moisture in oil samples using oil/paper moisture equilibrium curves such as Fabre-Pichon curves, Oommen curves, Griffin curves, MIT curves [11] [16] Infra red techniques (IR) and Interfacial polarization (IP) [17] [18] [19].

5. Breakdown Voltage (BDV)

The breakdown voltage (BDV) is an important parameter to gauge the condition of oil. The BDV of oil is high when it is dry and clean, it goes down slowly as the moisture contents and conducting impurities increase as a result of oxidation of oil [20]. The BDV decreases consistently with aging because of release of moisture in the oil, due to increase in the size and number density of free particles generated due to dissolved gases and polar compounds, etc. [21]. The BDV bears a non-linear relationship with aging [20]. The breakdown characteristics depend on initial moisture of the insulation, initial temperature and temperature gradient.

6. Results and Discussions

A. MOISTURE CONTENTS

The moisture of oil sample has been measured by automatic coulometric karl fischer titration equipment. As per IS 335:2005 and IS 13567:1992, moisture content in virgin oil should not be more than 50 ppm. **Figure 2** indicates the variation of moisture content with aging at 190˚C, 200˚C and 210˚C. The insulation was aged at 0, 150, 300, 450, 600 and 750 hours. The moisture content of virgin oil sample was 32.8 ppm. It increased to maximum value of 67.6 ppm at 210˚C after 750 hours of aging. **Figure 3** indicates the graphical representation of moisture with ATAF. The most affective prediction model is with R^2 = 93.3%. The mathematical correlation between moisture and ATAF is shown in Equation (1):
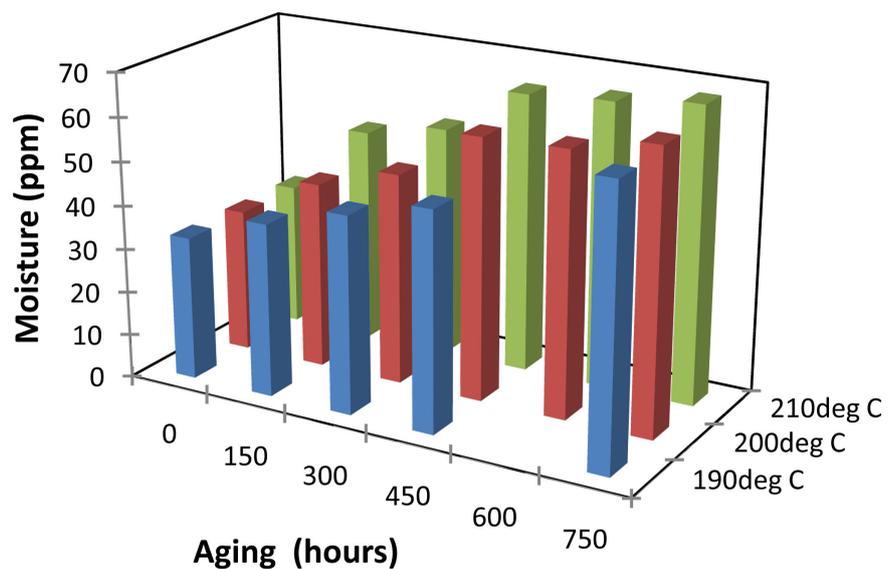
Figure 2. Variation of moisture with aging at 190˚C, 200˚C and 210˚C.
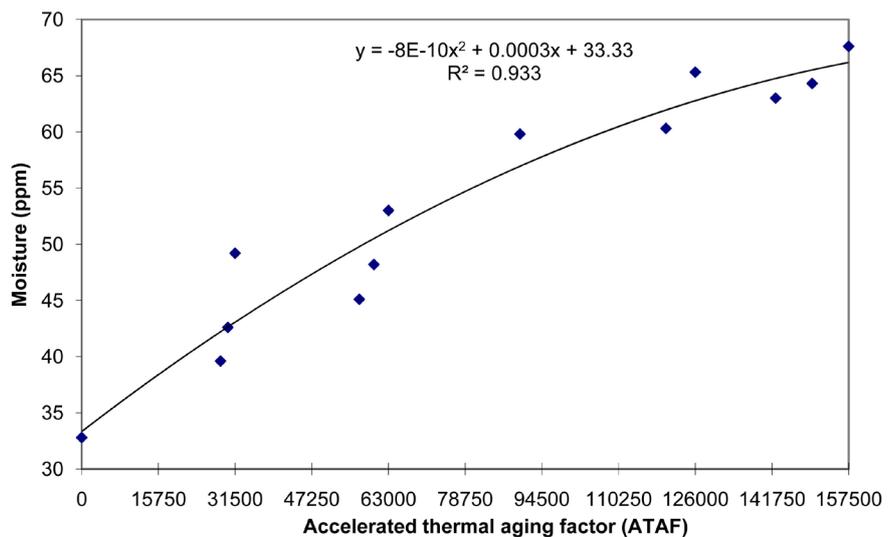
Figure 3. Correlation between moisture and ATAF.

$$\text{Moisture} = \left(-8\times10^{-10}\right)\text{ATAF}^2 + 0.0003\text{ATAF} + 33.33 \qquad (1)$$

In Figure 4, the variation of moisture with aging and electrical stresses of 2 kV/mm, 4 kV/mm and 6 kV/mm have been presented. The insulation was aged at 0, 150, 300, 450, 600 and 750 hours. The maximum increase of moisture content is 61.7 ppm at 6 kV/mm after 750 hours of aging. It indicates that the moisture content increases during thermal and electrical stress with aging.

Figure 5 shows the correlation between moisture and AEAF. The most effective prediction model is found with R^2 = 94.5%. The mathematical correlation generated between moisture and AEAF is shown in Equation (2):

$$\text{Moisture} = -2\times10^{-6}\text{AEAF}^2 + 0.013\text{AEAF} + 35.10 \qquad (2)$$
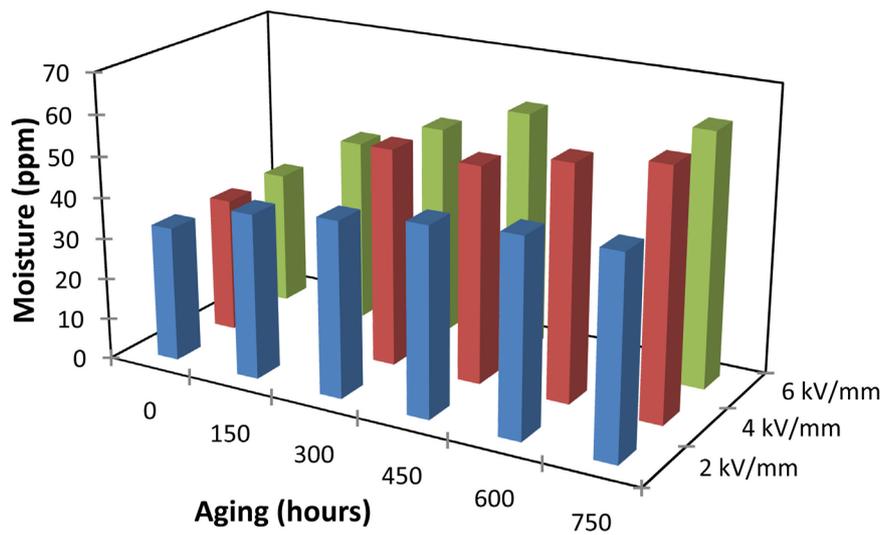
Figure 4. Variation of moisture with aging at 2 kV/mm, 4 kV/mm and 6 kV/mm.
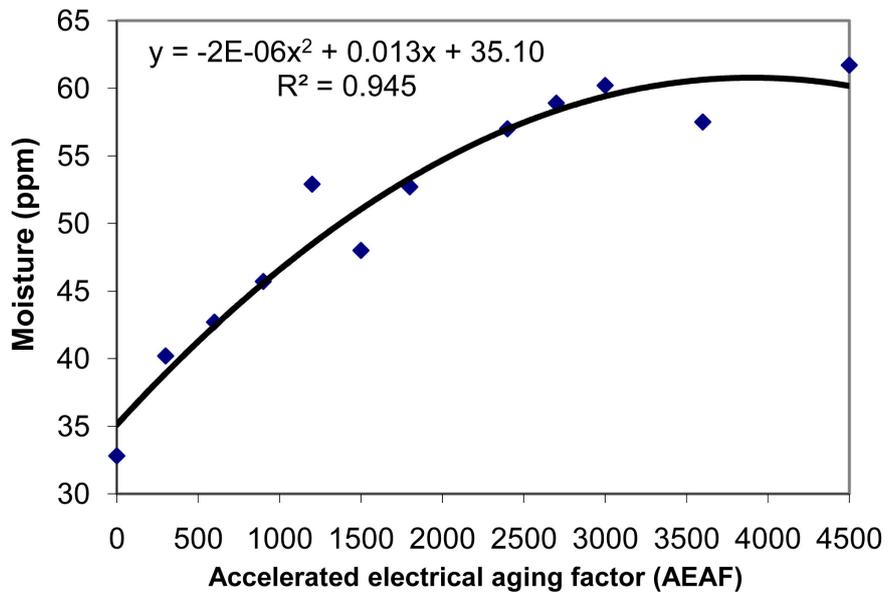
Figure 5. Correlation between moisture and AEAF.

According to Fofana [22], due to aging process, the decomposition of hydrocarbon molecules takes place by thermal and electric stresses. The energy required for the decomposition of weakly bonded hydrocarbons is supplied by the high voltage stress. The absorption of large amount of energy causes excitation of molecules, which in certain cases leads to the hemolytic breakdown of weak chemical bonds generating "gases" (along with low molecular weight hydrocarbons)". When this process takes place, the evolved gases leave the broken molecules in the liquid phase, which act as free radical, and there is high probability that it will react with other similar free radical which is no longer soluble in the blend of hydrocarbons. Due to the decomposition of long hydrocarbon chains that leave molecules with a broken covalent bond in the oil, it increases the conductivity which further affects the moisture and breakdown.

B. BREAKDOWN VOLTAGE (BDV)

The BDV of oil sample have been measured by oil breakdown test set [23]. As per IS 335:2005 and 6792:1972, BDV of new oil should be 30 kV (rms) minimum.

Figure 6 indicates the variation of BDV with aging for 190°C, 200°C and 210°C. The BDV of virgin oil sample was 45.2 kV. After 750 hours of aging, the BDV decreases to 13.1 kV at 210°C. The scattered results in Figure 7 indicate that the BDV decreases with increase in ATAF. The most effective prediction model is found with R^2=92.9%. The Equation (3) represents the mathematical correlation between BDV and ATAF.

$$\text{BDV} = \left(1 \times 10^{-09}\right)\text{ATAF}^2 - 0.0004\text{ATAF} + 44.13 \qquad (3)$$

Figure 8 indicates that the variation of the BDV with aging for 2, 4 and 6 kV/mm. After 750 hours of electrical stress, the maximum decrease of BDV is 29.4 kV at 6 kV/mm. Figure 9 exhibits a decreasing pattern of AEAF wih BDV [24]. The most effective prediction model is found with R^2=91.9%. The Equa-
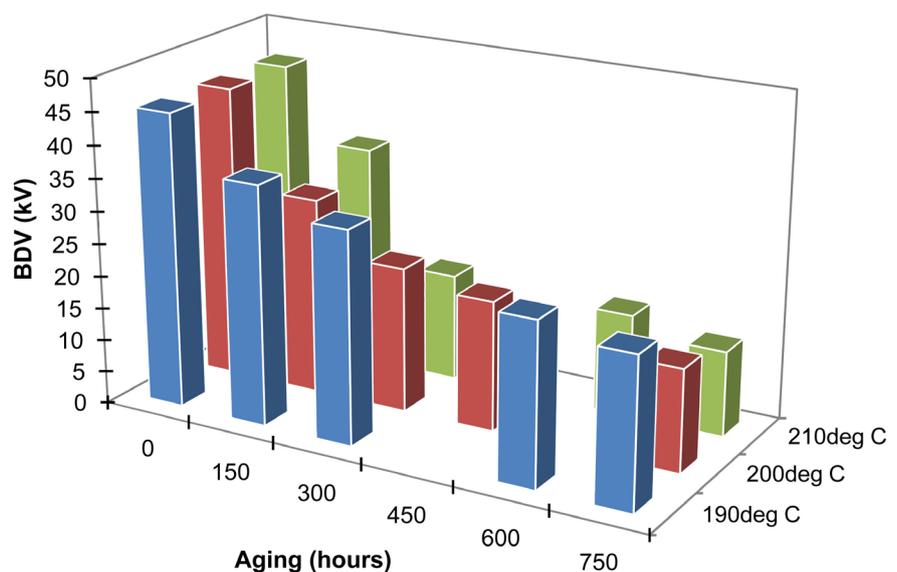
Figure 6. Variation of BDV with aging at 190°C, 200°C and 210°C.
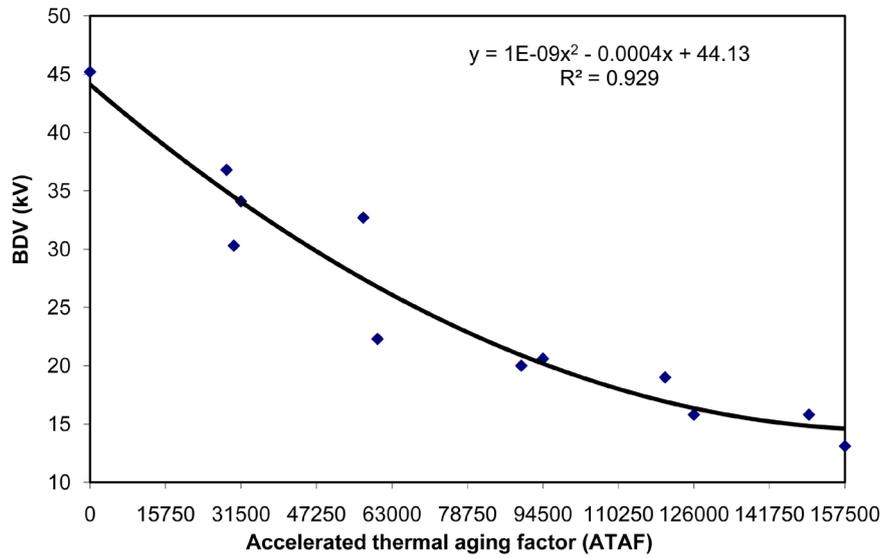
Figure 7. Correlation between BDV and ATAF.
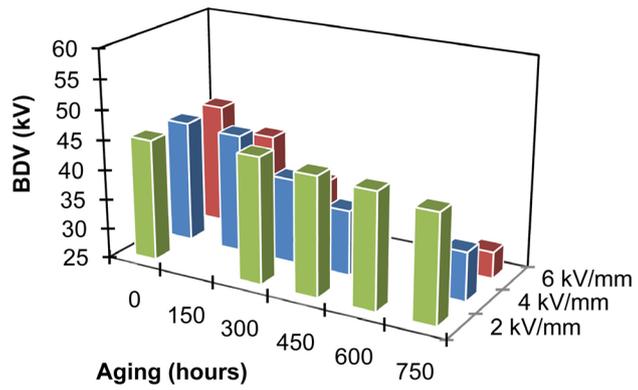
Figure 8. Variation of BDV with aging at 2 kV/mm, 4 kV/mm and 6 kV/mm.
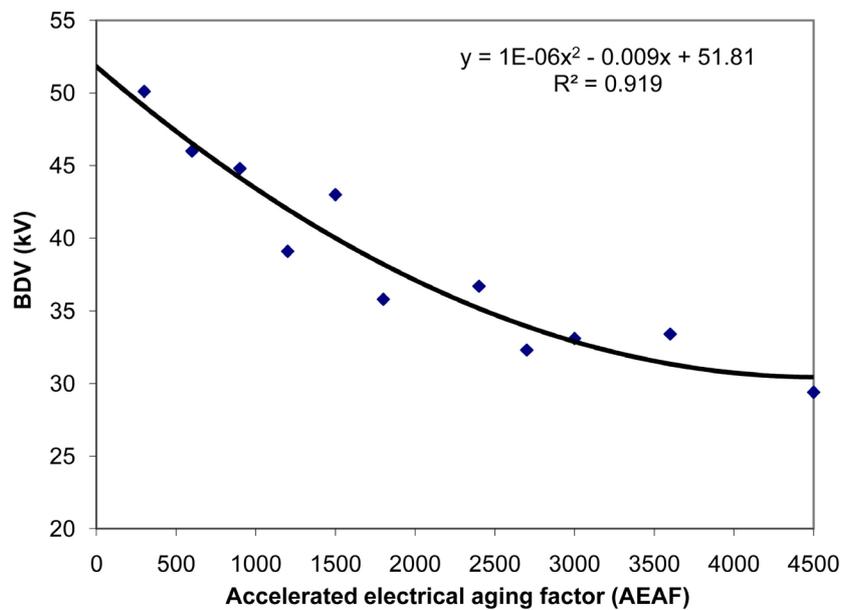
Figure 9. Correlation between BDV and AEAF.

tion (4) represents the mathematical correlation between BDV and AEAF.

$$BDV = \left(1 \times 10^{-06}\right) AEAF^2 - 0.009 AEAF + 51.81 \qquad (4)$$

7. Dielectric Dissipation Factor or Tan Delta

The tan δ is very important parameter to measure the quality of the insulation. The variation of tan δ with applied voltage provides useful information about the source of any imperfection in the insulation. It increases with insulation deterioration and serves as an early indicator of failure hazards. A low value of tan δ is generally desirable. The high value of tan δ gives an early indication of the contamination and presence of moisture content, conductive contamination, soluble varnishes, resins etc. [25].

8. Resistivity

Resistivity is the most sensitive property of oil, it varies with temperature. It is desirable to have resistivity of oil as high as possible. It reduces considerably due to presence of moisture, acidity and solid contaminants [17] [26]. High resistivity reflects low content of free ions and ion-forming particles, and indicates a low concentration of conductive contaminants [27]. Contamination of oil, which would not otherwise be detected by acidity test, will immediately be detected by the changes in the value of resistivity.

9. Results and Discussions

A. Resistivity

The resistivity of oil sample has been measured by Automatic dielectric constant, tan delta and resistivity (ADTR-2K) equipment. As per IS 335:2005 and IS 6103:1971, the resistivity of fresh oil is 35 TOhm-cm (35 × 10^{12} Ohm-cm) at 90°C, minimum.

Figure 10 indicates the variation of resistivity with aging for 190°C, 200°C and 210°C respectively. The resistivity of fresh oil sample at 90°C was very high,
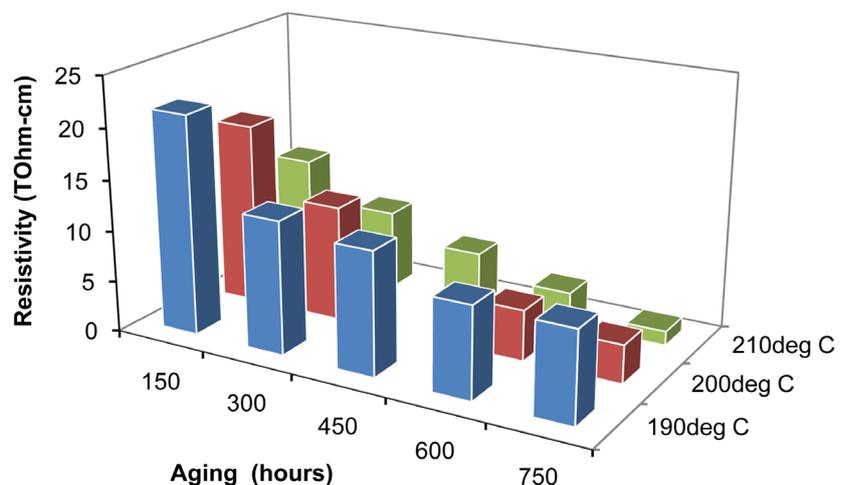
Figure 10. Variation of resistivity with aging at 190°C, 200°C and 210°C.

so it should be neglected in the graphical representation. After 750 hours of aging, maximum decrease of resistivity was 1.374 TOhm-cm at 210˚C. The results of **Figure 11** indicate that resistivity decreases with ATAF. The most effective prediction model is found with R^2=94.4%. The mathematical correlation generated between resistivity and ATAF is given in Equation (5):

$$\text{Resisivity} = \left(1 \times 10^{-09}\right) \text{ATAF}^2 - 0.0004 \text{ATAF} + 29.67 \tag{5}$$

Figure 12 indicates the variation of resistivity with aging for 2, 4 and 6 kV/mm. After 750 hours of aging under electrical stresses, maximum decrease in resistivity was 2.087 TOhm-cm at 6 kV/mm. The non-linear relation of resistivity with AEAF is shown in **Figure 13**. The most effective prediction model is
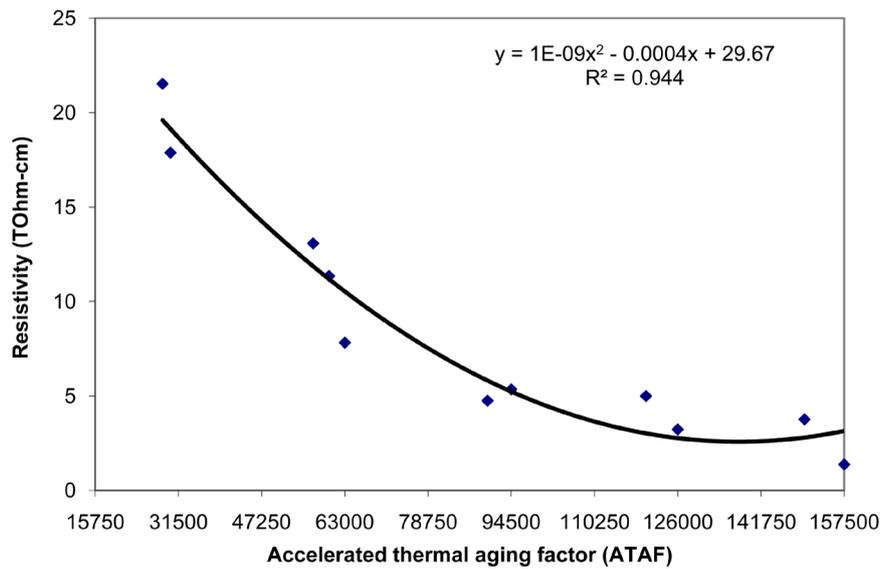
Figure 11. Correlation between resistivity with ATAF.
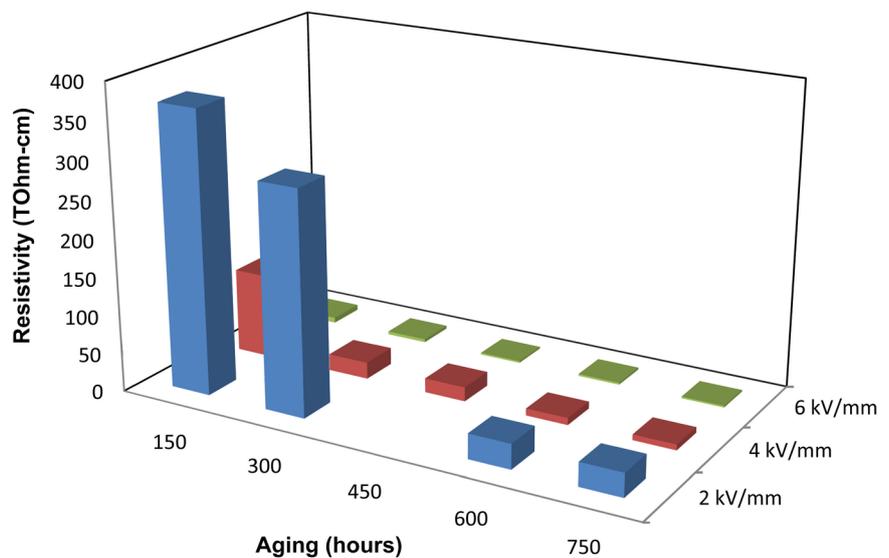
Figure 12. Variation of resistivity with aging at 2 kV/mm, 4 kV/mm and 6 kV/mm.
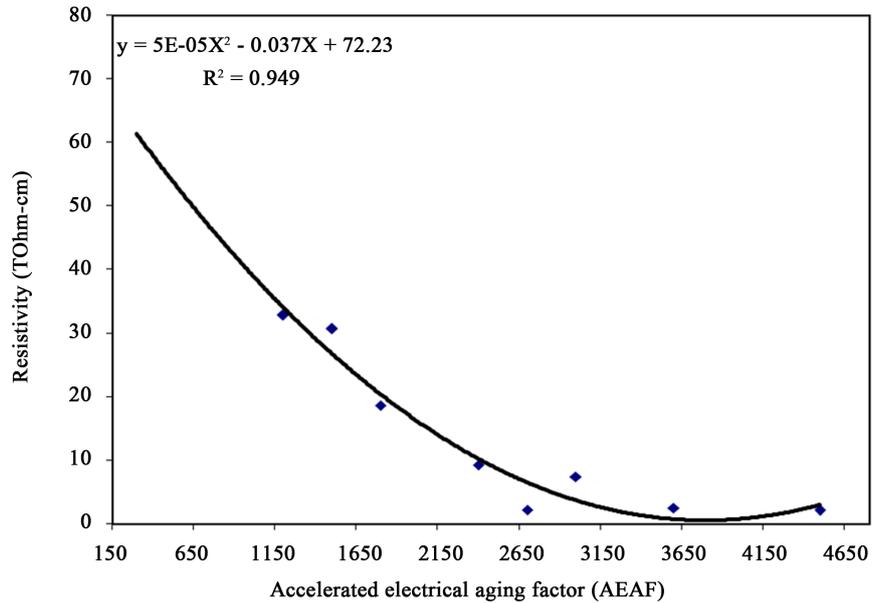
Figure 13. Correlation between resistivity and AEAF.

found with R^2 = 94.9%. The mathematical correlation generated between resistivity and AEAF is given in Equation (6):

$$\text{Resisivity} = (5 \times 10^{-06})\text{AEAF}^2 - 0.037\text{AEAF} + 72.23 \tag{6}$$

B. Dielectric Dissipation Factor (DDF) or Tan Delta

Figure 14 shows the variation of tan δ with aging for thermal stresses at 190°C, 200°C and 210°C. The tan δ of oil sample has been measured by Automatic dielectric constant, tan delta and resistivity (ADTR-2K) equipment. As per IS 6262:1971 and IS 335:2005, good oil should have tan δ of 0.002 (maximum) at 90°C. In our finding, tan δ of fresh oil sample at 90°C was 0.00216. After 750 hours of aging, the maximum increase of tan δ was 0.1067 at 210°C.

The scattered results of Figure 15 indicate that tan δ increases with ATAF. There is generally a relationship between tan δ and resistivity, both being affected by same contaminants. A decrease in resistivity is coupled with an increase in tan δ. The most effective prediction model is found with R^2=95.1%. The mathematical correlation generated between tan δ and ATAF is shown in Equation (7):

$$\tan \delta = \left(8 \times 10^{-12}\right)\text{ATAF}^2 - \left(6 \times 10^{-07}\right)\text{ATAF} + 0.013 \tag{7}$$

Figure 16 indicates the variation of tan δ with aging for 2, 4 and 6 kV/mm. After 750 hours of electrical stress, maximum increase of tan δ was 0.031 at 6 kV/mm. It indicates that tan δ is affected by aging, thermal stresses and electrical stresses. In Figure 17, resistivity increases polynomial with accelerated electrical stresses. The most effective prediction model is found with R^2 = 94.3%. The mathematical correlation generated between tan δ and AEAF is shown in Equation 8:

$$\tan \delta = \left(1 \times 10^{-09}\right)\text{AEAF}^2 + \left(1 \times 10^{-06}\right)\text{AEAF} + 0.001 \tag{8}$$

Figure 14. Variation of tan δ with aging at 190˚C, 200˚C and 210˚C.

$$y = 8E\text{-}12x^2 - 6E\text{-}07x + 0.013$$
$$R^2 = 0.951$$
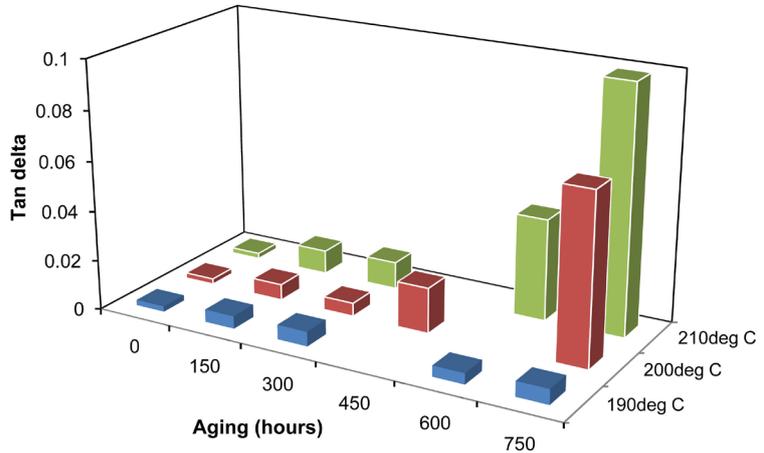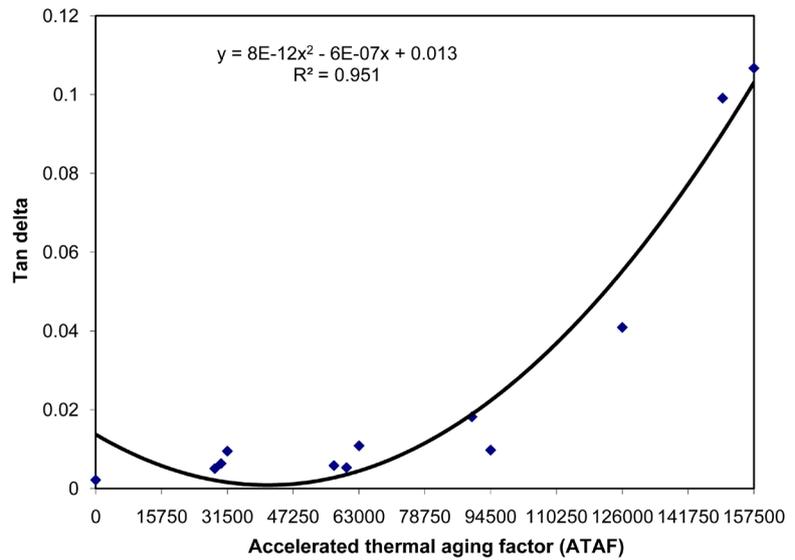
Figure 15. Correlation between tan δ and ATAF.
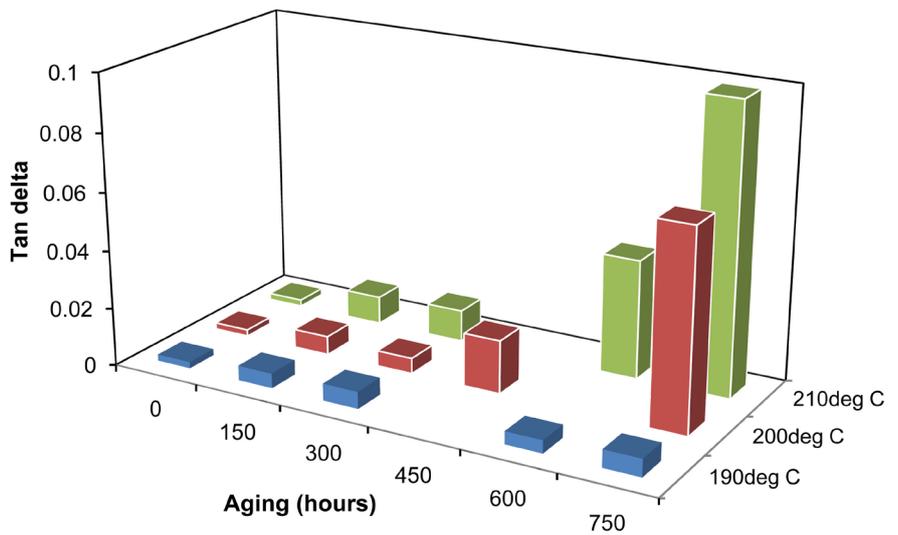
Figure 16. Variation of tan δ with aging at 2, 4 and 6 kV/mm.

$$y = 8E\text{-}12x^2 - 6E\text{-}07x + 0.013$$
$$R^2 = 0.951$$
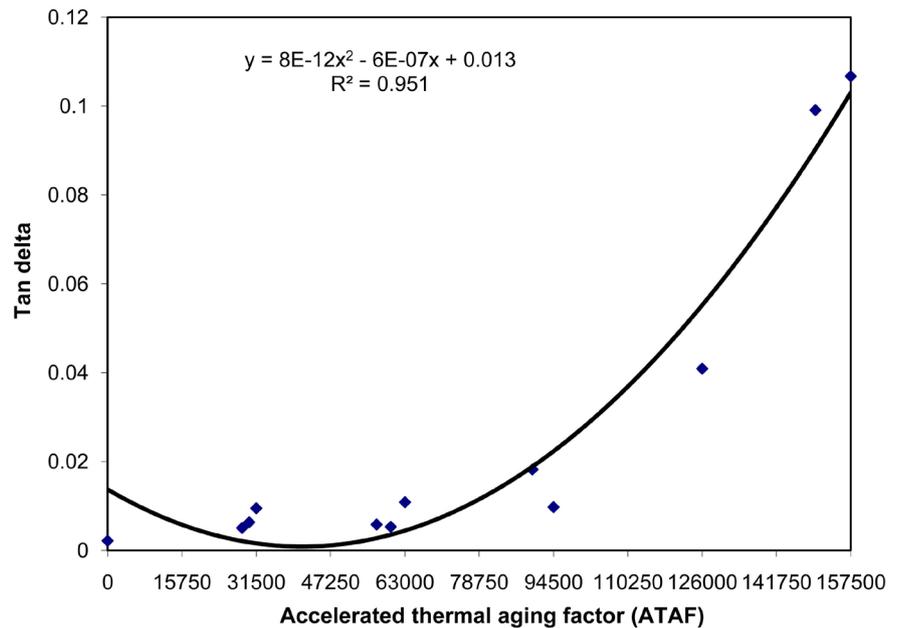
Figure 17. Correlation between tan δ and AEAF.

10. Conclusions

The effect of thermal and electrical stresses on the transformer oil has been experimentally investigated in this paper. The term accelerated thermal aging factor (ATAF) and accelerated electrical aging factor (AEAF) have been introduced in order to quantify the thermal and electrical stresses. The graphically representation between moisture, BDV, tan delta and resistivity with aging, ATAF and AEAF has been presented. It is presented that as the moisture increases with ATAF and AEAF, the BDV decreases in same pattern. Similarly as tan delta increases with ATAF and AEAF, resistivity decreases with same pattern. It is due to the fact that these properties are affected by the same contaminants.

This paper contributes that electrical stresses also play an important role in the degradation of the insulation along with thermal stresses but the degradation of insulation by thermal stresses is comparatively more as compared to electrical stresses. Further, all the properties were correlated with ATAF and AEAF and mathematical correlation has been generated.

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