PAPER

Effects of magnetite and titania nanoparticles on properties of transformer insulating oil

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Abstract

Transformer oil-based nano fluids have become popular research topic due to their enhanced dielectric and thermal properties. Considering the sustainability aspects of extending the life of transformer oil, it is imperative to conduct research on the effect of transformer oil with nano fillers. In the present work, the influence of conducting magnetite (Fe₃O₄), semiconducting titania (TiO₂) nanoparticles and combination of Fe₃O₄ and TiO₂ nanoparticles (multi-nanoparticle) on AC breakdown voltage are investigated for various concentrations. Nano fluid prepared using multi-nanoparticle shows enhanced AC breakdown voltage (BDV) of transformer oil compared with unfilled oil. Enhancement in BDV of 22% is observed with combination of 0.0025 wt% Fe₃O₄ and 0.0075 wt% TiO₂. In addition, the effect of titania nanoparticles dispersed into service-aged transformer oil with a weight percentage of 0.01% is investigated. Comparative study of breakdown strength and viscosity of nano fluid with unfilled oil is performed. Service-aged oil sample shows increased BDV of 15% with TiO₂ nanoparticles. The degradation in service-aged transformer oil is analyzed using UV–vis and Fourier Transform Infrared (FTIR) spectroscopy. The characteristics of oil samples are analyzed using fluorescence spectroscopy.

1. Introduction

The reliable operation of a power system network depends on the insulation status of various equipment. Transformer is one of the major equipment in power transmission and distribution systems. Failure in the transformer is mainly due to the deterioration of the solid/liquid insulation. Mineral oils have been used in transformers as an insulating and coolant material for almost over a century due to its superior dielectric and thermal properties. However, during the operation, insulation oil or transformer oil is subjected to electrical, thermal, mechanical and environmental stresses and can cause deterioration of insulation [1]. Thermal stress in transformer oil is one of the major causes of failure. Thermal ageing happens due to winding ‘hot spots’, which in turn can decompose the oil, and can affect its electrical, physical and chemical properties [2]. The condition monitoring of transformer oil plays a major role in the identification of incipient faults that can lead to premature failure of the equipment.

The potential solution to enhance the properties of transformer oil is by the addition of nano fillers to the transformer oil [3]. Recently, many researchers have investigated different compositions of nano fluids to evaluate their suitability as an alternative to traditional transformer oil. Several nanoparticles have been identified as nano fillers to improve the dielectric properties of the insulating liquid. Nano fillers are generally classified as conducting nanoparticles (Fe₃O₄, Fe₂O₃, ZnO, SiC), semiconducting nanoparticles (TiO₂, CuO, Cu₂O) and insulating nanoparticles (Al₂O₃, SiO₂, BN). Of late, researchers have turned their attention to multi-nanoparticle technique instead of individual nanoparticles on account of its enhanced dielectric properties [4, 5].
It has been proved that dielectric nanoﬂuids prepared using nanoparticles such as magnetite (Fe3O4), titanium dioxide (TiO2), aluminum oxide (Al2O3) and silicon dioxide (SiO2) show favorable dielectric and thermal characteristics, with a potential to replace the conventional mineral oil [6–8].

Studies on thermally aged transformer oil with addition of different weight percentages of TiO2 nanoparticles were conducted in [9]. The aging duration was maintained at three days, six days and ten days with a temperature of 120° C. The result showed that the nanofluid enhanced the breakdown strength in comparison with unfilled sample [9].

Three different types of insulating ﬂuids such as natural ester, mineral oil and natural ester mixed with Fe3O4 nanoparticles were explored for their AC breakdown strengths and it was shown that natural ester mixed with Fe2O3 nanoparticles has better breakdown strength compared with mineral oil and natural ester [10]. Silica based nanofluid exhibits improved breakdown strength even at a higher moisture level compared with conventional transformer oil [11].

Breakdown strength and role of surfactant in the dispersion stability of nanofluid were investigated with TiO2 nanoparticles and Cetyl Trimethyl Ammonium Bromide (CTAB) as surfactants. An increase in breakdown strength of TiO2 ﬁlled mineral oil in comparison with unfilled oil was observed [12].

It has been observed that vegetable oil-based nanofluid shows improved electrical properties and lower chemical degradation when compared with unfilled vegetable oil and mineral oil [13]. Farade et al developed graphene oxide and h-BN (hexagonal boron nitride) nanoparticles infused cottonseed oil as an electrical insulating material and cooling medium in transformers [14, 15].

The breakdown strength under ac and positive impulse voltage application showed improvement when thermally aged mineral oil was added with TiO2 nanoparticles [16, 17]. Singh et al conducted studies on inﬂuence of service ageing on properties such as breakdown voltage, moisture, resistivity, tan δ, interfacial tension and flash point. It was found that all these properties degraded due to ageing [18].

The charging dynamics of conducting and semiconducting nano-particles inside the oil is different and has been proposed to inﬂuence the breakdown strength [19–21]. Thus, it is worth to explore the effect of breakdown strength of transformer oil ﬁlled with conducting and semiconducting nanoparticles. It is seen that the studies on transformer oil mixed with multinationaparticle are least reported. Transformer oil when aged under service conditions undergo deterioration due to several factors including moisture absorption, impurities, oxidation and other environmental conditions. Extending the life of transformer oil can greatly enhance the sustainability of the power industry. The reported studies are based on TiO2 nanofluid based on virgin oil. The potential benefits of adding nanoparticles in service-aged transformer oil has not yet been studied well, particularly the effect of adding TiO2 nanoparticles to service-aged transformer oil.

In this paper, an attempt is made to understand the properties of viscosity and AC breakdown strength of transformer oil when added with various compositions of nanoparticles. The nanoparticles chosen are: (a) titania (TiO2) nanoparticles; (b) magnetite (Fe3O4) nanoparticles; (c) combinations of the these (multi-nanoparticles) with different volume fractions. Furthermore, AC breakdown strength and viscosity of aged oil with titania nanoparticles were analyzed. FTIR, UV and ﬂuorescent spectrum of the oil samples were analyzed to understand the effect of aging.

2. Experimental studies

2.1. Characterization of nanoparticles

Titania (TiO2) 100 nm (purity 99.5) and magnetite (Fe3O4) nanoparticles (50–100 nm, purity 99.7) were obtained commercially from Sigma-Aldrich chemicals. Scanning Electron Microscopy (SEM) at nanometric scale using Nova Nano SEM-450 Field Emission Scanning Electron Microscope (FEI-USA) was used to study the particle size and morphology of the nanoparticles. Figures 1 and 2 show SEM images of titania and magnetite nanoparticles, respectively. The image shows that the particles are roughly spherical and polydispersed with the particle size is ≈120 nm for TiO2 and ≈70 nm for Fe3O4.

x-ray diffraction pattern (XRD) of titania and magnetite nanoparticles were done using Bruker D8 Advanced Diffractometer (USA), which is equipped with a Lynx Eye position-sensitive detector with Cu – Kα X rays of wavelength (λ) 1.5406 Å and data was taken for Bragg angle (2θ) in the range of 10° to 70°. Figures 3 and 4 present the XRD patterns of both nanoparticles. The absence of any extra peak or impurity in the XRD pattern suggests the phase purity of nanoparticles. The dominant peaks at 25.26° and 47.98° confirm anatase structure of TiO2. XRD pattern of Fe2O3 was indexed with cubic structure with Fd-3 m. The size of the nanoparticle was calculated using Debye–Scherrer equation given by (1) [22].

\[ D = \frac{0.9 \lambda}{(\beta \cos \theta)} \] (1)

Where D is the particle size, \( \lambda \) is the wave length of X ray, \( \beta \) is the full width at half maximum in radians (FWHM) and \( \theta \) the Bragg angle in radians. The size of the titania nanoparticle is ≈120 nm and that of Fe3O4 is ≈50 nm.
Figure 1. SEM image of titania nanoparticles.

Figure 2. SEM image of magnetite nanoparticles.

Figure 3. XRD of titania nanoparticles.
2.2. Preparation of nanofluid
Nanoparticles were dispersed into the base oil using magnetic stirring and ultra-sonic mixing. Before preparing the nanofluid, the nanoparticles were kept in a hot air oven at 150 °C for eight hours to remove moisture content. The stability of nanoparticles in oil depends on the type of surfactant and its concentration. In the present work, 0.001 wt% oleic acid was used as surfactant. Prepared nanofluids are 0.01 wt% Fe3O4, 0.01 wt% TiO2, 0.005% TiO2 + 0.005% Fe3O4, 0.0025% Fe3O4 + 0.0075% TiO2 with virgin oil as base fluid and 0.01 wt% TiO2 + service-aged oil. Aged oil samples were obtained from a 11 kV/430 V, 250 kVA transformer in service with an aging duration of 5 years. The transformer oil is a paraffin based mineral oil with a density of 0.828 g cm⁻³ and kinematic viscosity of 9.1 mPa at 40 °C. Figure 5 shows the preparation steps.

2.3. Breakdown study
Breakdown voltage of the oil samples under AC voltage application was measured as per ASTM D 1816 standards [23]. Figure 6 shows the experimental setup. The test circuit consists of 100kV, 10 kVA transformer, current limiting resistance of 10 MΩ and a capacitance divider to measure the AC voltage. The test cell consists of sphere electrode systems having a diameter of 19.8 mm with a gap spacing of 2.5 mm. The AC voltage was...
increased at the rate of 2 kV/s until breakdown. The average of eighteen values was considered as the breakdown voltage of the oil sample.

2.4. Fluorescence spectroscopy measurements
Recently, fluorescence spectroscopy has become more popular due to its high sensitivity, non-intrusive and possible in situ condition assessment. In the present work, fluorescence technique is used to characterize the aged and nanoparticle filled transformer oil. The fluorescence measurements were done using Horiba-Fluoromax 4 spectrofluorometer (Japan) with a 150 W ozone free Xenon arc lamp. The excitation wavelength was kept 350–600 nm in an interval of 10 nm. Emission wavelength ranges from 320–600 nm in an interval of 10 nm. Slit width used is 1 nm.

2.5. Viscosity
Viscosity of transformer oil is important in order to understand its heat transfer capability. While in service, a transformer is subjected to electrical and thermal stresses. These lead to degradation of the insulating oil. The quality of oil is adversely affected due to dissolved gases and other decomposition byproducts. The viscosity of the samples were measured using BROOKFIELD DV3T rheometer (speed 0.01–250 rpm, 1% of full scale range accuracy, 0.2% of full scale range repeatability) from 30 °C to 70 °C as per ASTM D445 standards [24]. The results were compared with unfilled sample.

3. Results and discussion

3.1. Fourier Transform Infrared (FTIR) analysis
FTIR spectrum of virgin and aged samples were measured using a Jasco 6800 FT Mid-IR/Far-IR Spectrometer (Japan). A Mid-IR (KBr) beam splitter and temperature stabilized fast-recovery deuterated triglycerine sulphate (FR-DTGS) detector is used for the measurements.

The spectrum was analyzed between wave numbers 500–4000 cm⁻¹. Figure 7 shows FTIR spectrum of virgin and aged oil samples. Peaks were obtained at 718 cm⁻¹, 1374 cm⁻¹, 1456 cm⁻¹, 2363 cm⁻¹, 2854 cm⁻¹ and 2918 cm⁻¹. An additional peak is observed at 2160 cm⁻¹ in aged oil sample, which indicate the presence of carboxylic acid (C(=O)OH) and is a known oil degradation byproduct. Peaks at 1374 cm⁻¹ and 1456 cm⁻¹ indicates C-H bond stretching. The peaks between 718 cm⁻¹ is the indication of aromatic C-H bending functional group [25].

3.2. U-V vis spectroscopy
U-V spectrometric analysis has been carried out using SHIMADZU UV-2401 PC spectrophotometer (Japan). U-V spectrum in the range of 200 nm to 800 nm is shown in figure 8. U-V spectrum gives information about light absorption at each wavelength. In the virgin sample, the spectra shows a maximum absorption at 240-nm, that corresponds to the aromatic hydrocarbons present in the transformer oil. In the case of service-aged oil, the intensity is enhanced as well as the maximum is shifted to 340-nm. It also shows a small peak at 340 nm. According to Beer–Lambert law the absorption of the incident light passing through a sample is proportional to
the concentration of the absorbance (see (2)).

\[
A = \epsilon l c
\]  

(2)

Where, \(\epsilon\) is the molar absorptivity, \(l\) is the path length and \(c\) is the concentration. The enhancement in absorbance of aged sample indicate the presence of decomposition byproducts [26].

3.3. Analysis of service-aged and nanofluid using Fluorescence spectroscopy

Fluorescence is the process of spontaneous emission of photons due to optical excitation. The emission wavelengths and intensity of the spectra are used to probe compositions, concentration and quality of the sample. The maximum absorption wavelength depends on the energy levels of molecules. The emission intensity \(I\) is proportional to photo-luminescence quantum yield \(\phi\), where \(\phi\) is a ratio of the number of photon emitted to the number of photon absorbed as shown in equation (3).

\[
I = kI_0\phi(1 - 10^{-\epsilon l})
\]  

(3)

Where \(k\) is a proportionality constant, \(I_0\) is the incident light intensity, \(\epsilon\) is the molar absorptivity, \(l\) is the path length and \(c\) is the concentration [27].

Hence, the intensity of the emission wavelength of the spectrum depends on factors such as fluorophores (chemical compounds that absorb visible light), quenching species, physical parameters such as viscosity and optical density or absorbance.

Figure 9 shows the variation of fluorescence intensity as a function of emission wavelength with a single excitation wavelength (390- nm) of virgin oil, aged oil and nanofluid. In the virgin sample, the emission maximum is obtained around 347 nm and aged sample shows a red shifting of about 421 nm. Transformer oil is a complex mixture of aromatic, aliphatic and several high molecular weight hydrocarbon compounds. The obtained emission spectra in the region between 330–450 nm of the virgin oil is ascribed to hydrocarbons in the transformer oil. In the aged oil the emission spectra is changed to higher wavelength regions. The red shift in the emission wavelength signifies the deterioration of the transformer oil due to oxidation [28]. In addition, the emission peak width is observed to increase with aging. The increase in width is quantified by calculating the full width half maximum (FWHM) of the emission peak (refer to table 1). For the virgin sample, FWHM is 51 nm and with aged oil it is observed to be 89 nm. The increase in FWHM is due to the decomposition by-products formed during aging. Moreover, the intensity of the spectra is found to decrease with aging, which is attributed to the decrease in the concentration of hydrocarbons molecules in the aging process.

Figure 9 also presents emission spectra TiO2 based nanofluid, which contain two maxima at 430 nm and 472 nm. The peak at 430 nm corresponds to emission spectra of hydrocarbons and the peak at 470 nm indicate the emission spectra of surface modified TiO2 [29]. The decrease in intensity of emission spectra of nanofluid indicate the quenching effect due to dispersion of TiO2 nanoparticles in the aged transformer oil [28]. These spectral changes evidences the stability of nanofluid.

The contour plots (figure 10 to figure 12) show the emission spectra for different values of excitation energies. The change in the intensity and line width of fluorescence spectra with aging and TiO2 nanoparticle filling can easily monitored from the contour maps. Thus, the aging condition and quality of the nanofluid could be effectively monitored from the fluorescence data.
3.4. Measurement of viscosity

Viscosity of oil is important when it is used as a coolant. Figure 13 shows the variation of viscosity of virgin oil and nanofluids. The results indicate that the addition of nanoparticles causes a marginal increase in viscosity in the measured temperature range. It is reported that the viscosity of nanofluid depends on various factors such as particle size, shape, volume fraction, distribution, surfactant etc. In the present work magnetite based nanofluid shows high viscosity compared to other samples at lower temperature which is attributed to the increase in interface resistance due to its high density and smaller size [30]. In all the samples it is observed that viscosity decreases with increase in temperature. This is due to the increase in inter-molecular distance with temperature. Figure 14 presents the viscosity of aged oil and titania filled aged oil. It is known that the viscosity increases with

Table 1. Fluorescence spectral parameters.

| Sample       | FWHM | Emission Wavelength | Intensity     |
|--------------|------|---------------------|---------------|
| virgin       | 51   | 347                 | $5.24 \times 10^6$ |
| 0 wt % TiO$_2$ | 81   | 421                 | $1.84 \times 10^5$ |
| 0.01 wt% TiO$_2$ | 106  | 430, 472            | $1.13 \times 10^5$ |
Figure 11. Excitation Emission spectra of Aged oil.

Figure 12. Excitation Emission spectra of titania filled aged oil.

Figure 13. Viscosity of virgin, magnetite and titania filled oil.
increase in oxidation and furan contents [31]. The high value of viscosity is an indication of degradation of the transformer oil.

### 3.5. Measurement of AC breakdown voltage

AC breakdown voltage is measured to assess the dielectric strength of oil sample. Breakdown strength is important when transformer oil is used for insulation purpose. Breakdown voltages of samples were measured according to the standard of ASTM D 1816. Statistical distribution of test results were analyzed using two parameter Weibull distribution given by

\[
F(\chi) = 1 - \exp\left(-\left(\frac{\chi}{\alpha}\right)^{\beta}\right)
\]

where \(F(\chi)\) is the cumulative probability of breakdown, \(\alpha\) is the scale parameter and \(\beta\) is the shape parameter.

Figure 15 shows the variation of average breakdown voltage for nanofluids with TiO\(_2\) and Fe\(_3\)O\(_4\) nanoparticles. The addition of TiO\(_2\) with 0.01wt% results in an average breakdown voltage of 28.4 kV. The enhancement in breakdown voltage is a marginal 6.3% when compared with virgin sample, as reported earlier [12, 33].

It is observed that nanofluid with 0.0025wt% Fe\(_3\)O\(_4\) and 0.0075 wt% TiO\(_2\) shows highest breakdown voltage. Improvement in breakdown voltage is 22.87% with respect to virgin sample. And by the addition of 0.005wt%
Fe₃O₄ and 0.005wt% TiO₂ the percentage enhancement is about 15.49%, behaviour is similar to the reported mutinanoparticle using Fe₃O₄ and MgO, exhibiting superior property than individual nanoparticles [19].

Figure 16 shows two parameter Weibull distribution of breakdown voltage for nano fluids with different nanoparticles. The shape parameter is equal to the slope of the line and the scale parameter which is related to the scattering of the data.

Figure 17 shows two parameter Weibull distribution of breakdown voltage for aged and TiO₂ based aged transformer oil sample. The probabilities of failure in BDVs are noted at 10, 50 and 63.2% of failure instance and is given in the table 2. It can be seen that the addition of nanoparticles enhances the breakdown voltage (BDV) of base oil. In aged oil sample with the addition of TiO₂ nanoparticles improves BDVs by 15%. The probable reason for decrease in BDV of service aged sample is the increased ingress of moisture in aged samples. Addition of nanoparticles to oil forms a double layer consisting of stern and diffuse layers. Stern layer is between diffuse layer and nanoparticles, and it mainly consists of high density of ions. The interface region has a charge that depends on the types of absorbed group. Nanoparticles absorb hydroxyl group in moisture and its surface become negatively charged, thus mitigating the effect of moisure [9, 34]. As a result, the aging process is retarded.

As proposed, the enhancement in breakdown strength of nanofluid is associated to its electron trapping nature of the nanoparticles. The mismatch in the electrical properties of nanoparticles and oil form potential
The addition of magnetite and titania nanoparticles enhance the electrical properties of the un-filled oil. Breakdown voltage (BDV) of TiO$_2$, Fe$_3$O$_4$ and multi-nanoparticle were analyzed. In all cases the BDV of nanofluid samples were higher than that of fresh samples. The enhancement in BDV is marginal when the samples were added with TiO$_2$, Fe$_3$O$_4$ nanoparticles separately. On the other hand, multi-nanoparticle dispersed transformer oil showed increased breakdown strength compared with base oil. Enhancement in BDV of 22% is observed with the combination of 0.0025 wt% Fe$_3$O$_4$ and 0.0075 wt% TiO$_2$. The increase in

| Sample code | Sample                          | Breakdown voltage in different probabilities | Weibull distribution parameters |
|-------------|---------------------------------|-----------------------------------------------|---------------------------------|
|             |                                 | 10% | 50% | 63.2% | $\alpha$ | $\beta$ |
| 1           | Virgin                          | 26 kV | 28.4 kV | 28.9 kV | 29.2 | 14.6 |
| 2           | 0.01 wt% Fe$_3$O$_4$            | 27.2 kV | 29.8 kV | 30.2 kV | 30.0 | 21.4 |
| 3           | 0.01 wt% TiO$_2$                | 28.2 kV | 30.2 kV | 30.8 kV | 30.7 | 25.18 |
| 4           | 0.005 wt% [TiO$_2$+Fe$_3$O$_4$] | 29.9 kV | 32.8 kV | 33.3 kV | 33.4 | 19.9 |
| 5           | 0.0025wt% Fe$_3$O$_4$+0.0075 wt% TiO$_2$ | 31.5 kV | 34.9 kV | 35.8 kV | 35.75 | 16.95 |
| 6           | Aged oil                        | 19.9 kV | 22.1 kV | 23.4 kV | 23.0 | 12.64 |
| 7           | Aged oil+ 0.01 wt% TiO$_2$      | 23.6 kV | 26.2 kV | 26.5 kV | 26.7 | 16.3 |

In this work the characteristics of TiO$_2$ and Fe$_3$O$_4$ nanoparticles dispersed transformer oil are studied. Characterization of aged oil has been performed using UV–vis, FTIR and fluorescence techniques. The stability of samples was identified using fluorescence spectroscopy. AC breakdown studies of aged and nanofluids were carried out as per ASTM D 1816. Two parameters Weibull distribution is used to understand the breakdown probability of aged oil and nanofluids. During the service life transformer oil is subjected to different stresses and finally leads to degradation of oil. Degradation of oil is evident from UV–vis, FTIR and fluorescence spectrum. TiO$_2$ filled aged samples were characterized using excitation-emission matrix. The outcomes of the present study are summarized as follows:

- The notable red shift in the emission maxima and change in the intensity of the fluorescence spectra indicates the aging and nanofilling of the transformer oil.
- Nanoparticle filled transformer oil shows a slight increase in viscosity at 30 °C and at higher temperatures viscosity is almost equal to that of the virgin sample
- The addition magnetite and titania nanoparticles enhance the electrical properties of the un-filled oil.

4. Conclusion

In this work the characteristics of TiO$_2$ and Fe$_3$O$_4$ nanoparticles dispersed transformer oil are studied. Characterization of aged oil has been performed using UV–vis, FTIR and fluorescence techniques. The stability of samples was identified using fluorescence spectroscopy. AC breakdown studies of aged and nanofluids were carried out as per ASTM D 1816. Two parameters Weibull distribution is used to understand the breakdown probability of aged oil and nanofluids. During the service life transformer oil is subjected to different stresses and finally leads to degradation of oil. Degradation of oil is evident from UV–vis, FTIR and fluorescence spectrum. TiO$_2$ filled aged samples were characterized using excitation-emission matrix. The outcomes of the present study are summarized as follows:

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- The addition magnetite and titania nanoparticles enhance the electrical properties of the un-filled oil.

where $\epsilon_1$ is the permittivity of oil, $n$ is the total number of used nanoparticles, $m$ is the total number of conductive nanoparticles, $\theta$ is the angle of negative charges on the positive hemisphere and $\epsilon_{i+1}$, is the permittivity of the dielectric or semiconducting nanoparticles. The other factor which influence the streamer propagation is the saturation charge of the nanoparticles. It corresponds to the maximum charge that electrons could stand on their surface. It is expressed as,

$$Q_{st} = -12\epsilon_1 E_0 \left( \sum_{i=1}^{n} R_{i(i+1)}^2 \frac{\epsilon_{i+1} - \epsilon_1}{2\epsilon_1 + \epsilon_{i+1}} + \sum_{j=1}^{m} R_j^2 \right)$$

where $R_i$ is the radius of the conductive nanoparticles, $n$ is the number of used nanoparticles, $m$ is the total number of conductive NPs, $R_{i+1}$ is the radius of the dielectric or semi-conductive NP. In the current study, the multi-nanoparticle (Fe$_3$O$_4$+ TiO$_2$) dispersed oil show higher vales of breakdown strength compared with individual counter parts and is attributed to the enhanced surface charge density and saturation charge [19, 20].
breakdown voltage is attributed to the enhanced surface charge density and saturation charge of multinnanoparticle that increase its ability to trap streamer electrons.

- Dispersion of titania nanoparticles in service-aged oil showed improved dielectric strength compared with unfilled oil. Breakdown voltage of aged sample is 22.1 kV. It has been observed that addition of 0.01 wt% TiO$_2$ causes an enhancement in BDV by 18.5%. Addition of 0.01 wt% TiO$_2$ in aged sample show higher BDV compared with the same wt% of TiO$_2$ in virgin sample. The increase in BDV of service aged sample mixed with TiO$_2$ nanoparticles happens on account of the electron trapping and the moisture-mitigating effect of surface charge formed in the interface of layers. The influence of nanoparticle mixing in reducing the aging is hence established.

- Breakdown probability of transformer oil and aged oil sample dispersed with nanoparticles were analyzed at 10%, 50% and 63.2%. It has been observed that the three instances the nanofluid has lower breakdown probability than unfilled sample.

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