Ageing Performance on Mineral Oil Using ZnO Nanofluids

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Abstract- In this work, an effort has been made to enhance the dielectric properties of mineral oil by mixing ZnO nanoparticles in different concentration. The critical properties of mineral oil like AC breakdown voltage, volume resistivity, Flash point and Fire point with and without nanoparticles are studied to establish the role of ZnO nanoparticles with different concentration in mineral oil, for enhancement of the dielectric properties of mineral oil. It is found that new mineral oil with ZnO nanoparticles in a particular concentration shows improved AC breakdown voltage of 63.5% in new mineral oil. The Flash point & Fire point also shows an enhanced result at a particular concentration with ZnO nanoparticles in new and aged mineral oil. The above studies navigate a new research area in the field of development of new insulation material for High Voltage (HV) Power apparatus industries.

Keywords- Mineral oil, Breakdown voltage, Volume resistivity, Flash point, Fire point, Semiconductive nanofluids

I. INTRODUCTION

The transformer is commonly used for either stepping up or stepping down the voltage for transmission and distribution of power in any electrical system. In transformer, mainly two types of insulation material are used namely solid & liquid insulation material where the condition of insulation material plays a crucial role for the reliability of transformer in an electrical system. In a transformer, mineral oil as liquid insulation is mainly used for insulation as well as cooling medium. The mineral oil is a composition of paraffin (40 to 60%), naphthene (30 to 50%), aromatic (5 to 20%) and olefin (< 1%) which are degraded with time due to mainly three type of stresses such as electrical, thermal, mechanical [1]. In addition to the above degradation process, moisture and other contaminants/impurities act as a catalyst, it is considered to be most influential factor for lowering down the dielectric strength of mineral oil [2-4]. For breakdown phenomena of mineral oil, the streamer propagation velocity in mineral oil plays a crucial role where the velocity of the streamer propagation is reached nearly 15-100 km/sec [5]. It has been also established that the streamer propagation is more dangerous for initiation of electrical breakdown in any liquid insulating material compare to suspended particle and bubble mechanism for explaining the breakdown phenomenon of mineral oil in a transformer. For deciding the size and rating of the transformer, quantity of oil and rate of heat transfer are considered to be the key parameter as it overall optimizes the size of the transformer and its cost effectiveness [6]. It is a challenge to the design engineers/researchers globally to enhance the dielectric strength and cooling properties of mineral oil and the present work can address the same in view of the compactness of the transformer as well as HV power apparatus which are filled with mineral oil in HV power industries.

Recently, the nanofluid which is a mixture of mineral oil and nanoparticles coined by Choi et al in 1995 at the Argonne National Laboratory where nanofluid was prepared by dispersing nanoparticles in the mineral oil [7]. It has opened a new area of research in the field of optimization of mineral oil as insulation in high voltage power apparatus. It is possible due to the new development of nanoparticles such as insulating (Al_2O_3 and SiO_2), semiconducting (TiO_2, SiC, CuO & ZnO), and magnetic (Fe_2O_3 and Fe_3O_4) in the field of nanotechnology [8]. In order to explain the enhanced breakdown strength of mineral oil, a theory was developed by M. Zhan et al where it was explained that nanoparticles have a lesser relaxation time constant compare to the streamer propagation. The relaxation time constant is estimated by the following Equation 1:

Relaxation time: $r = (2\varepsilon_1 + \varepsilon_2) / (2\sigma_1 + \sigma_2)$ (1)

where ε_1, ε_2, σ_1 and σ_2 are the permittivity of mineral oil & nanoparticle, and electrical conductivity of mineral oil & nanoparticles respectively [9,10].

In this paper, electrical properties such as AC breakdown voltage (BDV) & volume resistivity and physical properties such as Flash & Fire point of new & aged mineral oil with and without ZnO nanoparticles have been studied and presented. It is observed that new mineral oil with ZnO nanoparticles in a particular concentration shows improved BDV compare to new mineral oil without ZnO nanoparticles. The Flash point & Fire point of new mineral oil with ZnO nanoparticles also shows enhanced result with a particular concentration of ZnO nanoparticles of 0.01%. However, there is no extensive variation in case of aged mineral oil with ZnO nanoparticles. Therefore, new mineral oil with ZnO nanoparticles may be an alternative efficient insulation for transformer which can reduce the size of the transformer. Overall, it may be a cost effective alternative insulation as nanofluid filled high voltage power apparatus based industries.

II. PREPARATION OF NANOFLUID

For preparation of nanofluid, mineral oil is procured from M/S Anand oil company, Kolkata and the nanoparticle (ZnO) ALDRICH Chemistry, particle size < 50nm, (BET), > 97%, is procured from M/S Sigma-Aldrich, Bangalore.

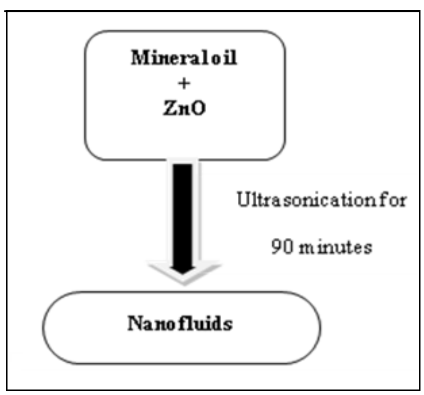


Figure. 1 Flowchart for preparation of nanofluids

The nanofluid is prepared by two steps process. Firstly, 500 ml of mineral oil with 0.28, 0.56, 0.84 and 1.12 gms of ZnO is mixed in a beaker to make the fluid matrix in a particular concentration of 0.01%, 0.02%, 0.03% and 0.04% respectively and secondly it is subjected to ultra sonication for 90 minutes for stable fluid mixture. The flow chart for the nanofluid preparation process is shown in Figure. 1. After proper mixing with the help of ultra sonication, it is carefully preserved in a nonreactive and non corrosive container for the characterisation of the nanofluid. The preservation of nanofluid with new mineral oil is shown in Figure. 2. The Sample of different concentration of nanoparticles are marked as S1, S2, S3, S4 and S5 which are prepared at various particle volume fraction of nanoparticles of 0%, 0.01%, 0.02%, 0.03% and 0.04% respectively and it is shown in Table 1. In table 1, the new mineral oil is indicated as 0% of nanoparticles with new mineral oil. The above prepared samples of various particle volume fractions of semiconducting nanofluids (SNFs) are tested in the "High Voltage and Insulation laboratory" at National Institute of Technology, Durgapur.

Fig.2 Preservation of nanofluid with new mineral oil

For preparation of aged oil, SNFs of different concentration are subjected for accelerated ageing. The procedure for ageing is followed as per ASTM D1934 standard where the sample of SNFs is kept in an oven for 120 hrs, at 125^0C [11] and it is shown in Figure 3 (a). Following the same process as described above, the sample of the aged mineral oil have been carefully preserved for testing in a nonreactive and non corrosive container for the characterisation of aged SNFs, it is shown in Figure 3 (b).

(a) (b)

Fig. 3 (a) Oven for ageing with monitoring system (b) Preservation of nanofluids with aged mineral oil after the preparation

Sample	Composition of New and Aged mineral oil (500ml) with and without ZnO	ZnO mixed in gms
S1	New mineral oil + 0%	0
S2	New mineral oil + 0.01%	0.28
S3	New mineral oil + 0.02%	0.56
S4	New mineral oil + 0.03%	0.84
S5	New mineral oil + 0.04%	1.12
S6	Aged mineral oil + 0%	0
S7	Aged mineral oil + 0.01%	0.28
S8	Aged mineral oil + 0.02%	0.56
S9	Aged mineral oil + 0.03%	0.84
S10	Aged mineral oil + 0.04%	1.12

Table 1 Description of samples

III. EXPERIMENTS FOR EVALUATION OF NEW AND AGED MINERAL OIL WITH OR WITHOUT NANOPARTICLES

A. Breakdown Voltage Measurement

The breakdown voltage (BDV) of mineral oil indicates the health of the transformer in an electrical system. The BDV depends on pressure, temperature, humidity, nature of applied voltage, gap between the electrode, contaminates and geometrical configuration of electrode for a BDV testing system. BDV is measured with the help of AC breakdown voltage oil test kit as per standard IEC 60156 [12]. The test kit of consists of 0-100kV voltage source and spherical electrode set at 2.5 mm gap between the electrodes, make M/S Shruti Electronics. The rate of rise of voltage is controlled at 2 kV/sec during the test. BDV test kit is shown in Figure 4 (a) and the Oil test cell is shown in Figure (b).

At first, the oil test cell is rinsed with samples as described in Table 1, and then oil is filled in the test cell of 500 ml and waits for 5 minutes to settle the oil before applying the voltage. The time delay is set as 2 minutes for dispersing the by-product after each breakdown. Following the same procedure for each sample as shown in Table 1, five successive breakdown voltages are noted and recorded for further analysis and evaluation.

(a) (b)

Figure 4. (a) 100kV BDV test Kit (b) Oil test cell

B. Volume resistivity measurement

Volume resistivity of liquid insulating material is one of the most critical parameter to determine the Oil condition. It is a ratio of dc potential gradient in volts per centimeter parallel to the current flow within the specimen, to current density (A/cm^2) at a given instant of time. It is numerically equivalent to the resistance between opposite side of one centimeter cubic block of liquid. For measurement of the volume resistivity of mineral oil, a volume resistivity test apparatus, make M/S Sivananda Electronics is used in the laboratory and the volume resistivity of new and aged mineral oil is measured and recorded as per the standard ASTM D257 [13].

C. Flash point and Fire point measurement

Flash point is known as the minimum temperature of mineral oil at which oil-vapor is produced due to the heating in a test cell. The minimum temperature of the oil at which vapor is produced due to the heating effect, causes a continuous fire at the surface of the oil is known as Fire point. Flash and Fire point test was carried by Pensky-Martens open cup apparatus as per standard ASTM D93 [14].

IV. RESULTS AND DISCUSSION

A. Breakdown Voltage (BDV) Measurement

The breakdown voltage of mineral oil is the key parameter for quality checking of the health of the transformer. BDV is the voltage at which oil starts conducting when the oil will not act as insulator and the current starts to flow through or surface of the electrode. BDV of S1 to S10 as described in Table 2 is measured and the Percentage Enhancement (PE) & Percentage Decrement (PD) of BDV is calculated as below:

PE of the BDV of n^{th} sample as S(n) with respect to the BDV of S1 is calculated as:

$$\text{PE of BDV for } S(n) = ((\text{BDV of } S(n) - \text{BDV of } S(1)) / \text{BDV of } S(1)) \times 100 \qquad (2)$$

Where, n= 2,3,4,5

The Percentage Decrement (PD) of BDV for S(n+5) with respect to S(n) is calculated as:

$$\text{PD of BDV for } S(n) = ((\text{BDV of } S(n) - \text{BDV of } S(n+5)) / \text{BDV of } S(n)) \times 100 \qquad (3)$$

Where, n=1, 2, 3, 4, 5

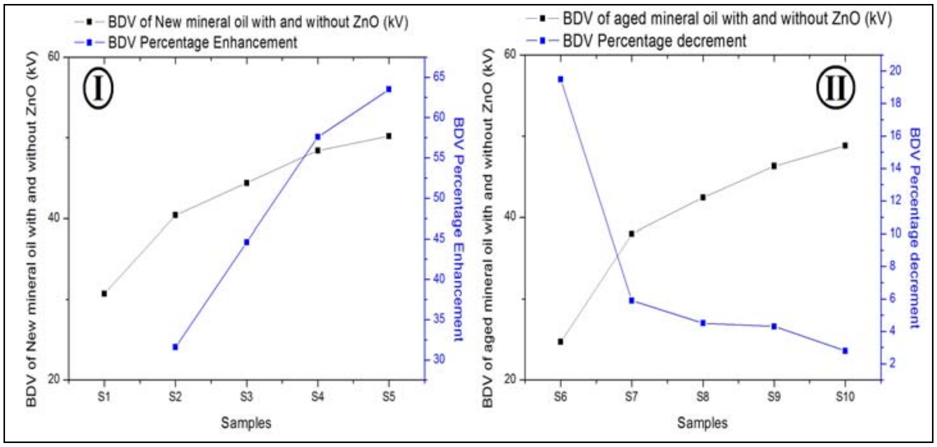
The BDV of samples S1 to S5 is measured and thereafter, PE of S2 to S5 is calculated by using Eq. 2 and it is presented in Table 2. It is observed from Table 2 that BDV of S1, S2, S3, S4 and S5 are 30.7 kV, 40.4 kV, 44.4 kV, 48.4 kV and 50.2 kV and PE of S2, S3, S4 and S5 are 31.6%, 44.6%, 57.6% and 63.5% respectively. It is also observed from the above table that the PE of BDV for S2 & S3 is in between 31.6 to 44.6%. However, the PE of BDV for S4 and S5 is in between 57.6 to 63.5% which is more than the PE of BDV for S2 and S3. It is due to the formation of less number of nanoparticles polarisation happens in S2 &S3 compare to samples S4 & S5. Therefore, it is understood from the above results that the PE of BDV is superior for new mineral oil with nanoparticles of different concentration compare to new mineral oil without nanoparticles.

New mineral oil with and without nanoparticles			
Index of Sample	**Particle volume fraction of ZnO in percentage (%)**	**Breakdown voltage (kV)**	**Percentage enhancement (%)**
S1	0	30.7	-
S2	0.01	40.4	31.6
S3	0.02	44.4	44.6
S4	0.03	48.4	57.6
S5	0.04	50.2	63.5
Aged mineral oil with and without nanoparticles			
Index of Sample	**Particle volume fraction of ZnO in percentage (%)**	**Breakdown voltage (kV)**	**Percentage Decrement (%)**
S6	0	24.7	19.5
S7	0.01	38.0	5.9
S8	0.02	42.4	4.5
S9	0.03	46.3	4.3
S10	0.04	48.8	2.8

Table 2. BDV & PE and BDV & PD of new and aged mineral oil with and without ZnO

The BDV of samples S6 to S10 is measured and thereafter, PD of S6 to S10 is calculated by using Eq. 3 which is shown in Table 2. It is observed from Table 2 that the BDV of S6, S7, S8, S9 and S10 are found to be 24.7 kV, 38.0 kV, 42.4 kV, 46.3 KV, 48.8 kV and PD of BDV for S6, S7, S8, S9 and S10 are found to be 19.5%, 5.9%, 4.5%, 4.3% and 2.8% respectively. It is also observed from the above table that the PD of BDV for S6 is 19.5%, but PD of BDV for S7 to S10 varies from 5.9% to 2.8% which are less compare to S6, it is due to the ageing of mineral oil that produces the organic compound along with water [3, 15] and causes a large decrement of BDV in S6. Therefore, it is understood from the above results that the PD of BDV is superior for aged mineral oil with nanoparticles of different concentration compare to aged mineral oil without nanoparticles.

The BDV and PE of new mineral oil with and without nanoparticles are summarised in Figure 5 (a). The BDV and PD of aged mineral oil with and without nanoparticles are summarised in Figure 5 (b).



(a) (b)

Figure 5 (a). The BDV & PE of new mineral oil with and without nanoparticles (b) BDV & PD of aged mineral oil with and without nanoparticles

B. Volume resistivity

The volume resistivity of new and aged mineral oil with and without nanoparticles is measured at 90^0C. It is shown in Table 3. It is observed from the Table 3 that the volume resistivity of S1, S2, S3, S4 and S5 are of 1.34, 7.55, 58.50, 29.60 and 20.50 Terra ohm-cm respectively. It is also observed from the Table 3 that the volume resistivity of S6, S7, S8, S9 and S10 are of 0.05, 3.77, 15.00, 8.18 and 6.35 Terra ohm-cm respectively. It is found that the volume resistivity is increased till the nanoparticles concentration of 0.02% for both new as well as aged mineral oil. It is due to the multi molecular moisture content in the mineral oil breaks down into single molecular moisture content till the nanoparticles concentration of 0.02% is reached [9]. When the concentration of the nanoparticles is increased beyond 0.02%, the effect of electrical conductivity of nanoparticles (ZnO) starts dominating [16]. Thus, the volume resistivity for both new and aged mineral oil with nanoparticles is decreased. The results are shown in Table 3. The comparison of the volume resistivity of the new and aged mineral oil samples with & without nanoparticles is shown in Figure 6.

New mineral oil with and without nanoparticles	
Sample	**Volume resistivity (Terra ohm-cm)**
S1	1.34
S2	7.55
S3	58.50
S4	29.60
S5	20.50
Aged mineral oil with and without nanoparticles	
Sample	**Volume resistivity (Terra ohm-cm)**
S6	0.05
S7	3.77
S8	15.00
S9	8.18
S10	6.35

Table 3. Volume resistivity of New and Aged mineral oil with & without nanoparticles

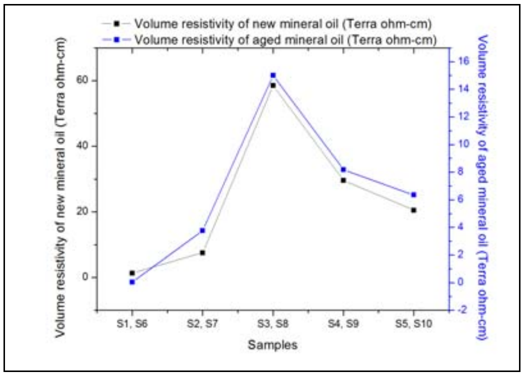


Figure 6. Comparison of Volume resistivity of new and aged mineral oil with & without nanoparticles

C. *Flash and Fire point*

The Flash and Fire point of new & aged mineral oil with and without nanoparticles are measured and the results are shown in Table 4. It is observed from Table 4 that the Flash point as well as Fire point is increased for both new and aged mineral oil with a particular ZnO concentration of 0.01%. It is due to the increase of thermal conductivity of ZnO compare to the thermal conductivity of mineral oil till a particular concentration of ZnO of 0.01% is reached. There is an increase in viscosity inside the mineral oil with nanoparticles in a particular concentration of nanoparticles of 0.01%. It is also observed that there is a decrease in the Flash and Fire point in S6 to S10 due to the formation of organic compounds in aged mineral oil with or without nanoparticles. However, there is a marginal increment of Flash and Fire point for both new as well as aged mineral oil beyond the concentration of 0.01% [3,17-20].

New Mineral Oil with and without ZnO		
Sample	**Flash point (^oC)**	**Fire point (^oC)**
S1	160	170
S2	185	190
S3	190	193
S4	195	200
S5	195	200
Aged Mineral Oil with and without ZnO		
Sample	**Flash point (^oC)**	**Fire point (^oC)**
S6	157	168
S7	184	188
S8	188	192
S9	193	198
S10	193	197

Table 4. Flash point and Fire point of new aged mineral oil sample with and without ZnO

V. CONCLUSIONS

In this work, nanofluid is prepared with ZnO nanoparticles dispersed in mineral oil with different concentration of nanoparticle volume fractions. The following observations are made to establish an alternative liquid insulating material as nanofluid for high voltage power industries in view of higher BDV, Volume resistivity and Flash & Fire point compare to mineral oil as insulation only:

- The electrical properties like breakdown voltage and Volume resistivity of nanofluid in different concentration for both new and aged oil shows enhanced values compared to base oil samples as new aged mineral oil without ZnO.
- The physical properties like Flash point shows the nature of higher thermal stability in both new and aged oil samples with and without ZnO. Hence, increased particle volume fraction shows, enhanced flash point values.
- The volume resistivity increases with the increased concentration of the ZnO till certain critical value of the concentration of the ZnO is reached. The Flash & Fire Point increases with an increased

concentration of the nanoparticles and thereafter it saturates. The rate of the ageing phenomena is slowed down with the addition of nanoparticles as ZnO.

The above studies open a new research area in the field of development of new liquid insulation material as nanofluid for High Voltage Power apparatus industries which will minimize the overall size and cost of the liquid insulation filled High Voltage power apparatus.

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