

A Review on Electrical Characteristics of Nanofluid based Transformer Oil

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Abstract

Objectives: To review the electrical property of different nanofluids such as AC/DC and impulse breakdown strength, partial discharge inception characteristic, dielectric loss factor and electrical resistivity. **Methods:** Dispersion of nanoparticles to host fluid is carried out by single-step and two-step methods to enhance the basic properties of nanofluids such as electrical and thermal conductivity, dielectric constant, denseness and relaxation time constant. Single step method follows the dispersion of nano particles into host fluid directly. In two-step method, dry powders of nano particles are prepared in first stage, which is dispersed to host fluid through magnetic stirrer or ultrasonic methods in second stage. **Findings:** The nanofluid in transformers can enhance the dielectric strength by almost 15-20% compared to mineral oil. The performance of the nanofluids under heavy electrical stress depends upon the types, volume fraction, shape and size of the nanoparticles dispersed in host fluid. The investigations conducted over the mixture of nanoparticles and transformer oil concludes that the electrical performance of the carrier oil is highly influenced by dispersing the nanoparticles of different varieties, mass and shape. The dispersion of nanoparticles will change the mode of ionization, reduces the formation of the electrons responsible for the breakdown, and thus delay the breakdown time. **Applications:** The excellent heat transfer and electrical isolation characteristics are the prerequisite of insulating liquids used in power transformers. Because of superior electrical and cooling performance of nanofluid compared to mineral oil at high voltage levels, the dielectric world has recognized the nanofluid as a promising insulating substitute for transformers.

Keywords:Electrical Characteristics, Dielectric Strength, Nanofluid, Review, Transformer Oil, PDIV

1. Introduction

The EHV and UHV transmission networks are required for bulk power transfer over long distances as to cater ever increasing electrical demands. It has brought the new challenges to provide the insulation system for the different equipment coming across the transmission path from generation end to the consumer end. The level of switching surges for the forthcoming EHV and UHV transmission networks are predominantly high and therefore the high voltage equipment must operate reliably to deal with more volatile and dynamic operating conditions.

Power transformer, one of the most important electrical equipment in transmission network for providing reliable energy flow and shares the largest investments for an electric utility in project executions¹. The prospective upshot of transformer miscarriage may react in unfavorable destruction of power system that in turn forces the system into collapse². Henceforth, the operational consistency and lifespan of transformers principally depend on attributes and standard of non-conducting material used for heat transfer and electrical isolation purposes³.

One of the conceivable disputes with present-day liquid-solid insulation structure in power transformer

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that confines the smallness in blueprint/design of a transformer is the conflicting permittivity between them. Since the low standards and attributes, the liquid dielectric was pressurizing more than the solids at ac and/or impulse voltages, which force transformer to be explosive in operation⁴. Aside from the crucial job like shielding solid dielectrics, arc extinguishing and cooling, liquid insulations can also diminish the acoustics in transformers⁵. As a result, the mineral oil's characteristics to survive with emerging demand of high voltage transmission networks are undeniably essential³.

At present time, the word nanofluid becomes eminent and well known that leads the challenges and opportunities to the analysts over the past decades. The names “nanofluids” and “Nano-liquids” are employed collaboratively to express transformer oil/nanoparticle combination for electrical isolation and chilling purposes³. Particles (single, multiple or hybrid) with nano scaled dimensions are scattered with small percentage figure in transformer oil will construct the nanofluid and was introduced by experimenters at the Argonne National Laboratory⁶.

Recently, many researchers have published the articles, which are based on thermal properties of nanofluids^{6-10,43}. However, a very less attention has been given to examine the electrical characteristics of Nano liquids. Hence, an attempt is made in this paper to present the comprehensive review on electrical characteristics of nanoparticle based transformer oil.

2. Types of Nanoparticles for Transformer Oil

The mineral oil is commonly used for chilling and isolation purpose in transformers due to its excellent physical, chemical and dielectric characteristics, which is the utmost requirement for better performance and long life expectancy of transformers. The investigations reported so far in the literatures on the adoption of nanostructured materials in mineral oil have demonstrated the drastic improvement in its chemical, heat transfer and electrical isolation properties¹¹.

To attain these attributes of nanofluids, most remarkable trouble is the choice of the nano-dimensioned particles. Varieties of nano scaled particles have been experimented so far¹²⁻⁴² and they are labeled as per electrical conductivity and permittivity into three considerable classifications:

- Conducting Nanoparticles: Fe_3O_4 , Fe_2O_3 , ZnO, SiC
- Semiconducting Nanoparticles: TiO_2 , CuO, Cu_2O , CdS
- Dielectric Nanoparticles: Al_2O_3 , SiO_2 , BN

Figures 1 and 2 show the host fluids and various hybrid nanoparticles used by researchers during investigations, respectively⁴³.

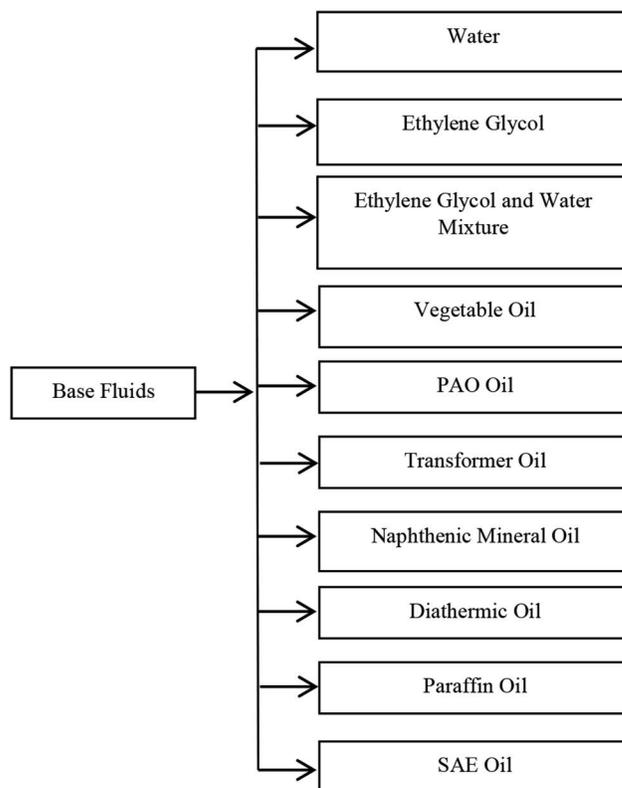


Figure 1. Host Fluids⁴³.

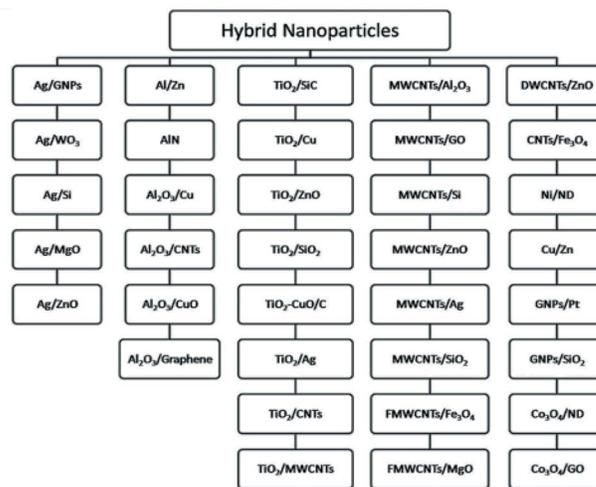


Figure 2. Hybrid Nano-composites⁴³.

The properties of a mineral oil based nanofluid developed after dispersion of either mono or hybrid nanoparticles widely be influenced by type, shape, size, constancy of dispersed nanoparticles, type of host fluid used and weight percentage of concentrated nanoparticles. Extensive research on nanofluid has shown the evidence of remarkable improvement in cooling performance than conventional fluid and preparation techniques for nanofluids is discussed in following section.

3. Dispersion Techniques of Nanofluid

The nanoparticles dispersed with an intention to enhance the insulation and cooling performance should keep the basic properties such as electrical and thermal conductivity, dielectric constant, denseness and relaxation time constant.

Out of these attributes, the rate of electron conduction and electron hindrance are the key properties to enhance electrical characteristic of nanoparticle based transformer oil. After the selection of an appropriate host fluid and nanoparticles as given in Figures 1 and 2, the crucial challenge encountered by the scholars is to take the appropriate method to devise the transformer oil based nanofluids. In general, the nanofluids can be formulated by using single step or 2-step methods as described.

Single-step Method: Inside single step approach, the nano scaled particles are disseminated conventionally into a host fluid to lessen the possibility of forming cluster with augmented stability^{3,12}. One of the potential issues with this approach is the origination of agglomeration during the bulk creation. The cluster formation of the nanoparticles can be prevented by evaporation-condensation method.

Two-step Method: This method is largely used for fabricating the nanofluids. In first stage of development, the particles of different shapes at nano range are firstly manufactured as dry powders via physical and chemical processes. In second stage, magnetic stirrer or ultrasonication achieves the steady dispersal of particles in host fluid. This method uses the distillation process for bulk creation of nanofluids that makes this mechanism of producing nanofluids high-priced. The basic flow of this method is shown in Figure 3. Table 1 outlines the methodologies adopted by different analysts to develop the nanofluids.

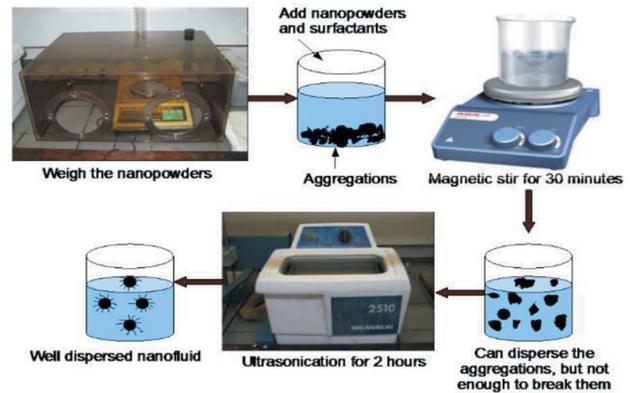


Figure 3. Two-step method for preparation of nanofluid⁴⁴.

4. Electrical Properties of Nanofluids

The reliability and efficient performance of power/distribution transformers are extremely biased by the physical, chemical and electrical properties of the dielectrics used within. The mineral oil is the most preferred coolant and insulator in the transformers as it possesses all these features. The nanofluids prepared for augmentation should demonstrate its excellent performance upon the application of high AC, DC and impulse voltages. In addition to that its characteristic behaviour should be evaluated for the partial discharge, electrical conduction nature and relative permittivity. This section comprehensively deliberates the insulation behavior of nanofluids considering the dimension/mass, nature and concentration of nanoparticles, moisture level and ageing.

4.1 AC Dielectric Strength

Supreme prerequisite for the liquid dielectric that governs the harmless operation of transformers, which are cooled by such liquids, is the dielectric strength. Generally, a numerous procedures suggested by the standards are employed to investigate the electrical stress withstanding capacity of the dielectric liquid by emphasizing them to nearly homogenous electric field. The magnitude of AC sparking potential deliberately specifies the grade of the oil.

The presence of the impurities and chemical agents dissolved for achieving superior properties significantly affects the liquid's dielectric strength. Hereafter, in present time, the researchers have started to investigate

Table 1. Summary of single type and hybrid nanofluids and preparation methods adopted by researchers

| Ref. No. | Author (s) | Base Fluid | Type of NP | Method of Preparation |
|----------|---------------------|-------------------------------------|---|-----------------------|
| 02 | Chiesa and Sarit | Transformer oil | Al ₂ O ₃ , Fe ₂ O ₃ , SiC, SiO ₂ | Two step |
| 13 | Lv et al. | Kelamayi# transformer oil | Al ₂ O ₃ , SiO ₂ , TiO ₂ | Two step |
| 15 | Du et al. | Transformer oil | BN, Fe ₃ O ₄ | Two step |
| 16 | Huifei et al. | Diala S3ZXIG mineral oil | Silica | Two step |
| 19 | Eman et al. | Transformer oil | TiO ₂ | Two step |
| 21 | Purbarun et al. | Transformer oil | Graphene, CNT | Two step |
| 22 | Karthik et al. | Shell Diala D transformer oil | Silicon Dioxide, Tin oxide, magnetite | Two step |
| 23 | Yuefan et al. | Kelamayi# 25 transformer oil | TiO ₂ | Two step |
| 27 | Wang et al. | Kelamayi mineral oil | Al ₂ O ₃ , Fe ₃ O ₄ , TiO ₂ | Two step |
| 34 | John et al. | Paraffin oil | Al ₂ O ₃ , TiO ₂ , CuO, Cu ₂ O and Fe ₂ O ₃ | Two step |
| 35 | Jian et al. | Vegetable oil | Fe ₃ O ₄ | Two step |
| 41 | Andrea et al. | Shell Diala D | Magnetite, GO, SO | Two step |
| 42 | Jacek et al. | Ethylene glycol | TiO ₂ | Solid phase method |
| 45 | Sadegh and Amin | Transformer oil | WO ₃ -Ag | Single step |
| 53 | Soo Hui et al. | Mineral oil | SiO ₂ -Graphene | Two step |
| 54 | Sandeepkumar et al. | Vegetable oil | Cu-Zn | Two step |
| 55 | Makmud et al. | Natural Ester | Fe ₂ O ₃ , TiO ₂ | Two step |
| 56 | Chitra and Gayathri | Transformer oil | Mg _{0.40} Mn _{0.60} -xNi _x Fe ₂ O ₄ | - |
| 57 | Diaa-Eldin et al. | Shell diala S2 ZU-I Transformer oil | Al ₂ O ₃ , TiO ₂ | Two step |
| 58 | Wittawat and Amnart | Natural Ester | ZnO | Two step |
| 60 | Georgios et al. | Natural Ester | MION | Two step |

Table 2. Transformer-oil based Nanofluids

| Nanoparticle/ Oil | Avg Particle size (nm) | Nanoparticle Loading (%) | % increase in BD Strength | Ref. |
|------------------------------------|------------------------|--------------------------|---------------------------|------|
| TiO ₂ /MO | 20 | 0.6 | 13 (AC) | 13 |
| Al ₂ O ₃ /MO | 20 | 5 | 90.5 (AC) | 13 |
| CuO/MO | 500 | 0.1 | 46.87 (AC) | 14 |
| Fe ₃ O ₄ /MO | 20 | 0.1 | 120 (DC) | 15 |
| | 20 | 0.1 | 100 (AC) | |
| BN/MO | 50 | 0.1 | 100 (DC) | 15 |
| | 50 | 0.1 | 80 (AC) | |

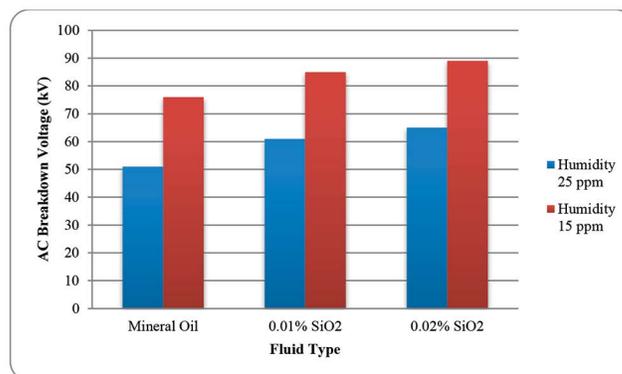


Figure 4. Dielectric strength of Mineral oil & SiO₂ based NF¹⁶.

the liquids formulated by dispersing the nanoparticles with an intention to replace the existing mineral oil. The discussions over the electrical withstanding power of various nanofluids investigated by the scholars have been given in subsequent section. Table 2 shows the enhancement reported by different researchers in breakdown strength.

The dielectric strength of SiO_2 based mineral oil under different ppm of moisture was investigated with different volume fraction of nanoparticles and the reported results are shown in Figure 4¹⁶. Due to hydrophilic nature, the surface of silicone dioxide can bind the water droplets effectively and thus reduces the effective electrical conduction in liquid. This will help in increasing the AC dielectric strength of prepared nanofluid by dispersing SiO_2 NPs in mineral oil.

In¹⁷ have demonstrated the results of AC BDV for transformer oil and magnetic fluid as a function of volume concentration at different ppm of water content. In Figure 5, remarkable improvement is observed in breakdown voltage with increasing the moisture level upto 0.2 g/l concentration. The conductive nanoparticles act as electron scavengers, trap the electrons, turn into low mobility particles, and thus enhance the dielectric strength. On the other hand, it is shown that the dielectric strength is declined with upturn the percentage level of nanoparticles.

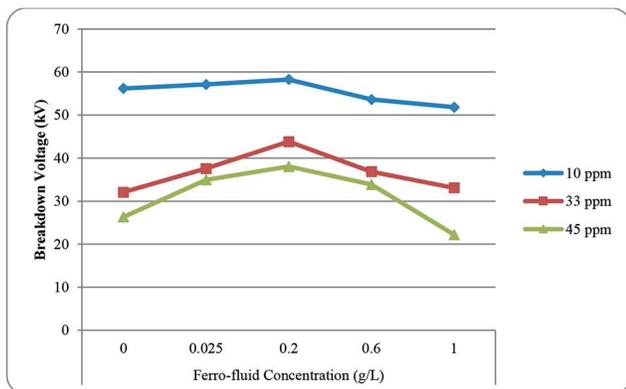


Figure 5. BDV mean values as a function of ferrofluid concentrations at 10 ppm, 33 ppm and 45 ppm moisture level¹⁷.

In¹⁸ have executed investigation on transformer oil mixed with magnetic nanoparticle at volume concentrations of 0.08% to 0.45% to evaluate the behavior of breakdown voltage. Figure 6 shows Notable enhancement in dielectric strength of nanofluid at lower

gap distance between two electrodes. The dispersed magnetic nanoparticles can act as electron scavengers to slow down the speed of massless electrons by transforming them into slow negatively charged atoms. On contrary, the dielectric strength is worsened when the distance is increased.

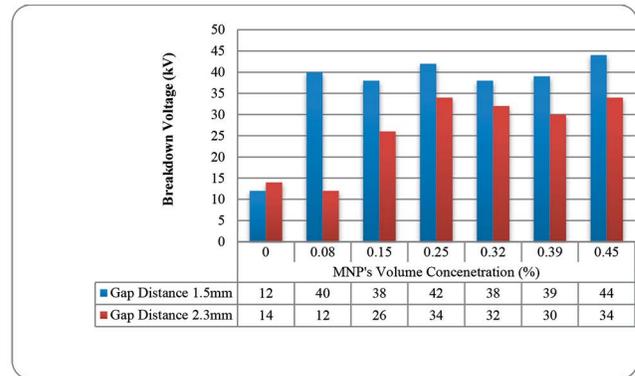


Figure 6. Breakdown voltage with different MNP's concentration¹⁸.

In¹⁹ have prepared TiO_2 based nanofluid using cationic surfactant Cetyl Trimethyl Ammonium Bromide (CTAB). They noticed the improvement in breakdown voltage because of the existence of suitable concentration of the surfactants which can effectively opposes the Van der Waals attraction force between the nanoparticles to stabilize them. Furthermore, the modified surface effectively influences on trapping and de-trapping process of electrons.

The effect of surface treatment on breakdown voltage of silica nanoparticles is examined by²⁰. The change observed is shown in Figure 7. As depicted in the figure, the enhancement has observed in dielectric strength when the mineral oil is prepared by dispersing the silicon dioxide nanoparticles with and without surface treatment. The discharged water droplets bound by the nanoparticles due to its hydrophilic nature-giving rise to high dielectric strength.

The Figure 8 shows the results reported by²¹ when the base liquid was modifying by dispersing the graphene nanoparticles and carbon nanotubes. The amelioration of the dielectric strength may occur due to: (1) the dispersed nanostructures alter the state of electrostatics within the host oil and (2) the bigger values of the electrical conductivities reduce the charge relaxation time constant.

In²² have examined the effect of aging on insulation strength of nanofluids prepared by dispersing conducting,

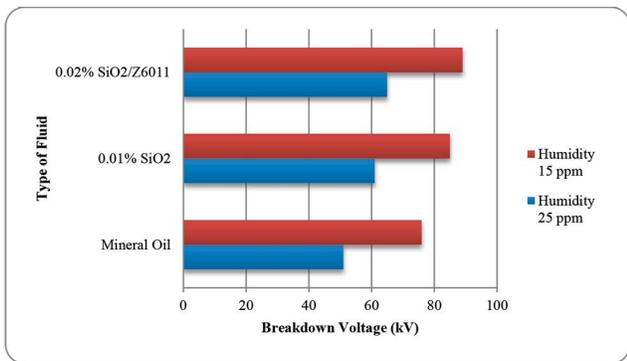


Figure 7. BDV for pure oil, modified and unmodified silica NFs²⁰.

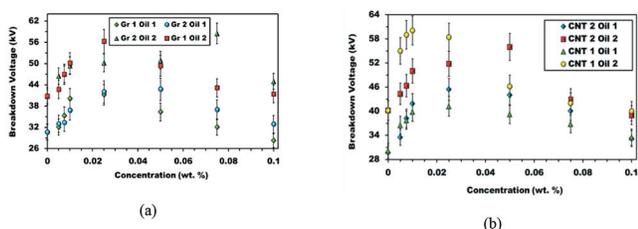


Figure 8. Sparking Potential of (a) Graphene & (b) CNT based nano-oils²¹.

semi-conducting and non-conducting nanoparticles. Figure 9 reveals that the electrical strength of ferrofluid and pure oil declines because of aging albeit the electrical stability of non-conducting and semiconducting nanoparticles shows less dependency over the thermal aging.

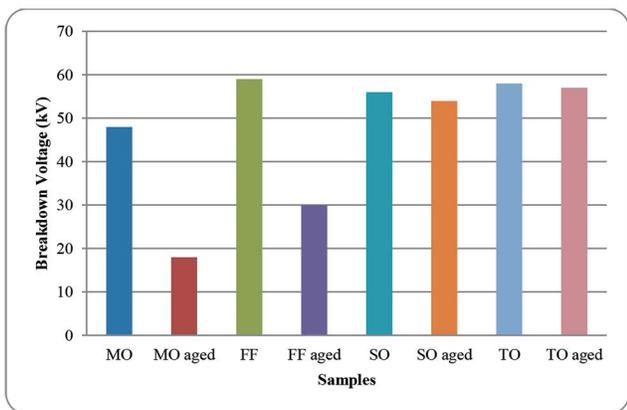


Figure 9. Sparking Potential of MO and various nanofluids²².

The influence of Ag-WO₃ based hybrid nanoparticles over the dielectric strength of transformer oil is investigated by⁴⁵. They have prepared the hybrid nanofluid by one-step method and measured the constancy by zeta

potential. The experiment shows little bit reduction in dielectric strength as compared to transformer oil due to higher electrical conductivity of silver nanoparticles and agglomeration occurs at high concentration.

In⁴⁶ have examined the electrical isolation power of transformer oil based nanofluids containing silica and silver-coated silica with Newtonian flow behavior. The reduction observed in dielectric strength after dispersing the silica in transformer oil is due to moisture absorption nature of silica. Furthermore, the conductive nature of silver nanoparticles reduces the dielectric strength considerably when hybrid (silver supported silica) nanoparticles were dispersed in transformer oil.

In contrast, the dispersion of numerous nanoparticles can enhance the electrical strength of transformer oil to great extent under the high electrical field compared to the fluid developed by individual nanoparticles⁴⁷. The amplification of electrical strength is achieved due to absorption offered by nanoparticles towards the free electrons when it is ionized by applied electrical field.

In⁴⁸ have examined the influence of plasma treated and untreated SiO₂ nanoparticle based nanofluid on insulation characteristic of transformer oil and shown in Figure 10. The dielectric strength can be improved by achieving the homogeneous dispersal and unwavering suspension of fine particles by applying plasma treatment on the nanofillers.

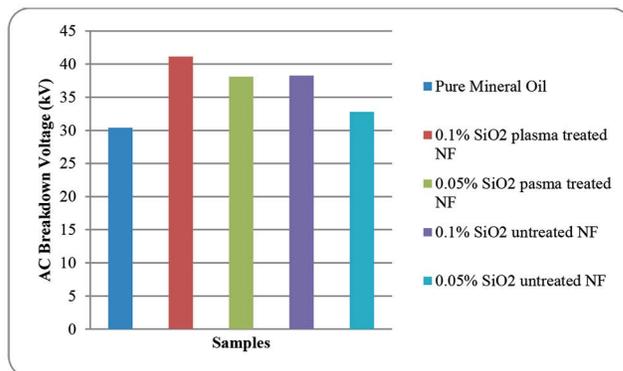


Figure 10. Comparison of AC BDV for treated and untreated NF⁴⁸.

In⁴⁹ have achieved the enhancement of 2.2% in full discharge voltage when transformer oil is modified by dispersing graphene quantum dots. The reduction in effective electron mobility due to electron charging phenomena of nanoparticles that convert fast moving electrons to slow negatively charge carriers can enhance

electrical stress withstanding capacity of transformer oil based nanofluid.

In ⁵⁰ have made the efforts to investigate the breakdown performance of SiO₂ dispersed mineral oil based nanofluid. The dielectric strength shows the dependency over the volume fraction of nanoparticles. The reduction observed in breakdown voltage at higher concentration is explained by electric double layer (EDL) model.

In ⁵¹ inspected the insulating properties of botanical transformer oil with three different nanoparticles at different level of concentrations. They found the augmentation in breakdown voltage as 44%, 32% and 11% for TiO₂, ZnO and CuO based nanofluids respectively. On contrary as shown in Figure 11, the dielectric strength of CuO based nanofluid is reduced dramatically as compared to others. The increase in size of CuO nanoparticles due to more aggregation reduces the surface to trap the electrons that harms the dielectric strength.

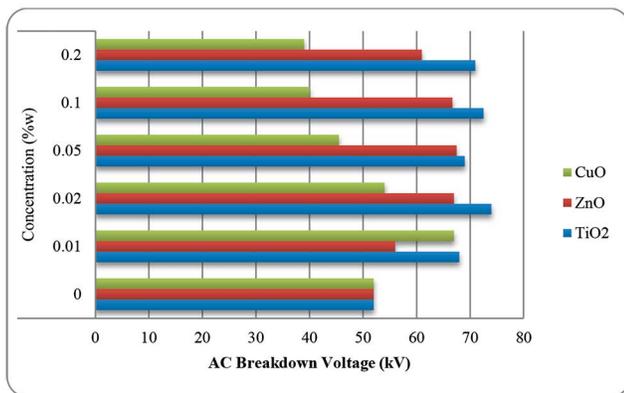


Figure 11. AC sparking potential at different mass fraction⁵¹.

In ⁵² have developed the vegetable oil based nanofluid by dispersing exfoliated hexagonal boron nitride (h-BN) and examined its AC breakdown voltage strength at 25°C and 90°C with gradual increase in volume fraction of nanoparticles. Figure 12 shows the influence of nanoparticle concentration on AC breakdown voltage.

Fluid developed by Yao et al.⁵² has shown remarkable improvement in dielectric strength of base fluid at different temperature ranges with different concentrations of h-BN nanoparticles.

4.2 DC Breakdown Strength

The dielectric strength of TiO₂ dispersed transformer oil under high voltage DC is examined by ²³. The addition of

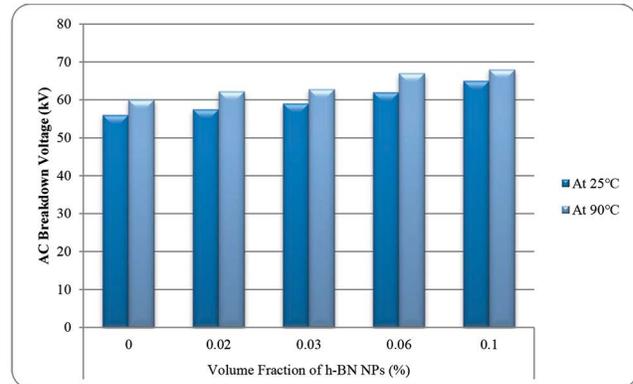


Figure 12. AC breakdown voltage strength with %age volume fraction⁵².

semiconductive nanoparticles can improve 28% value of negative DC breakdown strength. However, the positive DC breakdown voltage was lower than the host oil. Table 3 shows the obtained values during the investigations carried out by them²³.

Table 3. DC discharge voltage of pure oil and nanofluid²³

| Samples | (+) DC Breakdown Voltage (kV) | (-) DC Breakdown Voltage (kV) |
|-------------|-------------------------------|-------------------------------|
| Mineral Oil | 49.1 | 66.3 |
| Nanofluid | 45.1 | 84.6 |

In ²⁴ have observed that the dispersed semiconducting NPs can provide the augmentation to the insulation strength under DC voltage due to its trapping and de-trapping nature. The augmentation of dc dielectric strength of nanofluid was 1.27 times more than the host oil.

Figure 13 shows the results of investigation conducted by researchers for the influence of dispersing Fe₃O₄ nanoparticles as a function of gap length²⁵. The formation of bubbles due to localized heating and the injection of field-emitted electrons with and without magnetic field can reduce DC breakdown voltage at 2% concentration.

Figure 14 represents the influence of nanoparticle's volume fraction on DC breakdown voltage strength of vegetable oil based nanofluid examined by⁵². Due to the polarization of the nanoparticles under applied DC field, the electrons produced by the ionization will trapped by the formulated electrical charge around the surface of NPs and thus helps in reducing the probability of ionization to prevent the breakdown.

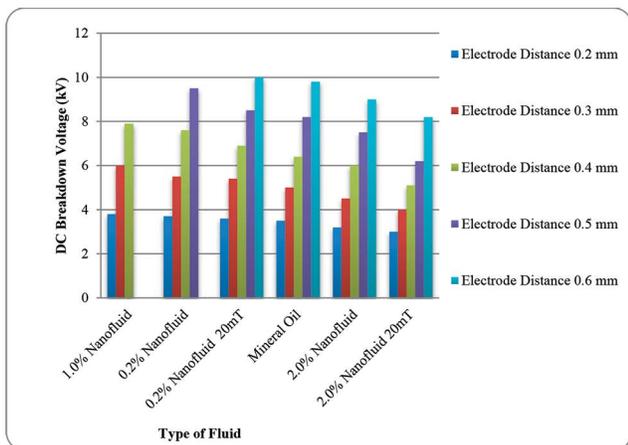


Figure 13. Dielectric strength with and without magnetic field of 20 mT under DC stress²⁵.

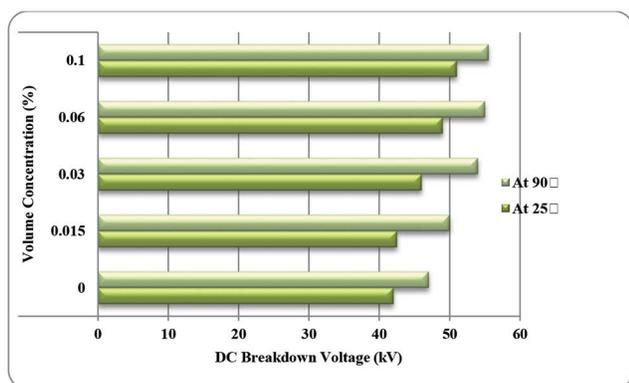


Figure 14. DC BDV as a function of %age absorption⁵².

To investigate the DC dielectric strength⁵⁹ have prepared the fluid by dispersing the single type and multiple type nanoparticles in transformer oil. They noticed that the breakdown strength is decreasing when the Fe_2NiO_4 nanoparticle is dispersed along with CdS in transformer oil. Increase in nanoparticles concentration would result in reducing the separation between two particles and increase the chance of agglomeration. These clusters lead to distort the electric field extensively and additionally reduce the electron trap surface.

In⁶¹ have inspected the DC strength of vegetable oil based nanofluid prepared by dispersing Boron Nitride (BN) nanoparticles at different volume size as a function of heat range. Figure 15 shows the results obtained by them.

The breakdown voltage is enhanced due to removal of moisture content from the liquid with rise in heat rate. The dispersion of BN nanoparticles at high concentration hinders the progression of dielectric breakdown.

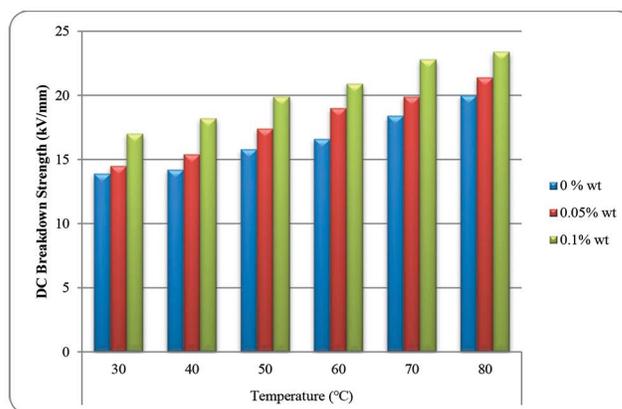


Figure 15. DC breakdown voltage⁶¹.

In⁶² have made the efforts to check the DC strength of transformer oil by preparing the nanofluid by adding Fe_3O_4 and BN nanoparticles. The result verifies the better performance when nanofluid is prepared by BN nanoparticles as compared to Fe_3O_4 based nanofluid.

In⁶³ have conducted the DC breakdown voltage test as per D3755 standard on TiO_2 transformer oil based nanofluid impregnated pressboard. The results show the remarkable improvement of 5.97% and 6.5% in positive and negative DC breakdown voltages respectively.

4.3 Impulse Breakdown Strength

Tables 4 and 5 shows the outcomes for failure of pure oil and TiO_2 based nanofluid studied by applying impulse voltage with positive and negative polarity²⁶.

Table 4. Positive breakdown strength of pure oil and NF²⁶

| Samples | Breakdown Voltage (kV) | Time to breakdown (μ s) |
|-------------|------------------------|------------------------------|
| Mineral Oil | 74.27 | 13.18 |
| Nanofluid | 97.16 | 97.16 |

Table 5. Negative breakdown strength of pure oil and NF²⁶

| Samples | Breakdown Voltage (kV) | Time to breakdown (μ s) |
|-------------|------------------------|------------------------------|
| Mineral Oil | -116.42 | 49.58 |
| Nanofluid | -108.46 | 11.39 |

The dispersion of semiconductive nanoparticles effectively changes the scattering of space charge caused

by shallow traps and thus modifies the appearances of streamer transmission and interruption. At the head of streamer during positive polarity, the electrical field is distorted extensively due to induced negative charges that delay the propagation of streamer whereas it speeds up when negative impulse is applied.

Wang et al.²⁷ deliberated the effect of three dissimilar nanoparticles on impulse breakdown strength at different concentrations. Figures 16 and 17 shows the result of failure at applied impulse voltage as a function of size percentage for three dissimilar nanoparticles.

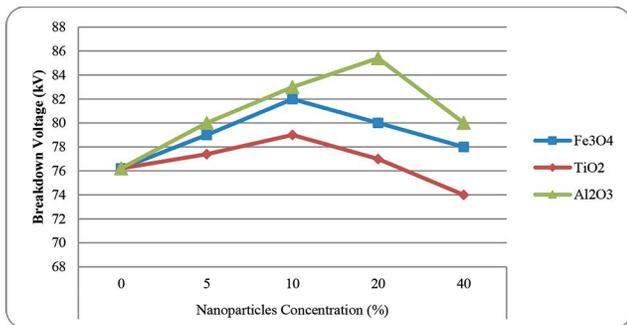


Figure 16. Positive impulse sparking voltage of different nanofluids²⁷.

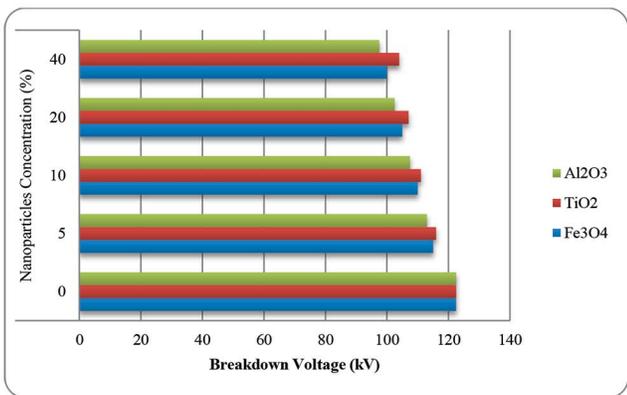


Figure 17. Negative impulse sparking voltage of different nanofluids²⁷.

The dielectric strength improves due to the alteration of space charge activity until the critical value of concentration is achieved. The nanoparticles with greater volume in transformer oil can lead to the evolution of the clusters and hence diminish the breakdown voltage.

The 11.2% augmentation in impulse strength of Fe₃O₄ modified transformer oil was examined by Yang et al.³². The electrons crossing the gap at fast velocity were trapped

and turned into slow running electrons that hinder the ionization process and thus improve the impulse strength.

The inspection on electrical strength of h-BN nanoparticle based vegetable nanofluid under application of an artificial lightning impulse as per the methodology of IEC 60897 is reported by ⁵². Figure 18 shows the results obtained for impulse BDV at positive and negative polarity of applied impulse wave for different densities of nanoparticles.

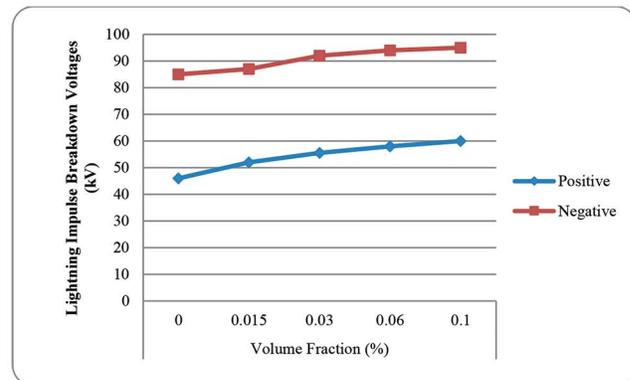


Figure 18. Positive and Negative Impulse BDV for vegetable oil based nanofluid⁵².

The impulse breakdown voltage strength of pure vegetable oil can be improved by dispersing the nanoparticles in the host fluid. They noticed 22.0% and 28.8% improvement in positive and negative impulse values respectively. Furthermore, the value of negative impulse was examined lower than the value obtained during application of positive impulse. The difference observed due to reversal of polarity was explained on basis of space charge behavior.

Zhou et al.⁶⁴ have demonstrated the test results of conducted impulse voltage test on transformer oil modified by suspending Fe₃O₄, TiO₂ and Al₂O₃ nanoparticles. The dispersed nano-structured particles can modify the beginning and transmission processes of positive streamers in transformer oil.

In ⁶⁵ have conducted an experiment to examine the alteration occurred in impulse dielectric strength when both mineral oil and natural esters modified by nanoparticles. The modification to the host fluids achieved by dispersing silica nanoparticles during the experimentation. The 30% augmentation achieved due to the hydrophilic property of silica nanoparticles, which has tendency to absorb the water to alter the degree of

polarization for preventing the fast ionization of liquid dielectric.

The dielectric capacity at applied impulse voltage for transformer oil modified by nanocrystalline $Mn_{0.2}Ni_{0.8}Fe_2O_4$ nanoparticles has been discussed by 66. The high voltage impulse test was conducted by concentrating the nanoparticles in host oil at weight of 0.02 g/l, 0.04 g/l and 0.06 g/l respectively. The results showed 42.3% of augmentation in impulse strength when nanoparticles were dispersed at weight of 0.04 g/l. The negative results were noticed when the concentration of the particles was more than the optimum value.

The experimentation to evaluate the impulse strength (with positive and negative polarity) of pure oil based magnetic nanofluid as a function of volume portion, dimension of nanoparticles and diverse gap lengths was conducted by 67.

Figures 19, 20 and 21 show the results of positive and negative impulse BDV value obtained by loading multiple nanoparticles in transformer oil by considering volume portion, size of nanoparticles and gap span between two electrodes67.

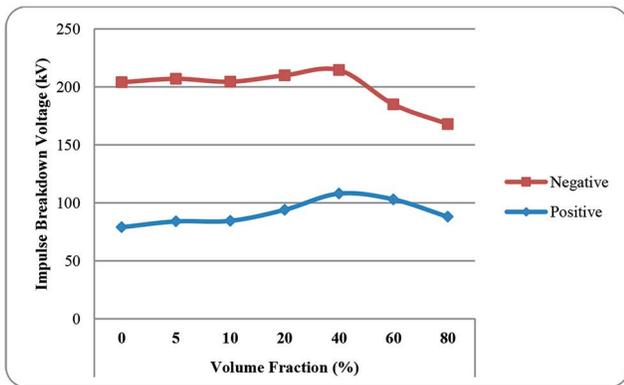


Figure 19. Flashing potential as a function of volume percentage67.

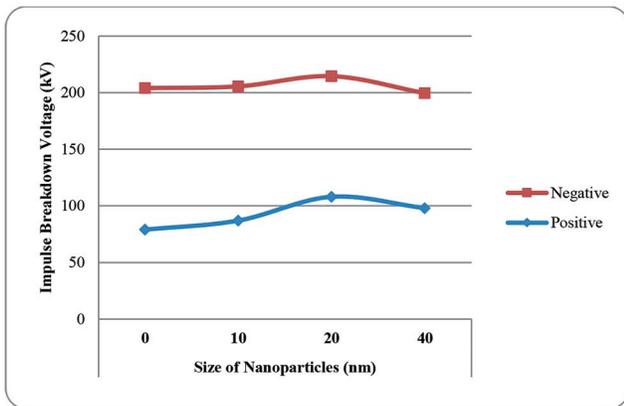


Figure 20. Impulse sparking potential as a function of nanoparticle's size67.

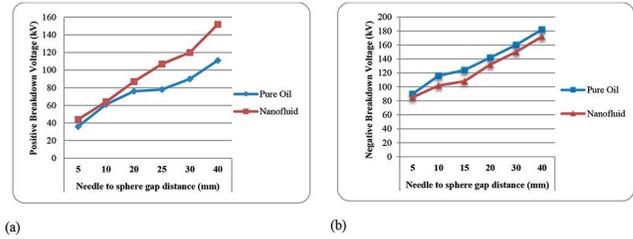


Figure 21. Impulse breakdown voltage at different gap span67. (a) With positive polarity (b) With negative polarity.

Investigation results have depicted 0.4 and 20 nm values as optimum concentration and size for nanoparticles respectively to obtain augmentation in electrical stress holding capacity of insulation under positively applied short duration voltage of high magnitude as compared to carrier oil. Contradictory, an application of negative impulse voltage shows worse performance as compared to base fluid.

In68 have prepared nanofluid by spreading ZnO nanoparticles in Refined Sunflower Oil (RSFO) type natural esters to investigate impulse dielectric strength. They evaluated 28.95% and 20.04% extension in impulse strength as compared to carrier fluid. The reduction in electrical conductivity due to slowing down the transmission velocity of streamer enhances the dielectric strength.

Table 6 represents the list of the researchers who have conducted the experiments to evaluate the impulse strength of nanofluids.

Table 6. List of researchers conducted impulse voltage test

| Ref | Author (s) | Base material | Nanoparticle (s) |
|-----|----------------|-------------------------|---------------------------|
| 35 | Li et al. | Vegetable oil | Fe_3O_4 |
| 39 | Sima et al. | Kelamayi# 25 TO | Fe_3O_4, TiO_2, Al_2O_3 |
| 69 | Rafiq et al. | Kelamayi# 25 TO | Alumina |
| 70 | Du et al. | Vegetable oil | Fe_3O_4 |
| 71 | Nazari et al. | NYTRO LIBRA TO | Fe_3O_4 |
| 72 | Y.Z.Lv et al. | Impregnated Press board | TiO_2 |
| 73 | Mu-tian et al. | Kelamayi# 25 TO | TiO_2 |
| 74 | Du et al. | Kelamayi# 25 TO | TiO_2 |

4.4 Partial Discharge Inception Voltage (PDIV)

PDIV characteristics before and after aging of pure oil and equivalent nanofluids was studied by²². Before aging, the ferrofluid does not modify the PDIV characteristic significantly as compared to tin oxide and SiO₂ based nanofluids. For both AC and DC voltages, silicone dioxide based nanofluids shows the improvement. Additionally, compared to the mineral oil and other nanofluids, aged SiO₂ shows the better response. The enhancement shown by silicon dioxide based nanofluid is due to its hydrophilic property.

The partial discharge test to examine the facts of nanoparticles on inception of partial discharges had been executed²³. Table 7 shows the results obtained after performing partial discharge test. The positive results are obtained for partial discharge inception voltage and discharge magnitude. The addition of semiconducting nanoparticles diminishes the probabilities of incidence of partial discharge initiation.

Table 7. PDIV value for TiO₂ based nanofluid²³

| Sample | Mean PDIV (kV) | SD (kV) | 63.2% Probability PDIV (kV) | 5% Probability PDIV (kV) |
|--------|----------------|---------|-----------------------------|--------------------------|
| MO | 30.6 | 2.7 | 31.7 | 25.0 |
| NF | 33.1 | 1.8 | 33.8 | 29.5 |

The trapping and de-trapping nature of semiconducting nanoparticles improves the PDIV characteristics for both new and aged TiO₂ based nanofluid²⁴. The 1.12% enhancement is achieved as compared to mineral oil.

Jin et al.²⁸ has studied the incomplete discharge performance of fluid produced by disseminating 0.01% of fullerene and silica nanoparticles. Under positive DC voltage, twenty percent improvement was noticed in PDIV value for silica based transformer oil compared to its pure state. Furthermore, the discharge magnitudes for silica and fullerene nanofluid were scaled down to 63% and 33% respectively. The reaction of the nanoparticle's surface with acid in mineral oil leads less effect on partial discharge behavior.

In²⁵ have developed the magnetite-based nanofluid to investigate partial discharge inception voltage characteristic. The lower concentration of nanoparticles could enhance PDIV characteristic as compared to carrier oil and at higher concentration. The conductive nanoparticles attract the electrons emitted due to

ionization and turns into negative ions to quench the avalanche.

In²⁶ have made an effort to develop the natural ester based nanofluid by dispersing TiO₂ nanoparticles for examining the partial discharge inception performance under applied ac voltages. The negligible enhancement in PDIV of nanofluid has noticed.

In²⁷ have made an effort to examine the PDIV for aged nanofluid prepared by dispersing the semiconducting nanoparticles at low and high moisture content. The aging to the fluid was achieved by heating the oil at 130°C for 6 days. The Figure 22 shows the results obtained for the voltage magnitude at which the partial discharge activity begins. Because of dispersion of semiconducting nanoparticles, the rate of moisture opposition and anti-ageing properties of aged pure oil enhances which further giving rise to corona inception voltage.

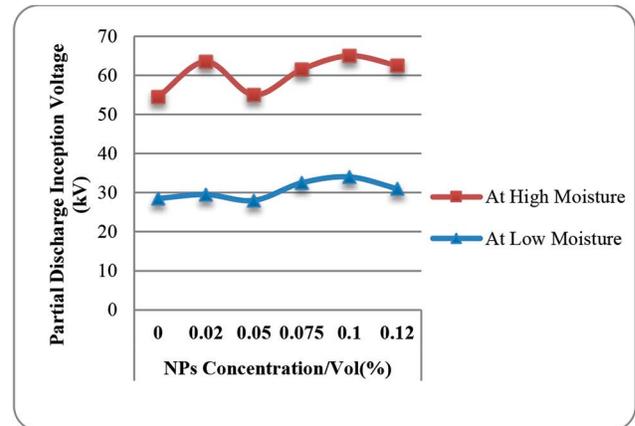


Figure 22. PDIV at low and high moisture for prepared NF²⁷.

Table 8 represents the list of the researchers who have conducted the experiments to evaluate the PD characteristics of nanofluids.

4.5 Critical Characteristics

Critical characteristics include the electrical conductivity, permittivity, dissipation factor, resistivity, flash point and fire point. Several researchers have contributed to identify the effect of nanoparticles on such unavoidable parameters. In²⁹ have investigated the influence of semi conductive Cadmium Sulfide (CdS) quantum dots on relative permittivity and dissipation factor by preparing the fluid at various concentrations. Figures 23 and 24

Table 8. List of researchers investigated PD characteristics of NF

| Ref | Author (s) | Base material | Nanoparticle (s) |
|-----|-------------------------------|-----------------|-------------------|
| 41 | Cavallini et al. | Shell Diala D | Magnetite, GO, SO |
| 63 | Z. You et al. | Transformer oil | TiO ₂ |
| 73 | Mu-tian et al. | Kelamayi# 25 TO | TiO ₂ |
| 78 | Y. Du et al. | Mineral Oil | TiO ₂ |
| 79 | D. Prasad and S. Chandrasekar | FR3 TO | SiO ₂ |
| 80 | M. Dehkordi | Transformer oil | TiO ₂ |

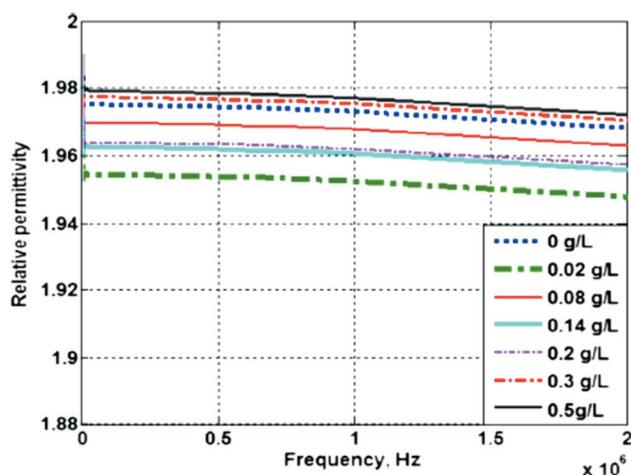


Figure 23. Dielectric constant Vs volume concentration of CdS quantum dots in host oil²⁹.

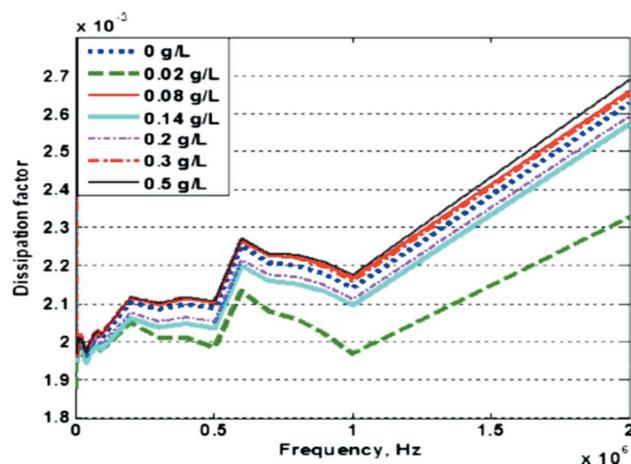


Figure 24. Dissipation factor of modified host oil²⁹.

shows the effect of nanoparticles' application on dielectric constant and tan delta of modified host oil respectively.

The slight increment in dielectric constant of nanofluid was because of the contribution to the net amount of dipoles in mineral oil. In general, due to the defects/impurities in the insulations during its development, it always possesses the two different kinds of permittivities i.e. real permittivity and imaginary permittivity.

The electrostatic forces exerted between the electrons and positive ions are greatly influenced by real part of permittivity whereas the dissipation factor/dielectric losses depend on imaginary part of permittivity. At small concentrations of nanoparticles, the real part of permittivity was enhanced but at concentration, more than the optimum value increases the electrical conductivity due to rise in its surface area that leads to increase in imaginary permittivity and hence dielectric losses.

In³⁰ have carried out the research on mixture of MgMnNi NPs and transformer oil to observe the performance of electrical conductivity at diverse volume percentage of nanoparticles. Figure 25 shows the dependency of electrical conductivity on volume fraction nanoparticles. They observed the linear increase in electrical conductivity with increase in concentrations.

The resistivity and electrical conduction property of transformer oil modified by AGQD nanoparticles as a function of thermal stress was investigated by⁴⁹ and showed in Figures 26, 27 respectively.

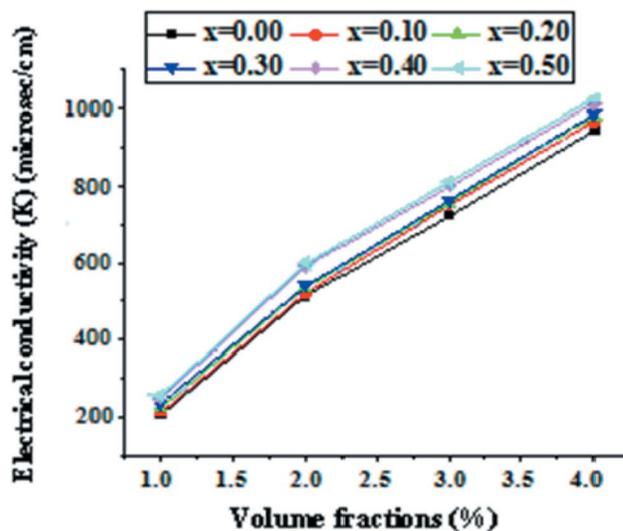


Figure 25. Dependency of electrical conductivity on volume fraction of Nanoparticles³⁰.

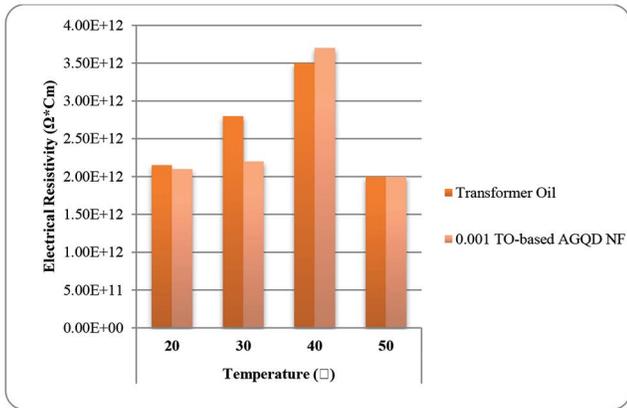


Figure 26. Resistivity of TO based AGQD NF.

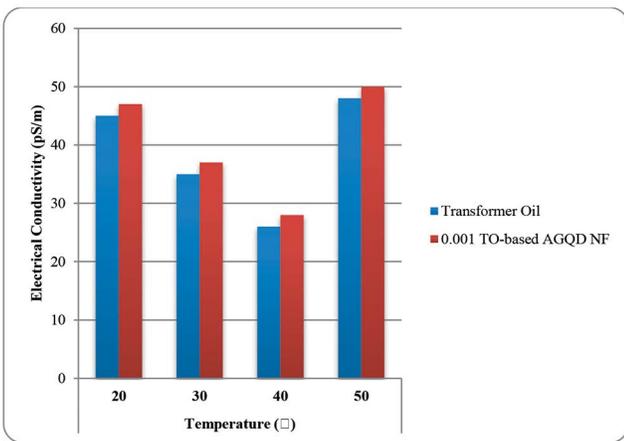


Figure 27. Electrical conductivity of TO based AGQD NF.

Because of inherent electrical transfer ability of dispersed nanoparticles, the electrical resistivity was slightly enhanced but conffliction has been observed as a reduction in electrical resistivity when 0.001% of nanoparticles were loaded. Furthermore, the electrical conductivity was not changed noticeably.

Table 9. List of researchers evaluated the critical parameters of NF

| Ref. | Author(s) | Base Fluid | Nanoparticle(s) | Parameter(s) examined |
|------|------------------|-----------------|---|---|
| 42 | J. Fal et al. | Ethylene glycol | SC-TiO ₂ | Electrical Conductivity & Permittivity |
| 53 | S. Quing et al. | Mineral oil | SiO ₂ -Graphene hybrid | Electrical Conductivity |
| 55 | M. Makmud et al. | Natural Ester | TiO ₂ , Fe ₂ O ₃ | Dielectric constant and Dielectric loss |
| 61 | B. Du et al. | Vegetable oil | BN | Relative permittivity, Dissipation factor & Electrical Conductivity |
| 62 | B. Du et al. | Transformer oil | BN & Fe ₃ O ₄ | Relative Permittivity, Dissipation factor & Resistivity |

Figure 28 shows the results of dielectric properties examined by Wei et al.⁵². With dispersion of 0.1% concentration of nanoparticle could enhance the relative permittivity by 3.11 at 25%, resistivity by 63% and decrease the dielectric losses by 28% at 25% and 90% compared to base oil without nanoparticles.

In ⁶⁸ have prepared a nanofluid by dispersing TiO₂ and ZnO nanoparticles in dielectric fluid derived from natural esters to investigate critical characteristics such as flash point and fire point.

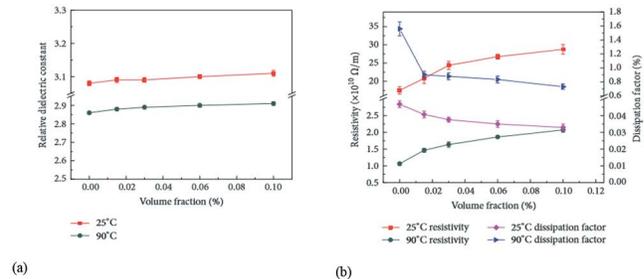


Figure 28. Critical parameters of nano-oil as a function of volume concentration at 25% and 90°C ⁵². (a) Relative Permittivity (b) Resistivity and Tan Delta.

Table 9 represents the list of the researchers who have conducted the experiments to evaluate the critical parameters of nanofluids.

5. Modification Mechanisms

The mechanisms by which the nanoparticles can disturb the electrical properties of host oil are still not fully revealed. In¹⁹ have proposed a double layer model to certify the strengthening of the electrical insulation properties

| | | | | |
|----|--------------------------|--|--|---|
| 70 | B. Du et al. | Vegetable oil | Fe ₃ O ₄ | Relative Permittivity, Dissipation factor & Resistivity |
| 81 | Chitra and Sendhilkathan | Transformer oil | Mg _{0.40} Mn _{0.60} ⁻ Ni _x Fe ₂ O ₄ | Electrical Conductivity |
| 82 | Raymon and Karthik | Transformer oil | Activated Bentonite | Flash point and Fire point |
| 83 | D. Jasper et al. | Silicone oil | SiO ₂ , ZnO | Flash point and Fire point |
| 84 | A. Raymon et al. | Coconut oil, Cottonseed oil, Ricebran oil, Rapeseed oil, Soybean oil and Sunflower oil | Al ₂ O ₃ , TiO ₂ , Cds, Fe ₂ O ₃ | Flash point and Fire point |
| 85 | M. Emara et al. | Mineral oil | TiO ₂ | Dielectric constant and Dissipation factor |
| 86 | D. Zmarzly and D. Dobry | Mineral oil | C ₆₀ Fullerenes | Permittivity, Tan Delta & Resistivity |
| 87 | M. Dong et al. | Transformer oil | AlN | Electrical Conductivity |
| 88 | J. Miao et al. | Transformer oil | ZnO | Relative Permittivity |

of nanofluids improved by surfactant. The surfactant plays a dynamic role in the stabilization of nanoparticles through two different mechanisms: (1) Steric stabilization and (2) Electrostatic stabilization. Steric stabilization was attained by capping the active surface of nanoparticles with surfactant to the degree that reduces surface activity and prevents agglomeration. Figure 29 shows the steric stabilization and role of surfactant.

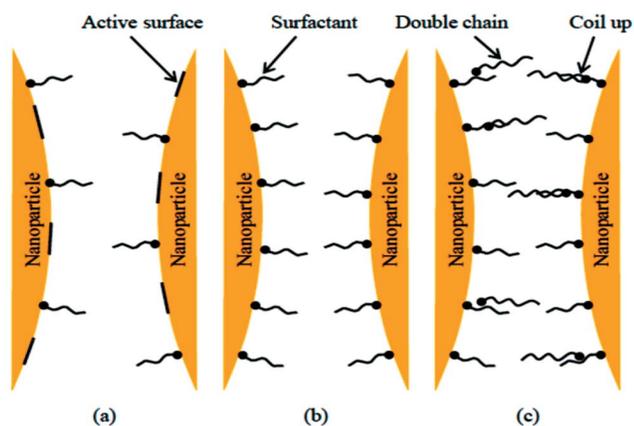


Figure 29. Steric stabilization and role of surfactant: (a) low coverage, (b) Full coverage and (c) Excess amount of surfactant¹⁹.

If the surfactant is covered with low surfactant, the agglomeration of nanoparticles may occur due to insufficient coating which do not cover the particle fully and hence unable to oppose the van der Waals attraction force which tends to reduce the electrical performance of the nanofluids developed for insulation purpose.

On the other hand, with excess amount of surfactant, adsorption sites on nanoparticle surface will be rare. Hence, surfactant will form a double chain around the surface of nanoparticles, resulting in a reverse effect.

The electrostatic stabilization is achieved by charging the particles with the same polarity as shown in Figure 30. In this model a layer of oppositely charged ions, called counter ions or coions, counter balances the charges. The coions exist in two distinct layers. The inner layer stuck to the nanoparticle surface called Stern layer, which is characterized by high concentration of coions. The other layer extends from the Stern layer to the zero charging region of the oil called the diffuse layer.

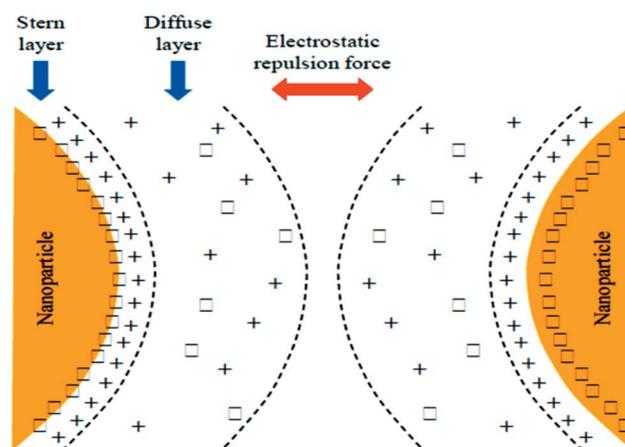


Figure 30. Electrostatic stabilization and double layer model¹⁹.

In²⁶ have proposed a mechanism to explain the significant change happened in the streamer transmission due to modification in space charge scattering when TiO₂ nanoparticles were dispersed in transformer oil.

The ionization probability reduces due to trapping and de-trapping charge transportation in oil as the TiO₂ nanoparticles upturns the shallow trap density in nanofluid and thus builds up the negative ions which modifies the electric field at the head of the streamer transmitting towards the ground electrode.

For positive polarity as shown in Figure 31(a), the electric field at the streamer tip is enhanced while at ground electrode it is weakened. Thus, it is tough for positive streamers in nanofluid to expand which results in increase in positive breakdown voltage. Contradictory, for negative polarity as shown in Figure 31(b), the electric field at the negative streamer tip is weakened as compared to ground electrode. As an effect, the streamers will propagate to the ground electrode at high velocity.

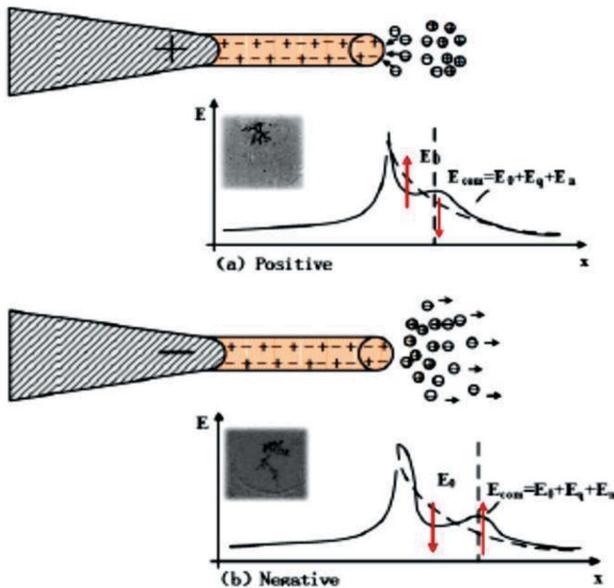


Figure 31. Distribution of electric field in nanofluid²⁶.

In²⁹ proposed that the quantum dots of smaller size can increase the surface area and allows more trapping to the electrons that helps in improvement of dielectric properties. The presence of appropriate content of surfactant can improve the morphology of nanoparticles and hinder the physical agglomeration of them³¹⁻³² projected a model based on space charge inhibition on improvement of dielectric strength. Figure

32 shows the space charge diffusion characteristics in modified transformer oil. The adsorption of free charge by nanoparticles could improve the insulation strength by (1) delaying electron's movement, (2) blocking charge injection in transformer oil, (3) sinking the space charge density and (4) augmenting the uniformity of the electric field.

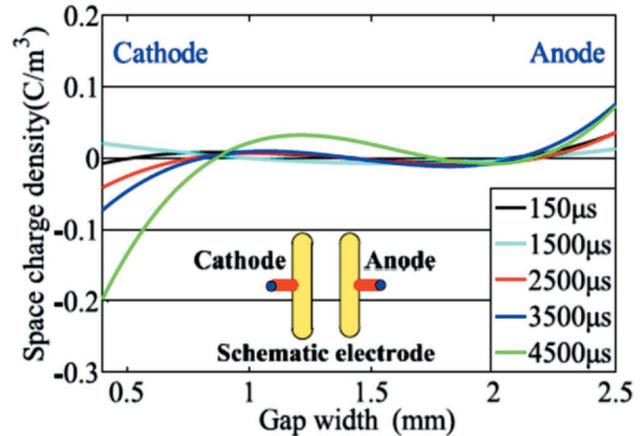


Figure 32. Concentration of space charge in modified transformer oil³².

According to the postulation proposed by Derjaguin-Landau-Verwey-Overbeek (DLVO), the cumulative reaction between two particles is the mixture of electrostatic repulsion force and van der Waals attraction force^{19,33}. When nanoparticles are separated by a distance larger than the combined thickness of their electric double layers, there would be no interaction between the nanoparticles. The repulsion takes place when the nanoparticles move closer and overlaps the double layer. Stabilization is maintained when the repulsion force becomes equal or exceeds van der Waals attraction force otherwise agglomeration occurs. The addition of surfactant will increase the number of coions and hence increases in electrostatic repulsion force which in turn enhance the dielectric property of nanofluid.

In⁴⁷ have analyzed the alteration achieved in dielectric possessions of transformer oil by dissolving discrete and manifold nanoparticles and discussed the mechanism of modification achieved in dielectric properties. The addition of multiple nanoparticles could improve the polarization and improves the rate of electron absorption as compared to individual nanoparticles.

Most of the researchers have also proposed the enhancement mechanisms in dielectric properties on the

ground of the relaxation time constant and polarization characteristics²⁷.

6. Conclusion

Emerging nanofluid research brings the ample opportunities to the researchers in developing the nanoparticle based high voltage electrical insulation fluids with superior properties as equaled to present mineral oil. The survey reported in this article discusses the efforts placed in past years with an intention to investigate the performance of nanofluid based transformer oil under heavy electrical stresses. Although, the superiority of the nanoparticle based transformer oil has been confirmed, still, many facts i.e. the mechanism of ionization that could be applicable equally to the variety of the nanoparticle based insulation fluid, performance of nanofluids under magnetic field, performance of nanofluids under contaminated state, selection of nanoparticles for providing both insulation and heat transfer performance when they intended to disperse in transformer oil, dissipation factor, arc suppression characteristics etc. need to be discovered. In-depth experimentation and multidisciplinary research is required for better understanding of mechanisms and behavior of nanofluids to resolve the prevailing challenges.

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