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Effects of nanostructure permittivity and dimensions on the increased dielectric strength of nano insulating oils

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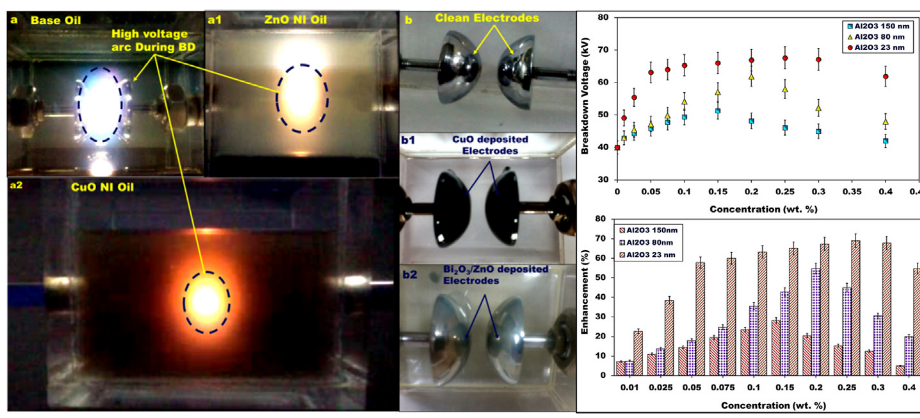
HIGHLIGHTS

- Dielectric performance of nano-oils with respect to different parameters is studied.
- Nanostructures of various permittivity and sizes are dispersed in mineral oil.
- Breakdown voltage of nano-oils is enhanced due to delay in the merger of streamers.
- Small size particles demonstrate high breakdown performance.
- Moisture and temperature are crucial parameters for breakdown performance.

GRAPHICAL ABSTRACT



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ABSTRACT

The influence of nanostructures concentration, morphology, permittivity and size on the augmentation of the dielectric breakdown characteristics of nano insulating oils has been experimentally examined and demonstrated in detailed for the first time. Various dielectric nanoparticles/structures, viz. zinc oxide (ZnO), zirconium oxide (ZrO_2) and aluminium oxide (Al_2O_3), of different sizes over a range of 25–125 nm have been employed to investigate the influence of nanoparticles concentration as well as size on the dielectric performance of nano insulating oils. Bismuth oxide (Bi_2O_3), magnesium oxide (MgO) and copper oxide (CuO) have been utilized to investigate the effect of nanoparticles concentration and all the nanoparticles contribute to the detailed study on the effects of morphology on the breakdown characteristics. Experimental findings reveal that particle size, permittivity as well as concentration affects the dielectric performance of nano insulating oils to large extents. Particles with smaller size offer higher enhancements in the dielectric breakdown voltage compared to the bigger size particles and its mechanism and role in hampering streamer development and

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growth has been deliberated. The influence of temperature and moisture content has been found to have major effects on the BD performance and experimentally examined and reported. The present work reveals the potential of nanomaterials towards designing more robust power systems employing liquid dielectrics by engineering their breakdown characteristics.

1. Introduction

The dielectric performance of the insulating oil such as transformer oil in particular; is of great practical interest in the power industries due to its ability to withstand the high voltage fluctuations without failure and has been widely studied by many researchers and engineers [1–7]. Insulating oil play significant role in the electrical power transformers i.e. it provides safer operation to the transformer by releasing the heat as well as protecting against high voltage fluctuations. The conventional oils have limitation to endure high loads in terms of voltage due to their inadequate dielectric properties. The nanomaterials are suitable for wide range of applications [8–10]. Thereby, the research communities are now attracting towards nanomaterial infused oils due to their smart physical properties. Nanomaterial infused oils demonstrates superior dielectric performance due to excellent permittivity of the nanomaterial (such as Titanium IV Oxide) and the polarization generated across the matrix materials and nanomaterial. Nano-fillers show the high surface density compared to micro-fillers, hence nano-filler infused oils demonstrate better dielectric performance compared to the micro-filler infused oils [11,12]. The carrier/base fluid characteristics also influence the dielectric behaviour of the nano oils [13]. The magnetic particles such as Fe_3O_4, Fe_2O_3 etc., if dispersed in the transformer oil, also enhance the dielectric performance of the suspension. The magneto-dielectric effect due to chain formation as well as reorientation of magnetite influences the particle distribution as well as stability of the suspension [14–19]. However, effect of particle size on the dielectric performance of nano insulating oils is rarely reported in the literature experimentally; hence need more attention towards experimentation of such phenomenon. Theoretically, almost all the nanostructures can be diffused in the conventional oil to enhance the dielectric performance. But the metallic oxides nanoparticles such as Al_2O_3, CuO, ZnO etc. are the more popular due to their better stability compared to the pure metals [20,21] and nanotubes [22] as well as low cost and easy manufacturing process, which make them possible for mass production, compromise with their electrical conductivity as well as permittivity. However, breakdown voltage is enhanced up to a certain particle concentration, depending upon the types of nanoparticles and then starts decreasing [23]. It is evident, that magnetite NPs are more capable to captured the free fast electrons; contributes to the streamer development and convert these fast electrons to slow-moving negatively charged particles [24,25]. This phenomenon depends on the relaxation time constant [26,27], which strongly affects the electrodynamics process in the insulating oils. If the relaxation time constant of nanoparticles is short compared to the time required for streamer development, the dielectric performance of the oil will be high. Otherwise, very little change was observed for reverse condition. In case of magnetite, relaxation time constant is very short ($\sim 7.47 \times 10^{-14}$) compared to the micro scale time required for streamer development; hence the dielectric performance is high. Furthermore, the dielectric performance of magnetite particles is significantly influenced by the alignment or orientation of the magnetite particles under external applied field. When the particles are subjected to magnetic field, they form the chain across the electrodes and provide the path to the electrons/molecules to move in between and reduction in the dielectric performance of nano insulating oils occurs [17]. The BD performance of the transformer oil has many influencing parameters which affect the BD strength of the oil significantly, viz. water content, temperature, impurities, gas content and flow velocities etc. [28]. The type of dispersed phase in the oil also affects the influence of moisture on the oil, since the water content and particles have the combined effect, which can increase reduction in the BD performance [29]. The Al_2O_3 NPs of the nanometer sizes have the tendency to absorb moisture from the surroundings on the grain surface due to the induced relative interfacial polarization [30,31].

The present artefact reports the effect of particles size, permittivity, concentration, temperature and moisture on dielectric performance of various nani insulating oils (NIOs). Five different particles of various size such as; Al_2O_3 (23 nm, 80 nm and 150 nm), ZnO (40 nm and 100 nm) and ZrO_2 (40 nm and 70 nm), Bi_2O_3 (15 nm), MgO (15 nm) and CuO (32 nm) have been utilized to investigate the effect of particle size and concentration on the BD performance in the present study. The influence of temperature and moisture presence in the insulating oils has also been discussed. The dielectric performance of NIOs has been experimentally examined over a nanoparticles (NPs) concentration range of 0.0–0.3 wt.%.

2. Materials and methodologies

2.1. Materials

The nanoparticles (NPs) utilized in the present study have been procured from Nanoshel Inc. (USA) and washed 2–3 times with acetone to remove any organic or inorganic impurities and finally dried in a hot air oven at temperature of 100 °C for 2–3 h before use for the experimentation. The size and morphology of the particles have been confirmed by High Resolution Scanning Electron Microscopy (HRSEM) and Transmission Electron Microscopy (TEM).

2.2. Characterization

The microscopy images of the nanoparticles captured by HRSEM and TEM are demonstrated in Fig. 1(a)–(d). The images of Al_2O_3 NPs reveal that the average sizes of the two samples of nanoparticles are ∼23 nm and 80 nm (Fig. 1(a) and (b)). The image of CuO NPs captured by TEM is demonstrated in Fig. 1(c). It is observed that particles have near spherical shapes with average size ∼32 nm. ZrO_2 NPs are characterized by HRSEM for their morphology and dimensions (Fig. 1(d)) and the average size is found to be ∼40 nm. The morphology of ZnO, MgO and Bi_2O_3 NPs has been confirmed by HRSEM and TEM. The morphology of one type of ZnO NPs is confirmed by HRSEM as nanorod with average diameter of 100 nm and 330–340 nm length (Fig. 2(a)). The shape of the MgO NPs is determined as spherical with the dimension of ∼15 nm (as illustrated in Fig. 2b). The Bi_2O_3 NPs are observed to be in the form of nanoflakes. The dimension (thickness) of the nanoflakes is confirmed to be ∼15 nm (Fig. 2(c)).