Dielectric characterisation of Fe₃P nanoparticles based ester oil

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Abstract: The insulation as the root source of failure and ageing assessor makes it a crucial point for any power equipment design. The transformer’s insulation requires an efficient dielectric fluid that acts as an ideal electrical insulant and better thermal transformer. The objective of attaining that idealism in dielectric medium leads to the addition of solvents (i.e. additive and other fluids) in the conventional medium as one of its approach. This study presents addition of new magnetic nanoparticle iron phosphide (Fe₃P) in insulating oil to achieve improved dielectric strength and withstand capability of the same conventional oil. A comparative study of nanofluids with different concentrations of nanofluids based on different insulating medium (i.e. synthetic ester and natural ester) has been performed. The concentration of additives and role of surfactant positively influences the dielectric characteristics of the base oil. The increase in breakdown strength is observed with a slight concentration of Fe₃P nanoparticles added in the insulating medium.

1 Introduction

The electrical industries, nowadays, are demanding the compactly sized and high-power rated machines having inflated electrical and thermal stresses, thereby, demanding superior foolproof insulation [1]. The conventional insulating oils are not competing the existing requirements, therefore, needs to be excavitated. The insulating oils thus are either evolved or replaced with advanced variety of insulating oils with foremost upgraded electrical and thermal capability for modern equipment and operating conditions [2, 3]. To attain next generation insulation level, nanofluids were introduced and investigated by Choi [4] in 1993, and developed the first nanofluid as a coolant. The existence of remote nanoparticles in fluid insulators also shows propitious dielectric breakdown characteristics [5]. Nanoparticles emphatically influence both the dielectric as well as the thermal property of the liquid [6, 7]. Nanofluid consists of three different components: nanoparticles, carrier/base liquid (insulating oil), and stabilising agent (surfactant). The purpose of surfactant is to curtail the surface tension at the boundary between materials which control the coagulation of nanoparticles and does not influence the characteristics of the solution [8].

Magnetic nanofluids, also termed as ferrofluids, are solutions prepared from magnetic nanoparticles such as Fe₃O₄, Co₃O₄, iron phosphide (Fe₃P), γ-Fe₂O₃, cobalt (Co) ferrite, Co, Fe, or Fe–C evenly distributed in an insulating liquid [9]. Magnetic nanofluids on examination have shown thermal and dielectric advantages [6, 10–13]. Stability is the significant consideration for preparation of nanofluid to gain longer lifespan. The possibility of agglomeration pertains due to the attractive force between the nanoparticles, which eventually settles down in the bottom [14]. Magnetic nanofluids can enhance the cooling by elevating the liquid dissemination inside transformer windings; moreover, additionally, they can exaggerate the transformer ability to withstand switching and lightning impulse while limiting the impact of moisture in insulating liquids [15].

Magnetic nanoparticles as being of polarising nature [16] have greater permittivity than the surrounding liquid; therefore, exhibit the electrical force directly to the area having maximum stress [17]. Under uniform field electrodes, the driving of particles is supposed to be started by the surface anomalies on the electrodes, which gives increment to local gradient [16]. The aggregation of particles proceeds and tends to frame an extension over the gap that prompts the initiation of the breakdown [18].

The objective of this paper is to focus on the dielectric strength of ester oils under the influence of magnetic nanoparticle, i.e. Fe₃P (alloy powder) under different shaped electrode systems and evaluate the enhancement in the breakdown voltage of the nanofluid.

2 Experimental methods

2.1 Sample preparation

Dielectric or insulating liquid signifies insulating medium with extremely less electric conductive, highly thermal conductive, and show higher insulating nature such as mineral oil. Liquid insulation offers self-healing capability and provides insulation to complex geometry structures. The conventional mineral oil is non-renewable source product and suffers the flammability at some temperature. Ester oils are ideal alternatives of mineral oil with high fire point, biodegradable, and extremely low pour point with minimum influence of moisture. Insulating ester oils used in this experimental work are commercially available fresh rapeseed oil and synthetic ester oil having specification listed in Table 1.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Synthetic ester oil</th>
<th>Rapeseed oil</th>
</tr>
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<tbody>
<tr>
<td>density (20°C), kg/dm³</td>
<td>0.97</td>
<td>0.92</td>
</tr>
<tr>
<td>kinematic viscosity (40°C), mm²/s</td>
<td>28</td>
<td>37</td>
</tr>
<tr>
<td>flash point, °C</td>
<td>260</td>
<td>&gt;260</td>
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<tr>
<td>fire point, °C</td>
<td>316</td>
<td>&gt;350</td>
</tr>
<tr>
<td>pour point, °C</td>
<td>−60</td>
<td>−31</td>
</tr>
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</table>
minimisation of agglomeration and enhancement of the stable dispersion of nanoparticles in fluids for long lifespan [21]. In this paper, the two-step preparation method with steps as shown in Fig. 2 is used to synthesise magnetic nanoparticles. The two-step process involves two phase processes: preparation of nanofillers into base fluid, i.e. the practises of drying, storage, and transportation of the nanoparticles are escaped, resulting in minimisation of agglomeration and enhancement of the stable nano-based oil [20].

Fig. 1 SEM of Fe₃P
(a) Powder, (b) Nanoparticles

The magnetic nature of nanoparticle Fe₃P is used in the present experimental work. Some properties of iron (Fe) alloy (Fe₃P) are enumerated in Table 2. Micron-sized alloy powder of size 2–4 μm gets disintegrated into nano-sized by top-down nanotechnology approach [19], which uses ball milling machine. Scanning electron microscopy (SEM) imaging are utilised for viewing clear morphology of Fe₃P at micro and nano phases as shown in Figs. 1a and b. Fe₃P nanoparticles have cauliflower-shaped growth due to tetragonal crystal system under the range of 200 nm.

Oleic acid acts as a strong stabilising agent for bonding of fatty acids with magnetic-natured nanoparticles when utilised under limit. Excessive surfactant reduced the capability of nanoparticles in insulating oil. The previous research [2] as well as the magnetic nature of Fe₃P nanoparticles make oleic acid as the ideal selection as stabilising reagent.

There are two different processes for synthesising nanofluids: one-step method and two-step method [1]. One-step process involves simultaneous synthesis and dispersion of nanoparticles into base fluid, i.e. the practises of drying, storage, and transportation of the nanoparticles are escaped, resulting in minimisation of agglomeration and enhancement of the stable nano-based oil [20]. Two-step process involves two phase processes: preparation of nanofillers such as nanotubes, nanoparticles usually in form of powder, and dispersion of nanofillers into base fluid using techniques such as magnetic stirring and ultra-sonication [11].

The surfactants are stabilising reagents added in liquid to provide the benefit of controlled particle–particle interactions and stable dispersion of nanoparticles in fluids for long lifespan [21]. In this paper, the two-step preparation method with steps as shown in Fig. 2 is used to synthesise magnetic nanofluids. The concentration of surfactant is limited to 10% oleic acid solution to maintain the active surface of nanoparticles. The properly intermixed surfactant in insulating oil is accomplished using magnetic stirrer for predetermined time. After the solution is thoroughly mixed, nanoparticle is added. In the present experimental work, four different concentrations (i.e. Table 3) of nanofluids are prepared. Owing to the magnetic nature of nanoparticle, it should be added after magnetic stirring. The degassing is also performed on each freshly mixed nanoparticle in fluid by sonication process using an ultrasonic bath for more than 2 h. Sonication is generally implemented in nanotechnology process for the dispersion of nanoparticles in liquids along with the removal of coagulated particles in the solution after stirring. It is also utilised to separate aggregates of micron-sized colloidal particles. The time duration for sonication depends on the nature and density of the preparing solution. The whole process has been performed at nearly room temperature to reduce the heating impact on insulating nature of oil.

After the sonication, the solution is kept isolated and covered for a day to stabilise the nanofluid. As the moisture influences the breakdown strength of insulating oil drastically [22], the nanofluids are kept in a completely sealed and isolated place to avoid ingress of moisture. The nanoparticles under prolong use may trap moisture content and congregate. To reduce the possibility of the cluster, the nanoparticles are kept inside a digital incubator at favourable temperature to remove moisture.

2.2 Experimental procedures

Fully automatic oil breakdown voltage tester is used for the measurement of AC breakdown strength of oil as well as nanofluid precisely and accurately. The experiment is conducted as per the standard with proper standby time and repetitive reading on each nanofluid samples with same setup setting and both electrodes configurations [i.e. hemispherical Verband Deutscher Elektrotechniker (VDE), spherical (SP)]. American Society for Testing and Materials (ASTM) D-1816 standard-based VDE electrode (Fig. 3a) provides uniform field at the central line and distorted field at the corners, which is helpful to analyse the dielectric breakdown characteristics at all field conditions. The breakdown of oil under proper uniform electric field can be obtained using SP electrode system as shown in Fig. 3b.

Nanofluids are poured inside the electrode configuration till the mark of the oil level. This is then kept inside the fully automatic oil breakdown voltage tester by opening the lid of the instrument. The experiment is conducted by adjusting the stand time, stirring time, and intermediate time accordingly to provide the proper dispersion of oil with each breakdown. The 12 repetitive breakdowns are performed on the same sample with same setup setting and both electrodes configurations.

3 Results

The dielectric breakdown is the final phase of the experimental work that engages several pre-breakdown phases. The breakdown is depicted by the arc formation; an electrical short circuit resulting in the large current flow between the electrodes. In present experimental work, the breakdown strengths of various prepared nano-based insulating oil samples have been measured and recorded. The experiment has been conducted on multiple standardised electrode systems (i.e. VDE electrode and SP electrode configuration) as shown in Figs. 3a and b, respectively. The enhancements in breakdown strength with the variation of nanoparticles have been observed. The average values of the breakdown strength of oil and the standard deviation are calculated.

At a certain range of concentration of nanoparticles as shown in Table 3, it is found that there is an enhancement of the dielectric breakdown strength of oil.

### Table 2: Properties of Fe₃P

<table>
<thead>
<tr>
<th>Properties</th>
<th>Fe₃P alloy</th>
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<tbody>
<tr>
<td>assay</td>
<td>99.5% trace metals basis</td>
</tr>
<tr>
<td>particle size</td>
<td>50–100 nm</td>
</tr>
<tr>
<td>surface area</td>
<td>50–80 m²/g</td>
</tr>
<tr>
<td>melting point (MP)</td>
<td>1100°C</td>
</tr>
<tr>
<td>bulk density</td>
<td>0.67 g/ml</td>
</tr>
</tbody>
</table>
breakdown strength. Graphs between average breakdown voltage and nanoparticle concentration have been plotted in Figs. 4–7. For the sample with Fe₃P in synthetic ester oil (Fig. 4), maximum enhancement has been observed at the 11 mg solution. After increasing the particle concentration, there is a sharp decrease in breakdown voltage. The reason might be due to particle agglomeration. For Fe₃P using rapeseed oil (Fig. 5), maximum enhancement is observed at 20 mg. The enhancement kept on increasing throughout the increment of particles. For Fe₃P in synthetic ester oil (Fig. 6), maximum enhancement is observed at the 11 mg solution. After increasing the particle concentration, there is a sharp decrease in breakdown voltage. The reason might be due to particle agglomeration. For Fe₃P using rapeseed oil (Fig. 7), maximum enhancement is observed at 20 mg. The enhancement kept on increasing throughout the increment of the particle.

For all the nanoparticles used in this experimental work, there is the enhancement in breakdown strength. The enhancement (%) is calculated by the formula given in the equation below:

\[
\text{Enhancement(\%)} = \frac{[\text{Voltage}(B \text{ to } F)/\text{Voltage of } A] - 1}{100}
\]  

For the better visualisation of the enhancement, graphs between enhancement (%) and nanoparticle concentration have been plotted in Figs. 8–11. Enhancement (%) is calculated by the formula given in the equation below:

From the graph between enhancement (%) and nanoparticle concentration, it is clear that the breakdown voltages rise up to a certain concentration of nanoparticles. Then, there is the degradation in the breakdown voltage. The utility of the nanofluids has, therefore, taken into account the optimised concentration of nanoparticles that provide the maximum breakdown voltage.

The maximum enhancement of Fe₃P nanofluids (VDE electrode) in the synthetic ester is 12.68% (Fig. 8) at 11 mg concentration and the enhancement decreases after further increase of nanoparticle concentration. The maximum enhancement of Fe₃P nanofluids (VDE electrode) in rapeseed oil observed is 12.95% (Fig. 9) at 20 mg concentration and saturation was not observed. The maximum enhancement of Fe₃P nanofluids (SP electrode) in the synthetic ester is 22.41% (Fig. 10) at 11 mg concentration, which is around the saturation point. The maximum enhancement of Fe₃P nanofluids (SP electrode) in rapeseed oil is observed as 25.63% (Fig. 11) at 20 mg concentration and saturation was not observed.

With the addition of nanoparticles in the insulating medium, the dielectric breakdown voltages have been increased to considerable extent. The enhancement gained with the influence of nanoparticle in insulating oil is the resultant of the electron trapping capability of magnetic nanoparticle, which delays the process of streamer propagation by reducing the mobility of electrons and hindered the breakdown of the nanofluid.
4 Conclusion

The smart fluid, i.e. nanofluids, has shown many current and promising future applications in the power sector. As the vegetable oils are eco-friendly and fire resistant but have shown an inferior dielectric and thermal characteristics thus minimising its commercialisation. These limitations can be removed with the addition of nanoparticles. The present work reveals the potential of nanomaterial toward designing more robust power systems employing liquid dielectrics by engineering their breakdown characteristics. In this experimental work, Fe$_3$P-based nanofluids have been synthesised taking base liquids as rapeseed oil and synthetic ester. The dielectric strength of the nanofluid is highly competing with conventional transformer oil. Further study and experimentation are needed to evaluate the better nature of Fe$_3$P-based NF and optimisation of the concentration of nanoparticles to achieve maximum dielectric nature of the NF. The experimental work, therefore, clarifies the capability of the vegetable oil-based nanofluids for designing better and reliable insulation system for smart power utilities.

5 References


