Review Article

A Review on Oil-Based Nanofluid as Next-Generation Insulation for Transformer Application

Sabrina N. Suhaimi1, Abdul R. A. Rahman1, Muhamad F. Md. Din,2 Muhammad Zahir Hassan,2 Mohd Taufiq Ishak,1 and Mohd Taufik bin Jusoh1

1Faculty of Engineering, National Defence University of Malaysia, Sg. Besi Camp, 57000 Kuala Lumpur, Malaysia
2Faculty of Mechanical Engineering and Manufacturing, Technical University of Malaysia, Malacca 76100, Malaysia

Correspondence should be addressed to Muhamad F. Md. Din; faizmd@upnm.edu.my

Received 27 June 2019; Revised 26 December 2019; Accepted 7 January 2020; Published 29 February 2020

Copyright © 2020 Sabrina N. Suhaimi et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Due to the increasing demand on developing good insulation, several researchers have performed experimental studies to prove the effectiveness and capabilities of transformer oil. This is done by suspending nanosized solid particles in the oil (nanofluid) for transformer applications. In brief, this paper presents a compilation of research studies which is divided into three parts. Part I discuss the preparation of the nanofluid which involves different types of nanomaterials, the optimal amount of concentrations, and applicable synthesisation methods for producing stably suspended nanofluids. In Part II, the nanofluid’s performances including the electrical breakdown voltages, impulse tests, and thermal and dielectric behaviour are reviewed in depth and compared. Part III emphasizes the limitation of nanofluids. Most researchers have agreed that appropriate concentrations of nanomaterials and the preparation method for nanofluids mainly affect the performance of nanofluids especially in terms of electrical properties. Meanwhile, types of nanomaterials and base oil also play a vital role in producing nanofluids as a better alternative transformer oil. However, among a few researchers, there are concerns regarding the issue of agglomeration and inconsistencies of findings that need to be resolved. Therefore, a few aspects must be taken into consideration to produce the next generation of high heat dissipation insulation.

1. Introduction

The transformer can be defined as a static piece of apparatus containing windings, with or without the presence of a magnetic core, for the purpose of transforming a system of alternating voltage and current into another system at the same frequency. A transformer failure causes economic losses during the power supply interruption, adds higher cost of replacement, and is time-consuming to repair. Therefore, it is important to ensure the safety of the transformer during its operation. Transformer postfailure analysis shows that the life of a transformer mainly depends on the condition of the insulation system and is the second leading cause of transformer failures [1]. Some of the factors that affect the life expectancy of insulation in a transformer include overload-
oxygen due to susceptibility of the transformer to oxidation. Better performance of transformer oil implies a high efficiency of the power system and enhances the power transfer capability. Hence, different approaches, preventive and spontaneous maintenance, and repair methods have been designed to eliminate or minimize the failures and breakdown probability.

Most oil-filled-type transformers use petroleum-based mineral oil which is normally obtained by fractional distillation and subsequent treatment of crude petroleum that contains high dielectric strength and has low electrical losses [3]. It also has a number of the desirable electrical, chemical, and physical properties for transformer application such as chemical stability, low viscosity, and a higher pour point. Generally, mineral oil is a mixture of liquid hydrocarbon attained from crude oil by particular methods of distillation and refining. The structure of mineral oil is quite complex which contains a wide range of molecular impurities of sulphur, oxygen, and nitrogen compounds. Since transformer winding and the core are immersed in a petroleum-based mineral oil, there are serious concerns regarding fire risk and environmental issues. Hence, the development of high thermal conductivity of transformer oil for critical application is required. One of the initiatives is by implementing nanotechnology with the aim of improving thermal characteristics of the insulating oil as well as enhancing its electrical performances.

The term of nanotechnology was conceptualized in Feynman’s speech (see [4]) in 1959; it has been implemented in several applications especially in physics, chemistry, biology, electronics, etc. Originally, the idea is related to the manipulation of matter at a nanoscale level. In this paper, general overviews of the concepts of fluids (mineral and natural ester oil) with nanotechnology alternatives known as nanofluids are discussed for the next generation of transformer oil. Nanofluids are defined as a liquid substance containing materials that are nanometer-sized, a term that has been proposed by Choi and Eastman in 1995 [5]. It can be regarded as the next-generation heat transfer fluid as it offers excellent properties with enormous potential. It not only has the capability to enhance the heat transfer of such fluids which exhibit higher thermal conductivities but is also capable of remaining suspended in the base fluid for a longer time compared to micro- or millimeter-sized particles. In 1998, Segal et al. [6] are the first researchers to study the modification of magnetic nanoparticles (Fe₃O₄). They found that its dielectric strength behaviour produces excellent dielectric breakdown voltage values (two times higher than mineral oil). For decades, research on nanofluids has been conducted experimentally and theoretically on various aspects of nanofluids. This review therefore focuses on the preparation, performance, and limitations of nanofluids for researchers to identify a better alternative nanoinsulating oil in the future. Most of the references present in this paper have been published over the past ten years.

2. Nanomaterials

A nanomaterial is defined as a nanoscale dimension material (size ranging from approximately 1 to 100 nm) that exhibits a variety of tunable and unique physical and chemical properties [7]. The wide range class of nanomaterials mostly includes nanoparticles, nanowires, nanoplates, nanoribbons, nanofibers, nanorods, nanotubes, nanocomposites, nanofoams, nanopores, and nanocrystals. Figures 1(a)–1(d) illustrate various types of nanomaterials captured with transmission electron microscopy (TEM) at different nanosizes [8–11].

Both hexagonal and spherical shapes are seen in Figure 1(a), while Figure 1(b) shows a nanowire pattern built on the substrate. As for Figure 1(c), the TEM image shows the morphology of fibers with a nanometer scale range. Figure 1(d) shows a long, hollow structure with the walls formed by a one-atom-thick sheet of carbon known as a carbon nanotube. Each of the nanomaterials has its particular thermophysical properties, different characterization, and functionality. With the development of nanotechnology, nanomaterials are used in many applications especially in medical, electronics, energy storage devices, and field-emission displays [12]. Recent advances in nanotechnology have allowed for a new invention of a fluid termed nanofluid which is an engineered colloidal suspension of nanomaterials in many types of base fluids such as ethylene, glycol, and oil.

Research work has been widely concentrated on finding the alternative transformer oil that can perform better than the existing transformer oil. It has been reported that dispersing nanomaterials with transformer oil could develop new types of insulating nanofluids [13], [14]. Zhen et al. compared the morphology of TiO₂ nanoparticles and TiO₂ nanofluids by using the TEM and HRTEM equipment as shown in Figure 2 [15]. It can be seen in Figure 2(a) that the TiO₂ exhibits a uniform particle size distribution and has an average diameter of 6 nm, while in Figure 2(b), the clear lattice fringes of single nanoparticles are seen, which demonstrate the single-crystalline nature of the nanoparticles when dispersed in the fluid.

Based on their conductivity, electron scavenging, and relaxation time constant, nanoparticles can be categorized into three types, namely, as conductive magnetic nanoparticles, semiconductivities, and nonconductivities. The conductive nanoparticles present in nanofluids can capture free electrons that are responsible for streamer inception that is much faster than nonconductive magnetic nanoparticles. However, the nonconductive magnetic nanoparticles are able to convert such fast-moving electrons into slow-moving negatively charged particles [16]. Some researchers studied that the addition of conductive nanoparticles such as oxonickel (Fe₃NiO₄), ferric oxide (Fe₂O₃), and copper at a certain amount of concentrations may reduce the dielectric strength of insulating oil [6, 17–20]. While zinc oxide (ZnO) [21] and copper oxide (CuO) [22] are categorized as classical semiconductive nanoparticles that are often used by researchers worldwide, they are also trusted as the main contributor to the enhancement of transformer oil performance [23, 24]. Later, some researchers also identified that nonconductive nanoparticles such as ferrofluid (FF), alumina (Al₂O₃), and titania (TiO₂) also contribute to the enhancement of dielectric strength of transformer oil [25–27].
3. Effects of Concentrations

Based on the findings of Kopčanský et al. [28], as the number of nanoparticles added in the insulating oil increases, the rate of collision between nanoparticles also increases. This is due to the Brownian motion and it appears as they are bridging between two conductors and leads to breakdown [29]. There are very limited comparative and systematic studies on the amount, weight, or volume concentrations of nanoparticles which can give a huge impact on the performance and suspension behaviour of nano fluids. Wang et al. [30] measured the influence of nanoparticles at 5%, 10%, 20%, and 40% volume concentrations after being added into mineral oil. The suspension of nanoparticles improved the breakdown voltage until the critical value: 10% nanoparticles for TiO$_2$ and Fe$_3$O$_4$ and 20% concentrations for Al$_2$O$_3$. Sun et al. [31] studied the effect of different TiO$_2$ nanoparticle concentrations in mineral oil ranging from 0.03 g/L to 0.18 g/L under lightning impulse voltage and switching impulse voltage as shown in Figure 3. Based on the graph, as the concentration increases, the breakdown voltage first also follows the pattern until at 0.06 g/L (lightning impulse) and 0.12 g/L (switching impulse), then decreases gradually. Hence, it can be concluded that the amount of appropriate concentrations may influence the performance of insulating oil in the transformer. It is necessary to determine suitable concentrations that require dispersal in nanomaterials.

![Figure 1: TEM image of (a) zinc oxide (ZnO) with 50 nm diameter [8], (b) silicon nanowires with 200 nm diameter [9], (c) titanium dioxide (TiO$_2$) nanofibers with 50 nm diameter [10], and (d) multiwalled-carbon nanotubes (MWCNT) with 15 nm diameter [11].](image1)

![Figure 2: Morphology of (a) TiO$_2$ nanoparticles and (b) TiO$_2$ nano fluids [15].](image2)
4. Synthesisation of Nanofluids

Nanofluids are commonly applied as heat carriers in power stations [34], cooling and heating systems in buildings, vehicle air conditioning systems, and cooling systems of most of the processing plants. The synthesis of nanofluids begins with direct mixing of the base fluid with the nanoparticles. Generally, there are two main techniques used by researchers to produce nanofluids: the one-step method and the two-step method as shown in Table 1 [35]. Nanoparticles can be produced by using several processes. They include the thermal decomposition and photochemical method [36–38], transition metal salt reduction electrochemical process [39, 40], and electrochemical synthesis [41, 42]. It is recommended to avoid the process of drying, storage, and transportation of nanofluids due to the possibility of agglomeration and sedimentation [43].

As mentioned in Table 1, the one-step method uses magnetron sputtering, which causes nanoparticles to hit the surface of a low vapor pressure liquid film formed by a rotating drum, which is soaked in the surfactant-presented base liquid. Generally, the one-step method is applied to produce small-scale nanofluids, while the two-step method is appropriate for mass production of nanofluids [44]. However, it mostly depends on numerous factors such as types of nanomaterials, concentration range, and diameter sizes. The idea of dispersing solid nanoparticles in liquid form initially came from Keblinski et al. [45], who thought of the way to improve the suspensions that contain millimeter- or microsized particles for enhancement of thermal properties.

Deagglomeration or dispersion is a significant aspect in sample production of every type of nanofluid. The procedure is considered successful when the process of delaminating exfoliating aggregates and breaking apart of the nanomaterial occur. Traditionally, the dispersion of nanomaterials in the liquid state known as the nanofluid has proven to be difficult and frequently results in phase separation and agglomeration. Different types of nanomaterials require different stability methods due to dissimilar characteristics of chemical structure and bonding. Table 2 shows the comparison of many types of dispersion methods that has been utilized by researchers and scientists all over the world [46].

Generally, there are inherently six different dispersion methods possible to use in order to achieve uniform particle dispersion and to develop simple yet effective techniques. The sonication bath and ultrasound sonication probe have similar techniques of dispersion where the ultrasound energy and frequency, temperature, and power applied by the sonicator [50, 51]. However, the optimum parameters for dispersing nanoparticles in fluids are still unknown.

According to Kole and Dey [52], the increment of sonication duration does not necessarily reduce the particle size. Instead, it can contribute to the increment of particle size as
illustrated in Figure 4. Dynamic light scattering (DLS) has been used in the study to estimate the size of ZnO nanoparticles in ethylene glycol (EG) against the sonication duration as shown in Figure 5. It is seen that the nanoparticle cluster size decreases rapidly between 4 and 60 hours, and the cluster size increases up to 220 nm after 100 hours of sonication. This is because the existence of acoustic cavitation induced by the sonicator contributed to a strong shear force that can break up the agglomeration of nanoparticles [53]. The diffusion rates can be improved in order to produce highly concentrated and uniform dispersions for nanometer-sized particles [54, 55].

The most important matter in the dispersion of nanofluids is achieving the desired stability for longer periods. Nanofluids were reported to be much more stable than microsized particles due to the vigorous Brownian motion of suspended nanometer-sized particles [45, 56]. Hence, many studies were conducted in order to achieve the desired stability while becoming a good insulator. One of the ways used was by adding surfactants such as sodium dodecyl sulphate (SDS) and gum Arabic which significantly reduce the particle agglomeration due to van der Waals forces of attraction [57–60].

However, Katliyar et al. [61] have the opinion that the existence of a surfactant has an insignificant effect on the viscosity, thermal conductivity, and breakdown voltages. Furthermore, Xuan et al. reported that the sodium dodecyl benzoic sulphate (SDBS) surfactant remarkably exerts a negative effect on the impinging heat transfer performance and suspension of nanofluids. The thin layer of SDBS is covered by the tested surface that hinders heat transfer from the surface to the nanofluid [62]. Table 3 lists recent research that studies various surfactants and methods for dispersing nanomaterials in different types of transformer oil.

Oleic acid has been used by most researchers as a surfactant to aid the dispersant of the proposed transformer oil [69–72]. However, excess amount of surfactant may cause a double chain around nanoparticles, which can result in reducing the efficiency and role of the surfactant as an active agent to improve stabilization of nanofluids. Zakaria et al. [73] have a strong opinion that nanoparticles should be treated by cold-atmospheric pressure plasma treatment before mixing with mineral oil and surfactant to exhibit higher stabilization while Dessouky et al. [74] applied infrared radiation after the sonication process to heat the nanofluids, remove moisture, and fully saturate the nanofluids.

Shukla and Aiyer [75] found that the mixture of SiO₂ and mineral oil can lead to dispersal times of 1 month, 2 days, and less than 24 hours at 0.01%, 0.02%, and 0.1% volume concentrations, respectively. This idea was supported by Krajnik et al. [76] which mentions that the addition of a large amount of surfactant might reduce the dispersant time of nanofluids, but not all the molecules of the surfactant will build bonds with nanoparticles. Different types of surfactant produce different properties and outcomes of nanofluids especially in terms of density, viscosity, thermal conductivity, and stability. Overall, based on most studies, it can be computed that there is still no standardized procedure for the dispersion of certain nanomaterials for the liquid state. Furthermore, there are conflicts of data regarding the optimum preparation method for nanofluids. Mostly, it depends on the types of nanomaterials used that suit with the based fluid, the precise weight or volume concentrations, and appropriate dispersion method. Specifically, the result of dispersion is

| Dispersion tools | Principle of operation | Advantages | Disadvantages |
|------------------|------------------------|------------|---------------|
| Mills (to include ball, stirred media, and centrifugal and jet mills) | Involves ultrafine grinding process | Useful for large batches | Slow/inefficient—ball milling may take days in some cases |
| Stirring (magnetic/overhead stirring) | Uses a magnetic bar or an overhead-stirring paddle; Has a rotational speed to create a vortex | Rarely results in attrition/breakage of nanoparticles | Inefficient |
| High-speed homogenizer | Use of a rotor & stator generator probe; the rotor acts as a centrifugal pump to recirculate the liquid and suspend the solids through the generator | Suitable for large liquid samples up to 2500 mL | Rarely results in deagglomeration and is often employed in order to improve homogeneity of dispersion |
| High-pressure homogenizer | Shear and cavitation provided via increase in the velocity of pressurized liquid streams in micro channels | Highly efficient | Potential metal contamination |
| Ultrasound sonication bath | Use ultrasound waves and cavitation in a bath | Cheap/affordable | Nanoparticle architecture can be altered; increase of temperature in the dispersion likely |
| Ultrasound probe sonication or ultrasonic disruptor | Similar to ultrasonic bath but aims to deliver more energy density in smaller volume in comparison to the corresponding bath format | Highly efficient | Expensive |

Potential metal contamination |

Both formats less effective (less shear) compared to probe format |

Probe tip disintegration can contaminate samples |

Can alter nanoparticle architecture; temperature increase (even for a few minutes) in dispersion highly likely

Table 2: Dispersion tools for nanofluids [46].
5. Performance of Nanofluids

Although there are a lot of contributions towards the advancement of insulation, there are still challenges that need to be confronted such as lack of agreement between performances of transformer oil results, the inadequacy of theoretical understanding of the mechanism, and poor behaviour of suspensions. The field of nanodielectrics is the future for the development of insulating oil with improved critical parameters that make it possible to operate for longer periods, with less cost and maintenance. In this paper, AC electrical breakdown voltage, lightning impulse tests for positive and negative polarity, thermal properties, and dielectric properties have been discussed further in the section below:

Figure 5: The cluster size of the ZnO nanofluid at different sonication durations based on Kole and Dey’s investigation [52].

Figure 4: TEM image of ZnO nanofluid after (a) 4 hours, (b) 12 hours, (c) 60 hours, and (d) 100 hours of sonication [52].

strongly dependent on the sample preparation, which plays a significant role in avoiding agglomeration and instability of the nanofluid.
followed by the combination TiO\(_2\) with ZnO. Other studies absorb a large number of electrons with less amount of time, for enhancing the electrical performance because it can MgO in transformer oil was found to produce the best twins (Fe\(_2\)O\(_3\) or ferric oxide, have slight improvement on the and nonconductive magnetic nanoparticle: iron(III) oxide Fe\(_3\)O\(_4\), MgO, SiO\(_2\), and graphite) after dispersion in the individual nanoparticles. The combination of Fe\(_3\)O\(_4\) and particles for trapping electrons while increasing the amount multinanoparticles are more e\(_83\). Based on the study, slow the fast-moving electron [79].

The authors conclude that the ability of multinanoparticles of nanoparticles that was deposited in the transformer oil. At elevated temperatures, the breakdown voltage achieves almost 45% enhancement for all oil samples. It is evident that mechanisms of nanoparticles are highly active at higher temperature, which in turn enhances the dielectric strength of oil samples. The authors claim that when these three types of nanoparticles react with free radicals, it delays the formation of peroxides which are susceptible to inception of chain oxidation. Hence, nanofluids remain stable at high temperature and possess high thermal strength during operation.

Thabet et al. [78], who studied the electrical breakdown behaviour of multinanoparticles (ZnO, TiO\(_2\), LiTaO\(_3\), Fe\(_2\)O\(_3\), MgO, SiO\(_2\), and graphite) after dispersion in the transformer oil, found that nanoparticles accumulate as electron scavengers in nanofluids that hinder the occurrence of breakdown by making highly charged shallow traps to slow the fast-moving electron [79–83]. Based on the study, multinanoparticles are more efficient than individual nanoparticles for trapping electrons while increasing the amount of nanoparticles that was deposited in the transformer oil. The authors conclude that the ability of multinanoparticles for the polarization-free electron is higher compared to individual nanoparticles. The combination of Fe\(_3\)O\(_4\) and MgO in transformer oil was found to produce the best twins for enhancing the electrical performance because it can absorb a large number of electrons with less amount of time, followed by the combination TiO\(_2\) with ZnO. Other studies found that nanofluids will lower the streamer propagation and improve the performance of breakdown voltage compared to conventional transformer oil [82–86].

In 2018, researchers studied the electrical breakdown performance effect towards nanofluids. Such a study was done by Ram et al. [87] who studied the breakdown performance combination of two nanoparticles, Al\(_2\)O\(_3\) (50 nm) and ZnO (20 nm), after dispersion in three types of natural ester oil (sunflower oil, rice bran oil, and corn oil) at different percentages of volume concentration. The natural ester oil and both nanoparticles react positively in the electrical breakdown value for all ranges of concentrations as illustrated in Figure 6 [88]. According to the researchers, the outcome may be due to the contribution of nanoparticles that leads to the formation of a shallow trap [89] and eventually results in the reduction of the existence of a breakdown mechanism.

Tables 4 and 5 list other recent research of the breakdown performance of mineral oil and natural ester oil after adding various types of nanomaterials. It can be seen that the addition of various types of nanomaterials could lead to enhancement of electrical breakdown voltages of mineral-based oil and natural ester oil for transformer application especially ZrO\(_2\) nanoparticles which have the highest increment, followed by anatase TiO\(_2\) and carbon nanotubes.

Primo et al. [104] investigated the breakdown strength of Fe\(_3\)O\(_4\) nanoparticles with the presence of moisture and concluded that nanoparticles improve the solubility of water in oil. Hence, enhancing the breakdown strength of nanofluids in some cases achieves better performance than the conventional transformer oil used by most of the industry. The researchers also suggested that higher concentration of nanoparticles is required to bind water molecules since the probability that they are bound to rely on the weight/volume concentrations of nanoparticles and water molecules exists. At lower temperatures, oil samples will have high relative moisture content while at higher temperatures, the opposite occurrence will happen. Adding a nanomaterial in the base oil could reduce the spread of moisture content at low temperature conditions as illustrated in Figure 7. It also helps

| Ref. | Nanomaterials | Types of oil | Surfactants | Magnetic stirrer duration | Sonication duration |
|------|---------------|--------------|-------------|--------------------------|--------------------|
| [63] | ZnO BaTiO\(_3\) TiO\(_2\) (<100 nm) | Mineral oil | Sorbitan monooleate | 30 minutes | 2 hours |
| [64] | TiO\(_2\) | Mineral oil | Cetyltrimethylammonium bromide | 15 minutes | 3 hours |
| [65] | TiO\(_2\) SiO\(_2\) | Mineral oil | Span 80 | 30 minutes | 2 hours |
| [66] | Fe\(_3\)O\(_4\) | Mineral oil | Silane coupling agent Z6011 | — | 2 hours |
| [67] | Fe\(_3\)O\(_3\) (50 nm) SiO\(_2\) (12 nm) | FR3 | Hexadecyltrimethylammonium bromide | — | 2 hours |
| [68] | SiO\(_2\) (15 nm) Synthetic oil, Therminol 66 (TH66) | | Benzethonium chloride (BZC) | 20 minutes | 2 hours |

5.1. Electrical Breakdown Voltages. Generally, there are three common types of nanoparticles that have been widely discussed to develop a nanofluid insulating oil that has conductive, semiconductive, and nonconductive nanoparticles as mentioned in Section 2 [66]. Raymon et al. [77] found that these three types of nanoparticles, conductive nanoparticles: aluminium oxide (Al\(_2\)O\(_3\)), semiconductive nanoparticles: titanium dioxide (TiO\(_2\)) or cadmium sulphite (Cds), and nonconductive magnetic nanoparticle: iron(III) oxide (Fe\(_2\)O\(_3\)) or ferric oxide, have slight improvement on the breakdown voltage of natural ester oil-based nanofluids for transformer oil. At elevated temperatures, the breakdown voltage achieves almost 45% enhancement for all oil samples.

Tables 4 and 5 list other recent research of the breakdown performance of mineral oil and natural ester oil after adding various types of nanomaterials. It can be seen that the addition of various types of nanomaterials could lead to enhancement of electrical breakdown voltages of mineral-based oil and natural ester oil for transformer application especially ZrO\(_2\) nanoparticles which have the highest increment, followed by anatase TiO\(_2\) and carbon nanotubes.
5.2. Electrical Impulse Test. Other than alternating current breakdown voltages, lightning impulse and switching impulse tests are also required to be conducted to demonstrate the level of transformer oil to withstand impulse during its operation period. There were various testing configurations that were implemented to demonstrate impulse withstand over the past decades such as the rising-voltage method or increasing the voltage until breakdown [106], the withstand test 15/2 or 3/0 (2 breakdowns in 15 pulses for self-restoring and 3/0 for non-self-restoring insulation), the up-and-down method, and the multiple-level method. Each testing method has its own pros and cons and validity range. As a transformer is equipment that works on an alternating current system, which steps up or steps down voltages, the switch in surge, transient system surge, and lightning surge of positive or negative are to be considered. It is necessary to test all types of transformer oil based on the standards for positive and negative impulse tests. Table 6 lists the recent investigation regarding performance of positive and negative impulse breakdown voltages studied by various researchers based on the IEC 60897 guideline [107].

Based on Table 6, it seems that there were still arguments and conflicts on performance of nanofluids for positive and negative lightning impulses. Most studies found out that nanomaterials could enhance the capability of mineral oil and natural ester oil for the positive impulse test; however, for negative polarity, references and contributions for transformer application were still lacking. Lots of decrement was found in the negative impulse test rather than positive polarity.

Focusing on quantity of nanomaterials in the base fluid, Muangpratoo et al. [63] investigated the performance of the impulse breakdown voltage of mineral oil after addition of zinc oxide (ZnO), barium titanate (BaTiO₃), and titanium dioxide (TiO₂) with a diameter less than 100 nm at two concentrations. Based on the results shown in Figure 8, they noticed that among the three types of nanoparticles, the impulse breakdown voltages for 0.01 weight percentage of Sunflower oil, rice bran, and coconut oil [88].
ZnO-mineral oil acquired the highest impact compared to other samples at positive polarity. As for negative polarity, there was no improvement noticed for all types of samples; however, the 0.03 weight percentage of BaTiO3 achieves compatible results compared to mineral oil. Other than Muangpratoo et al., Lv et al. [114] also studied on the positive and negative impulse performance of Fe3O4-based mineral oil at various concentrations (0.05 g/L, 0.1 g/L, 0.2 g/L, 0.4 g/L, 0.6 g/L, and 0.8 g/L). According to results shown in Figure 9, at positive polarity, breakdown voltage of nanofluids first raised up to the highest value, which is 0.4 g/L and then decreased significantly. As for the case of negative polarity, unexpectedly, nanoparticles tend to reduce the breakdown performance of transformer oil, which is incompatible with the view of Segal et al. [85].

The mechanism of the enhancement of positive impulse breakdown voltage properties is related to the relaxation time constant and polarization of nanoparticles that are dispersed in nanofluids. These are highly dependent on the conductivity and permittivity behaviour of nanoparticles. Different types of nanoparticles have different characteristics. If the relaxation time constant of free charges gathered on the surface of nanoparticles is shorter than the time scale of the streamer propagated, the presence of nanoparticles will definitely affect the alteration of the electrodynamics in the fluid. The equation of the relaxation time constant is as follows [83]:

\[ \tau = \frac{2\varepsilon_1 + \varepsilon_2}{2\sigma_1 + \sigma_2}. \]
where $\varepsilon_1$ is the permittivity of pure transformer oil, $\varepsilon_2$ is the permittivity of nanoparticles, $\sigma_1$ is the conductivities of pure oil, and $\sigma_2$ is the conductivities of nanoparticles.

Based on the Sima et al. [115] theory for positive impulse tests, it can be computed that, if the relaxation time constant of nanomaterials is shorter compared to the propagation time of the streamer, the surface of nanoparticles can absorb free electrons quickly. Hence, the dielectric strength of nano fluids is improved compared to that of the base oil. As for the negative lightning impulse voltage, the ionization of oil occurs around the negative needle electrode after space charge and corona generation. Hence, after the application of negative impulse was applied, a small positive ion created by field ionization is neutralized after approaching the needle electrode. Hence, the phenomenon strengthens the electric field at the plate electrode and weakens at the needle electrode which causes decrement of the negative impulse breakdown.

5.3. Thermal Properties. The research on oil-based nano fluids demonstrated that types of nanoparticles, surface modification, and weight concentrations are the critical factors that influence the enhancement of electrical and dielectric behaviour. However, the flammability of insulating oil also is a serious safety concern as there were many cases of explosion of the transformer. The heat transfer capability of a good insulating oil or cooling medium is vital to study. Typical specifications referred to by industry for flash point and pour point are usually 140°C and -30°C or lower [116] while the high fire point is at least 300°C which is referred to as less flammable [117]. Mansour and Elsaeed [118] were one of the researchers that studied the heat transfer properties of Al$_2$O$_3$ nano fluids at different nanoparticle concentrations (0.1 g/L to 0.6 g/L) and different surfactant (sodium dodecyl benzene sulphonate) weight percentages as shown in Figure 10. The heat transfer coefficient of nano fluids can be calculated as follows:

$$h = \frac{q}{(T_i - T_o)},$$

where $q$ is the heat flux, $T_i$ is the surface temperature, and $T_o$ is the mean fluid temperature.

Based on the results, the highest heat transfer coefficient for 0.1% surfactant was at the intermediate part of concentrations, while for 1.0%, the highest enhancement occurs at low concentrations. However, in terms of stabilization and dispersion of nanoparticles in the insulating oil based on heat transfer properties, the researcher suggested moderate nanoparticle concentrations with a small amount of surfactant. The researcher did not only study heat performance at various concentrations, but also compared heat performance of three types of nanoparticles (Al$_2$O$_3$ (13 nm), TiO$_2$ (21 nm), and SiO$_2$ (10-20 nm)) in mineral oil [119]. SiO$_2$ exhibited the
highest enhancement in heat transfer coefficient and increased as much as 31% compared to conventional transformer oil used in the industry.

Although Mansour et al. have similar opinions with Beheshti et al. [120] where it is suggested that a moderate amount of concentration is needed to achieve the maximum enhancement of thermal properties, most researchers found out that thermal conductivity, flash, and fire points increased along with nanoparticle volume percentage [121–123]. The flash point is considered as one of the quality indicators to determine the chance of fire hazard while the fire point is the temperature whose vapors continually burn after ignited. With proper amount, sizes, and types of nanomaterial combined with the base transformer oil, the thermal conductivity performance can be improved.

Chahal [97] studied the correlation of temperature and breakdown voltage performance of Al₂O₃ nanoparticles after dispersion in natural ester-based oil. The results show that breakdown voltage increases as temperature increased which is related to the increment of thermal fluctuations of nanostructure behaviour. Jeong et al. [124] also studied the effect of temperature after adding some nanomaterials and found that Fe₃O₄ can considerably lower the top-oil and hot-spot temperature in the transformer. The increasing temperature would lead to the reduction of nanoparticle surface energy, which significantly reduces the agglomeration, and makes the Brownian motion more intensive [125].

Overall, researchers have observed that the thermal conductivity enhancement along with rising temperature, regardless the selection of nanomaterials, is due to the Brownian motion, where absorption kinetic energy causes more particle collisions. However, the nanofluid’s thermal performance generally would depend on the appropriate amount of concentrations of weight/volume percentages, which will jeopardize other properties, mainly on stability and dielectric parameters.

5.4. Dielectric Properties. Relative permittivity, resistivity, and dissipation factor (tangent of the angle loss) were measured to monitor the health condition of transformer oil as an insulation medium in the transformer device. It is also considered as an aging indicator that detects the presence of contamination or moisture content level in the transformer oil. Therefore, it is vital to monitor these three parameters periodically to ensure the quality of insulating oil.

Generally, relative permittivity function is to determine the polarizability nature of insulating oil subjected to electrical stress [79], which commonly has a value of 2.2. Abdul-aleem [126] has investigated the relative permittivity of different types of nanoparticles: Al₂O₃, Pb₃O₄, and SiO₂ when dispersed in mineral oil, and found out that the Pb₃O₄ nanofluid has the highest value of permittivity, while Miao et al. [88] suggested ZnO nanofluids have a slightly higher relative permittivity compared to conventional transformer oil. However, the relative permittivity pattern decreased linearly along with temperature and increased linearly when the nanoparticle volumetric concentration decreased. It is suggested that volumetric concentrations could contribute to the effectiveness of relative permittivity of nanofluids [127].

Electrical resistivity of specific resistance is a measure of insulation properties in which a high resistivity value indicates low content of free ions, ion-forming particles, and low concentrations of conductive contaminants. Hence, it is necessary to have a higher resistivity value. Maharana et al. [128] observed that the resistivity of the TiO₂ nanofluid is superior compared to the resistivity of conventional transformer oil. However, this is in contrast with the study done by Shukla and Aiyer [75], who found that a nanodiamond mix with mineral oil below 0.2% concentrations has no significant effect towards the electrical resistivity. Generally, the resistivity value should be greater than 10¹¹Ω m. The presence of moisture or perceptible material will reduce the resistivity of insulating oil, which will cause short circuit and burn the transformer.

The dissipation factor is a measure of power dissipated in the transformer oil, where a low value indicates the minimum power dissipated while a high value indicates the presence of contamination. A researcher showed that there is an increment that produces a dissipation factor at 0.005 weight percentage when the mineral oil mixes with TiO₂ nanoparticles [129]. However, some opinions suggested that dispersion of 0.005 g/L of BT nanofluid-based mineral oil contributes to degradation of the dissipation factor value while a combination of BT and TiO₂ nanoparticles slightly elevated the DF value although still degraded compared to the mineral oil value [130].

The dielectric property measurements of the transformer oil are very important before being utilized in the transformer. However, based on most references, it seems that nanofluids have great potential in terms of electrical performance but are still not promising in the permittivity, resistivity, and dissipation factors. Appropriate selection of the nanomaterial used, preparation methods, and others might improve the condition of dielectric properties.

6. Limitation of Nanofluids

Although nanofluid-based mineral and ester oils are likely to be used and studied widely in electrical power systems in the future, there are still limitations that require improvement. One of them is the sustainability of nanoparticles after their dispersion in the base transformer oil. The aggregation contained in unstable nanofluids can easily cause sedimentation and adsorption on the inner surface of the base oil, which will probably result in degradation of the electrical and dielectric performance, under attractive forces and external stresses in nanofluids [131]. Ghadimi and Metselaar [132] suggested that combining the use of a surfactant, ultrasound vibration, controlling pH value, and sufficient amount of nanoparticles could contribute to long-term stability. In the meantime, He et al. [133] and Longo and Zilio [134] found that without a surfactant, the TiO₂ nanofluid can avoid agglomeration for months. Kudelcik et al. have a strong opinion on the limitation of nanofluids which affects the decrement in electrical breakdown voltage performance at certain weight or volume concentrations [135]. However, the above judgements are not very objective and accurate because of inconsistent results produced and no uniform
References

[1] W. H. Bartley, "An analysis of international transformer failures," *Business*, vol. 33, no. 3, pp. 1–5, 2008.
[2] M. Banovic and J. Sanchez, "Classification of Transformers Family," *Merit Media Int.*, vol. 1, pp. 26–33, 2014.
[3] M. J. Heathcote, *J & P Transformer Book*, Elsevier Science & Technology Books, 13th edition, 2007.
[4] S. W. Dean, G. A. Mansoori, and T. A. Fauzi Soelaiman, "Nanotechnology — an introduction for the standards community," *Journal of ASTM International*, vol. 2, no. 6, pp. 13110–131122, 2005.
[5] S. U. Choi and J. A. Eastman, "Enhancing thermal conductivity of fluids with nanoparticles," in *ASME International Mechanical Engineering Congress and Exposition*, vol. 66, pp. 99–105, Washington, DC, USA, 1995.
[6] V. Segal, A. Rabinovich, D. Nattrass, K. Raj, and A. Nunes, "Experimental study of magnetic colloidal fluids behavior in power transformers," *Journal of Magnetism and Magnetic Materials*, vol. 215-216, pp. 513–515, 2000.
[7] ISO/TS 80004-1:2015 - nanotechnologies - vocabulary-part1: core terms, p. 3, 2015.
[8] R. Yang, X. Qu, and M. H. Wang, "Sol–gel synthesis of Ba-doped ZnO nanoparticles and its use in varistor ceramics," *Micro & Nano Letters*, vol. 13, no. 10, pp. 1506–1509, 2018.
[9] M. I. Den Hertog, *Characterization of Silicon Nanowires by Transmission Electron Microscopy*, Joseph Fourier University, 2010.
[10] C. De Pascali, M. A. Signore, A. Taurino et al., "Investigation of the gas-sensing performance of electrospun TiO2 nanofiber-based sensors for ethanol sensing," *IEEE Sensors Journal*, vol. 18, no. 18, pp. 7365–7374, 2018.
[11] Y. Zhang, J. Zhang, and W. Zheng, "The stability of CdS QDSCs based on optimized MWCNs/CuS counter electrodes," *IEEE Journal of Photovoltaics*, vol. 8, no. 4, pp. 1142–1148, 2018.
[12] M. Endo, T. Hayashi, Y. A. Kim, and H. Muramatsu, "Development and application of carbon nanotubes," *Japanese Journal of Applied Physics*, vol. 45, no. 6A, pp. 4883–4892, 2006.
[13] Y. Z. Lv, Y. Zhou, C. R. Li, Q. Wang, and B. Qi, "Recent progress in nanofluids based on transformer oil: preparation and electrical insulation properties," *IEEE Electrical Insulation Magazine*, vol. 30, no. 5, pp. 23–32, 2014.
[14] V. Sridhara, B. S. Gowrishankar, Snehalatha, and L. N. Satapathy, "Nanofluids—a new promising fluid for cooling," *Transactions of the Indian Ceramic Society*, vol. 68, no. 1, pp. 1–17, 2009.
[15] Y. Z. Lv, C. Li, Q. Sun, M. Huang, C. R. Li, and B. Qi, "Effect of dispersion method on stability and dielectric strength of transformer oil-based TiO2 nanofluids," *Nanoscale Research Letters*, vol. 11, no. 1, p. 515, 2016.
[16] J. G. Hwang, F. O’Sullivan, M. Zahn, O. Hjortstam, L. A. A. Pettersson, and R. Liu, "Modeling of streamer propagation in transformer oil-based nanofluids," in *Annual Report - Conference on Electrical Insulation and Dielectric Phenomena*, Quebec, QC, Canada, 2008.
[17] M. Z. H. Makmud, H. A. Illias, and C. Y. Chee, "Partial discharge behaviour within palm oil-based Fe3O4 nanofluids under AC voltage," *IOP Conference Series: Materials Science and Engineering*, vol. 210, no. 1, article 012034, 2017.
[18] J. Zhang, F. Wang, J. Li, H. Ran, and D. Huang, "Influence of copper particles on breakdown voltage and frequency-dependent dielectric property of vegetable insulating oil," *Energies*, vol. 10, no. 7, p. 938, 2017.
[19] A. Cavallini, R. Karthik, and F. Negri, "The effect of magnetite, graphene oxide and silicone oxide nanoparticles on dielectric withstand characteristics of mineral oil," *IEEE
Transactions on Dielectrics and Electrical Insulation, vol. 22, no. 5, pp. 2592–2600, 2015.

[20] R. Karthik, T. S. R. Raja, and R. Madavan, "Enhancement of critical characteristics of transformer oil using nanomaterials," Arabian Journal for Science and Engineering, vol. 38, no. 10, pp. 2725–2733, 2013.

[21] N. Ranjan, R. A. R. Prasath, and N. K. Roy, "Ageing performance on mineral oil using ZnO nanofluids," International Journal of Innovations in Engineering and Technology, vol. 6, no. 3, 2016.

[22] J. A. Mergos, M. D. Athanasopoulos, T. G. Argyropoulos, and C. T. Dervos, "Dielectric properties of nanoparticle dispersions in paraffin oil," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 19, no. 5, pp. 1502–1507, 2012.

[23] Y. Du, Y. Lv, C. Li et al., "Effect of semiconductive nanoparticles on insulating performances of transformer oil," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 19, no. 3, pp. 770–776, 2012.

[24] Y. Zhong, Y. Lv, C. Li et al., "Insulating properties and charge characteristics of natural ester fluid modified by TiO2 semiconductive nanoparticles," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 20, no. 1, pp. 135–140, 2013.

[25] Y. Du, Y. Lv, C. Li et al., "Effect of electron shallow trap on breakdown performance of transformer oil-based nanofluids," Journal of Applied Physics, vol. 110, no. 10, p. 104104, 2011.

[26] T. Takada, Y. Hayase, Y. Tanaka, and T. Okamoto, "Space charge trapping in electrical potential well caused by permanent and induced dipoles," in 2007 Annual Report-Conference on Electrical Insulation and Dielectric Phenomena, pp. 417–420, Vancouver, BC, Canada, October 2007.

[27] K. Raj, B. Moskowitz, and S. Tsuda, "New commercial trends of nanostructured ferrofluids," Indian Journal of Engineering and Materials Sciences, vol. 11, no. 4, pp. 241–252, 2004.

[28] P. Kopćanski, L. Tomcô, K. Marton, M. Koneracká, M. Timko, and J. Potočová, "The DC dielectric breakdown strength of magnetic fluids based on transformer oil," Journal of Magnetism and Magnetic Materials, vol. 289, pp. 415–418, 2005.

[29] P. Kopčansky, K. Marton, L. Tomcô et al., "The DC- and AC-dielectric breakdown strength of magnetic fluids based on transformer oil," Magneto Hydrodynamics, vol. 41, no. 4, pp. 391–395, 2005.

[30] Q. Wang, M. Rafiq, Y. Lv, C. Li, and K. Yi, "Preparation of three types of transformer oil-based nanofluids and comparative study on the effect of nanoparticle concentrations on insulating property of transformer oil," Journal of Nanotechnology, vol. 2016, Article ID 5802753, 6 pages, 2016.

[31] P. Sun, W. Sima, D. Zhang, Q. Chen, L. Ye, and J. Chen, "Effects of impulse waveform parameters on the breakdown characteristics of nano-TiO2 modified transformer oil," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 25, no. 5, pp. 1651–1659, 2018.

[32] G. D. Peppas, A. Bakandritos, V. P. Charalampakos et al., "Ultrastable natural ester-based nanofluids for high voltage insulation applications," ACS Applied Materials & Interfaces, vol. 8, no. 38, pp. 25202–25209, 2016.

[33] M. Taró, D. Shill, A. K. Das, and S. Chatterjee, "Experimental investigation of transformer oil based nanofluids for applications in distribution transformers," in 2017 3rd International Conference on Condition Assessment Techniques in Electrical Systems (CATCON), pp. 367–370, Rupnagar, India, 2017.

[34] L. Coco-Enríquez, J. Muñoz-Antón, and J. M. Martinez-Val, "New text comparison between CO2 and other supercritical working fluids (ethane, Xe, CH4 and N2) in line- focusing solar power plants coupled to supercritical Brayton power cycles," International Journal of Hydrogen Energy, vol. 42, no. 28, pp. 17611–17631, 2017.

[35] Y. Hwang, J. K. Lee, J. K. Lee et al., "Production and dispersion stability of nanoparticles in nanofluids," Powder Technology, vol. 186, no. 2, pp. 145–153, 2008.

[36] D. K. Lee and Y. S. Kang, "Synthesis of silver nanocrystals by a new thermal decomposition method and their characterization," ETRI Journal, vol. 26, no. 3, pp. 252–256, 2004.

[37] S. U. Son, I. K. Park, J. Park, and T. Hyeon, "Synthesis of CuO coated Cu nanoparticles and their successful applications to Ullmann-type amination coupling reactions of aryl chlorides," Chemical Communications, vol. 10, no. 7, pp. 778-779, 2004.

[38] K. Mallick, M. J. Witcomb, and M. S. Scurrrell, "Polymer stabilized silver nanoparticles: a photochemical synthesis route," Journal of Materials Science, vol. 39, no. 14, pp. 4459–4463, 2004.

[39] D. L. Van Hyning, W. G. Klempner, and C. F. Zukoski, "Silver nanoparticle formation: predictions and verification of the aggregate growth model," Langmuir, vol. 17, no. 11, pp. 3128–3135, 2001.

[40] I. Sondi, D. V. Goia, and E. Matijevič, "Preparation of highly concentrated stable dispersions of uniform silver nanoparticles," Journal of Colloid and Interface Science, vol. 260, no. 1, pp. 75–81, 2003.

[41] H. Ma, B. Yin, S. Wang et al., "Synthesis of silver and gold nanoparticles by a novel electrochemical method," ChemPhysChem, vol. 5, no. 1, pp. 68–75, 2004.

[42] B. Nikoobakht, Z. L. Wang, and M. A. El-Sayed, "Self-assembly of gold nanorods," The Journal of Physical Chemistry. B, vol. 104, no. 36, pp. 8635–8640, 2000.

[43] Y. Li, J. Zhou, S. Tung, E. Schneider, and S. Xi, "A review on development of nanofluid preparation and characterization," Powder Technology, vol. 196, no. 2, pp. 89–101, 2009.

[44] H. Babar, M. Sajid, and H. Ali, "Viscosity of hybrid nanofluids: a critical review," Thermal Science, vol. 23, no. 3 Part B, pp. 1713–1754, 2019.

[45] P. Keblinski, S. R. Phillpot, S. U. S. Choi, and J. A. Eastman, "Mechanisms of heat flow in suspensions of nano-sized particles (nanofluids)," International Journal of Heat and Mass Transfer, vol. 45, no. 4, pp. 855–863, 2002.

[46] RUS Research Nanomaterials, The Methods of Nanoparticle DispersionUS Research Nanomaterials, Inc.Available: https://www.us-nano.com/nanoparticles___nanopowders___dispersion_methods.

[47] Y. Z. Lv, X. X. Li, Y. F. Du, P. C. Wang, and C. R. Li, "Preparation and breakdown strength of TiO2 fluids based on transformer oil," in 2010 Annual Report Conference on Electrical Insulation and Dielectric Phenomena, pp. 1–3, West Lafayette, IN, USA, 2010.

[48] B. Buonomo, O. Manca, L. Marinelli, and S. Nardini, "Effect of temperature and sonicattion time on nanofluid thermal conductivity measurements by nano-flash method," Applied Thermal Engineering, vol. 91, pp. 181–190, 2015.
[49] M. Noroozi, S. Radiman, and A. Zakaria, “Influence of sonication on the stability and thermal properties of Al2O3 nanofluids,” Journal of Nanomaterials, vol. 2014, Article ID 612417, 10 pages, 2014.

[50] C. Ying, Z. Zhaoqie, and Z. Ganghua, “Effects of different tissue loads on high power ultrasonic surgery scalpel,” Ultrasound in Medicine & Biology, vol. 32, no. 3, pp. 415–420, 2006.

[51] L. P. Fallavena, F. H. F. Antunes, J. S. Alves et al., “Ultrasonic technology and molecular sieves improve the thermodynamically controlled esterification of butyric acid mediated by immobilized lipase from Rhizomucor miehei,” RSC Advances, vol. 4, no. 17, pp. 8675–8681, 2014.

[52] M. Kole and T. K. Dey, “Effect of prolonged ultrasonication on the thermal conductivity of ZnO-ethylene glycol nanofluids,” Thermochimica Acta, vol. 535, pp. 58–65, 2012.

[53] E.-Q. Xia, X.-X. Ai, S.-Y. Zang, T.-T. Guan, X.-R. Xu, and C. Ying, Z. Zhaoying, and Z. Ganghua, “S. Sun, H. Zeng, D. B. Robinson et al., “Magnetic structure of magnetite/oleic acid/brine ferrofluids by small-angle neutron scattering,” Journal of Magnetism and Magnetic Materials, vol. 270, no. 3, pp. 371–379, 2004.

[54] P. Krajnik, F. Pusavec, and A. Rashid, “Enhancement and comparison of nanofluid performance of plasma treated mineral oil-based nanofluids,” IEEE Transactions on Dielectrics and Electrical Insulation, vol. 22, no. 5, pp. 2463–2472, 2015.

[55] H. Jin, Dielectric Strength and Thermal Conductivity of Mineral Oil Based Nanofluids, Delft University, 2015.

[56] B. Du, J. Li, B. M. Wang, and Z. T. Zhang, “Preparation and breakdown strength of Fe3O4 nanofluid based on transformer oil,” in 2012 International Conference on High Voltage Engineering and Application, pp. 311–313, Shanghai, China, 2012.

[57] V. P. Charlampakos, A. Bakandritsos, G. D. Peppas, E. C. Pyrgioti, and I. F. Konos, “A comparative study of natural ester based nanofluids with Fe3O4 and SiO2 nanoparticles,” in 2017 IEEE 19th International Conference on Dielectric Liquids (ICDL), pp. 1–4, Manchester, UK, June 2017.

[58] E. V. Timofeeva, M. R. Moravek, and D. Singh, “Improving the heat transfer efficiency of synthetic oil with silica nanoparticles,” Journal of Colloid and Interface Science, vol. 364, no. 1, pp. 71–79, 2011.

[59] M. V. Avdeev, M. Balasoiu, V. L. Aksenov et al., “On the magnetic structure of magnetite/oleic acid/benzene ferrofluids,” Physics Letters A, vol. 380, no. 4, pp. 604–608, 2016.

[60] J. Li, B. Du, F. Wang, W. Yao, and S. Yao, “The effect of nanofluid surfactant polarization on trapping depth of vegetable insulating oil-based nanofluids,” IEEE Transactions on Magnetics, vol. 49, no. 11, pp. 5499–5497, 2013.

[61] R. Karthik, F. Negri, and A. Cavallini, “Influence of ageing on dielectric characteristics of silicone dioxide, tin oxide and ferro nanofluids based mineral oil,” in 2016 2nd International Conference on Advances in Electrical, Electronics, Information, Communication and Bio-Informatics (AEEICB), pp. 40–43, Chennai, India, 2016.

[62] I. H. Zakaria, M. H. Ahmad, Z. Abdul-Malek, M. A. B. Sidik, Z. Nawawi, and M. I. Jambak, “AC breakdown strength performance of plasma treated mineral oil-based nanofluids,” in 2017 International Conference on Electrical Engineering and Computer Science (ICECOS), pp. 333–337, Palembang, Indonesia, 2017.

[63] S. S. Dessouky, S. A. M. Abdelwahab, and M. Shaban, “Effect of titanium oxide nanoparticles on breakdown strength of transformer oil,” in 2017 Nineteenth International Middle East Power Systems Conference (MEPCON), pp. 538–542, Cairo, Egypt, 2017.

[64] G. Shukla and H. Aiyer, “Enhancement of breakdown strength of transformer oil using functionalized nanodiamonds,” in IEEE Transactions on Dielectrics and Electrical Insulation, vol. 22, no. 4, pp. 2185–2190, Mumbai, India, 2015.

[65] P. Krajnik, F. Pusavec, and A. Rashid, “Nanofluids: properties, applications and sustainability aspects in materials processing technologies,” in Advances in Sustainable Manufacturing, Springer, Berlin, Heidelberg, 2011.

[66] A. Raymon, S. Sukhithaban, C. Cinthal, R. Subramaniaraja, and M. Yuvaraj, “Enhancement and comparison of nanofluid breakdown strength,” IEEE Transactions on Dielectrics and Electrical Insulation, vol. 23, no. 2, pp. 892–900, 2016.

[67] A. Thabet, M. Allam, and S. A. Shaaban, “Investigation on enhancing breakdown voltages of transformer oil nanofluids.
using multi-nanoparticles technique,” *IET Generation, Transmission & Distribution*, vol. 12, no. 5, pp. 1171–1176, 2018.

[79] R. A. R. Prasath, P. Thomas, A. P. Cruz, S. N. Mahato, and N. K. Roy, “Ageing analysis of mineral insulating oils using CCTO nanofluids,” in 2015 International Conference on Energy, Power and Environment: Towards Sustainable Growth (ICEPE), pp. 1–7, Shillong, India, 2015.

[80] M. Chiesa and S. K. Das, “Experimental investigation of the dielectric and cooling performance of colloidal suspensions in insulating media,” *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, vol. 335, no. 1–3, pp. 88–97, 2009.

[81] F. O’Sullivan, J. G. Hwang, M. Zahn et al., “A model for the initiation and propagation of positive streamers in transformer oil,” in Conference record of the 2008 IEEE international symposium on electrical insulation, pp. 210–214, Vancouver, BC, Canada, 2008.

[82] J. G. Hwang, M. Zhan, F. M. O’Sullivan, L. A. A. Petterson, and R. Liu, “Electron scavenging by conductive nanoparticles in oil insulated power transformers,” in *Electrostatics Joint Conference*, pp. 1–12, Boston, 2009.

[83] J. G. Hwang, M. Zahn, F. M. O’Sullivan, L. A. A. Petterson, O. Hjortstam, and R. Liu, “Effects of nanoparticle charging on streamer development in transformer oil-based nano-fluids,” *Journal of Applied Physics*, vol. 107, no. 1, article 014310, 2010.

[84] F. M. O’Sullivan, A Model for the Initiation and Propagation of Electrical Streamers in Transformer Oil and Transformer Oil Based Nano fluids, Massachusetts Institute of Technology, 2007.

[85] V. Segal, A. Hjortsberg, A. Rabinovich, D. Nattrass, and F. M. O’ Sullivan, J. G. Hwang, M. Zahn et al., “A model for the initiation and propagation of positive streamers in transformer oil,” in Conference record of the 2008 IEEE international symposium on electrical insulation, pp. 210–214, Vancouver, BC, Canada, 2008.

[86] P. Thomas and N. E. Hudedmani, “The effect of BaO.85CaO.15ZrO.1TiO.9O3 (BCZT) nanoparticles on the critical parameters of synthetic ester based nano fluids,” in 2018 IEEE 2nd International Conference on Dielectrics (ICD), vol. 3, pp. 5–8, Budapest, Hungary, July 2018.

[87] G. D. P. Mahidhar, R. Sarathi, N. Taylor, and H. Edin, “Study on performance of silica nanoparticle dispersed synthetic ester oil under AC and DC voltages,” *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 25, no. 5, pp. 1958–1966, 2018.

[88] J. S. Chahal, “Investigations on mustard oil for its suitability as insulating fluid in transformers,” 2017 IEEE 19th International Conference on Dielectric Liquids (ICDL), 2017, pp. 29–31, Manchester, UK, June 2017.

[89] C. F. Diego, A. Santisteban, and F. O. Fernández, “Effect of TiO2 nanoparticles on the performance of a natural ester dielectric fluid,” 2017 IEEE Electrical Insulation Conference (EIC), 2017, pp. 11–14, Baltimore, MD, USA, June 2017.

[90] P. Thomas and N. E. Hudedmani, “AC breakdown voltage characteristics of synthetic ester based egg shell nano fluids,” in 2017 3rd International Conference on Condition Assessment Techniques in Electrical Systems (CATCON), pp. 112–115, Rupnagar, India, November 2017.

[91] M. S. Mohamad, H. Zainuddin, S. A. Ghani, and I. S. Chauril, “Breakdown and partial discharge performance of palm fatty acid ester (PFAE) oil-based Fe3O4 nano-fluids,” in 2016 IEEE International Conference on Power and Energy (PCon), Melaka, Malaysia, November 2016.

[92] S. F. M. Nor, N. Azis, J. Jasni et al., “A study on the AC breakdown voltages of as-received palm oil and coconut oil under presence of TiO2,” in 2015 IEEE Conference on Energy Conversion (CENC0), pp. 354–357, Johor Bahru, Malaysia, 2015.

[93] J. Li, Z. Zhang, P. Zou, S. Grzybowski, and M. Zahn, “Preparation of a vegetable oil-based nano-fluid and investigation of its breakdown and dielectric properties,” *IEEE Electrical Insulation Magazine*, vol. 28, no. 5, pp. 43–50, 2012.

[94] C. Olmo, I. Fernandez, F. Ortiz, C. J. Renedo, and S. Perez, “Dielectric properties enhancement of vegetable transformer oil with TiO2, CuO and ZnO nanoparticles,” *The International Conference on Renewable Energies and Power Quality (ICREPEQ’20)*, vol. 1, no. 16, pp. 623–627, 2018.
104] V. A. Primo, D. Pérez, B. García, and J. C. Burgos, “Analysing the impact of moisture on the AC breakdown voltage of Fe$_3$O$_4$ based nanodielectric fluids,” in 2018 IEEE 2nd International Conference on Dielectrics (ICD),, 3 pages, Budapest, Hungary, July 2018.

105] D. H. Fontes, G. Ribatski, and E. P. Bandarra Filho, “Experimental evaluation of thermal conductivity, viscosity and breakdown voltage AC of nanofluids of carbon nanotubes and diamond in transformer oil,” Diamond and Related Materials, vol. 58, pp. 115–121, 2015.

106] Q. Liu and Z. Wang, “Streamer characteristic and breakdown in synthetic and natural ester transformer liquids under standard lightning impulse voltage,” IEEE Transactions on Dielectrics and Electrical Insulation, vol. 18, no. 1, pp. 285–294, 2011.

107] IEC60897, Methods for the Determination of the Lightning Breakdown Voltage of Insulating Liquids, p. 27, 1987.

108] M. Rafiq, C. Li, Y. Lv, K. Yi, and S. Hussain, “Preparation and study of breakdown features of transformer oil based magnetic nanofluids,” in 2017 International Conference on Electrical Engineering (ICEE), pp. 17–20, Lahore, Pakistan, March 2017.

109] D. Liu, Y. Zhou, Y. Yang, L. Zhang, and F. Jin, “Characterization of high performance AlN nanoparticle-based transformer oil nanofluids,” IEEE Transactions on Dielectrics and Electrical Insulation, vol. 23, no. 5, pp. 2757–2767, 2016.

110] Y. Lv, W. Wang, K. Ma et al., “Nanoparticle effect on dielectric breakdown strength of transformer oil-based nanofluids,” in 2013 Annual Report Conference on Electrical Insulation and Dielectric Phenomena, pp. 680–682, Shenzhen, China, October 2013.

111] M. Rafiq, Y. Lv, C. Li, and K. Yi, “Effect of different nanoparticle types on breakdown strength of transformer oil,” in 2016 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), pp. 436–440, Toronto, ON, Canada, October 2016.

112] S. Potivejkul, K. Jariyanurat, N. Pattanadech, and Y. Lv, M. Rafiq, Y. L., “Preparation and study of breakdown features of transformer oil based magnetic nanofluids,” in 2017 International Conference on Electrical Engineering (ICEE), pp. 17–20, Lahore, Pakistan, March 2017.

113] R. Liu, L. A. A. Pettersson, T. Auletta, and O. Hjortstam, “Fundamental research on the application of nano dielectrics to transformers,” in 2011 Annual Report Conference on Electrical Insulation and Dielectric Phenomena, pp. 423–427, Cancun, Mexico, October 2011.

114] Y. Lv, M. Rafiq, C. Li, and B. Shan, “Study of dielectric breakdown performance of transformer oil based magnetic nanofluids,” Energies, vol. 10, no. 7, p. 1025, 2017.

115] W. X. Sima, X. F. Cao, Q. Yang, H. Song, and J. Shi, “Preparation of three transformer oil-based nanofluids and comparison of their impulse breakdown characteristics,” Nanoscience and Nanotechnology Letters, vol. 6, no. 3, pp. 250–256, 2014.

116] M. M. Hirschier, Electrical Insulating Materials: International Issues (Online ed.), ASTM, West Conshohocken, 2000.

117] ASTM D5222-16, Standard Specification for High Fire-Point Mineral Electrical Insulating Oil, vol. 10.03, West Conshohocken, PA, 2016.

118] D. E. A. Mansour and A. M. Elsaeed, “Heat transfer properties of transformer oil-based nanofluids filled with Al$_2$O$_3$ nanoparticles,” in 2014 IEEE International Conference on Power and Energy (PECon), pp. 123–127, Kuching, Malaysia, December 2014.

119] D. A. Mansour and R. F. Emara, “Heat transport characteristics of oil-based nanofluids with different types of nanoparticles,” 2017 IEEE 19th International Conference on Dielectric Liquids (ICDL), pp. 29–32, Manchester, UK, June 2017.

120] A. Beheshti, M. Shanbedi, and S. Z. Heris, “Heat transfer and rheological properties of transformer oil-oxidized MWNT nanofluid,” Journal of Thermal Analysis and Calorimetry, vol. 118, no. 3, pp. 1451–1460, 2014.

121] R. T. A. R. Prasath, S. N. Mahato, N. K. Roy, and P. Thomas, “Dielectric and thermal conductivity studies on synthetic ester based SiO$_2$ nanofluids,” in 2017 3rd International Conference on Condition Assessment Techniques in Electrical Systems (CATCON), pp. 7–10, Rupnagar, India, November 2017.

122] R. T. A. R. Prasath, N. K. Roy, S. N. Mahato, and P. Thomas, “Mineral oil based high permittivity CaCu$_3$Ti$_4$O$_{12}$ (CCTO) nanofluids for power transformer application,” IEEE Transactions on Dielectrics and Electrical Insulation, vol. 24, no. 4, pp. 2344–2353, 2017.

123] M. I. Hasan, “Using the transformer oil-based nanofluid for cooling of power distribution transformer,” International Journal of Energy and Environment, vol. 8, no. 3, pp. 229–238, 2017.

124] G.-Y. Jeong, S. P. Jang, H.-Y. Lee, J.-C. Lee, S. Choi, and S.-H. Lee, “Magnetic-thermal-fluidic analysis for cooling performance of magnetic nanofluids comparing with transformer oil and air by using fully coupled finite element method,” IEEE Transactions on Magnetics, vol. 49, no. 5, pp. 1865–1868, 2013.

125] A. Naddaf and S. Zeinali Heris, “Experimental study on thermal conductivity and electrical conductivity of diesel oil-based nanofluids of graphene nanoplatelets and carbon nanotubes,” International Communications in Heat and Mass Transfer, vol. 95, pp. 116–122, 2018.

126] A. A. Abdul-aleem, “Experimental evaluation of creeping flashover at nanofilled oil/pressboard interface,” in 2017 Nineteenth International Middle East Power Systems Conference (MEPCON), pp. 19–21, Cairo, Egypt, December 2017.

127] A. Thabet, S. A. Shaaban, and M. Allam, “Enhancing dielectric constant of transformer oils using multi-nanoparticles technique under thermal conditions,” in 2016 Eighteenth International Middle East Power Systems Conference (MEPCON), pp. 220–225, Cairo, Egypt, December 2016.

128] M. Maharana, N. Baruah, A. Nanda, and S. K. Nayak, “Thermoelectrically enhanced nanofluid is a suitable replacement for transformer oil,” in 2018 IEEE Electrical Insulation Conference (EIC), vol. 6, pp. 204–207, San Antonio, TX, USA, June 2018.

129] S. C. Pugazhendhi, “Experimental evaluation on dielectric and thermal characteristics of nano filler added transformer oil,” in 2012 International Conference on High Voltage Engineering and Application, pp. 207–210, Shanghai, China, September 2012.

130] D.-E. A. Mansour, E. M. Shaalan, S. A. Ward, A. Z. El Dein, H. S. Karaman, and H. M. Ahmed, “Multiple nanoparticles for improvement of thermal and dielectric properties of oil nanofluids,” IET Science, Measurement and Technology, vol. 13, no. 7, pp. 968–974, 2019.
[131] A. Józefczak, “Study of low concentrated ionic ferrofluid stability in magnetic field by ultrasound spectroscopy,” *Journal of Magnetism and Magnetic Materials*, vol. 321, no. 14, pp. 2225–2231, 2009.

[132] A. Ghadimi and I. H. Metselaar, “The influence of surfactant and ultrasonic processing on improvement of stability, thermal conductivity and viscosity of titania nanofluid,” *Experimental Thermal and Fluid Science*, vol. 51, pp. 1–9, 2013.

[133] Y. He, Y. Jin, H. Chen, Y. Ding, D. Cang, and H. Lu, “Heat transfer and flow behaviour of aqueous suspensions of TiO$_2$ nanoparticles (nanofluids) flowing upward through a vertical pipe,” *International Journal of Heat and Mass Transfer*, vol. 50, no. 11–12, pp. 2272–2281, 2007.

[134] G. A. Longo and C. Zilio, “Experimental measurement of thermophysical properties of oxide-water nano-fluids down to ice-point,” *Experimental Thermal and Fluid Science*, vol. 35, no. 7, pp. 1313–1324, 2011.

[135] J. Kudelcik, P. Bury, P. Kopcansky, and M. Timko, “Dielectric breakdown in mineral oil ITO 100 based magnetic fluid,” *Physics Procedia*, vol. 9, pp. 78–81, 2010.

[136] F. Herchl, K. Marton, L. Tomčo et al., “Breakdown and partial discharges in magnetic liquids,” *Journal of Physics: Condensed Matter*, vol. 20, no. 20, p. 204110, 2008.

[137] P. P. C. Sartoratto, A. V. S. Neto, E. C. D. Lima, A. L. C. Rodrigues De Sá, and P. C. Morais, “Preparation and electrical properties of oil-based magnetic fluids,” *Journal of Applied Physics*, vol. 97, no. 10, p. 10Q917, 2005.