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Review Article

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

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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 overloading, high operating temperature, lightning or line surges, and improper lubrication. These aspects require careful consideration and are a huge responsibility of the person in charge for the operation and maintenance of the transformer.

Globally, there are two types of leading transformers specially designed to transfer the electrical energy from one electric circuit to another. They include oil-filled-type and dry-type transformers. However, the oil-filled-type transformer is the most common type used in electricity distribution systems [2]. Oil-filled transformers as indicative of their name are generally immersed with liquid known as transformer oil. The oil acts as an insulator and a coolant agent, making the transformer highly suitable for outdoor applications while helping to preserve the core and winding. Furthermore, the oil helps to prevent direct contact with atmospheric 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 (Fe_3O_4). 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 TiO_2 nanoparticles and TiO_2 nanofluids by using the TEM and HRTEM equipment as shown in Figure 2 [15]. It can be seen in Figure 2(a) that the TiO_2 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 (Fe_2NiO_4), ferric oxide (Fe_2O_3), 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 (Al_2O_3), and titania (TiO_2) also contribute to the enhancement of dielectric strength of transformer oil [25–27].

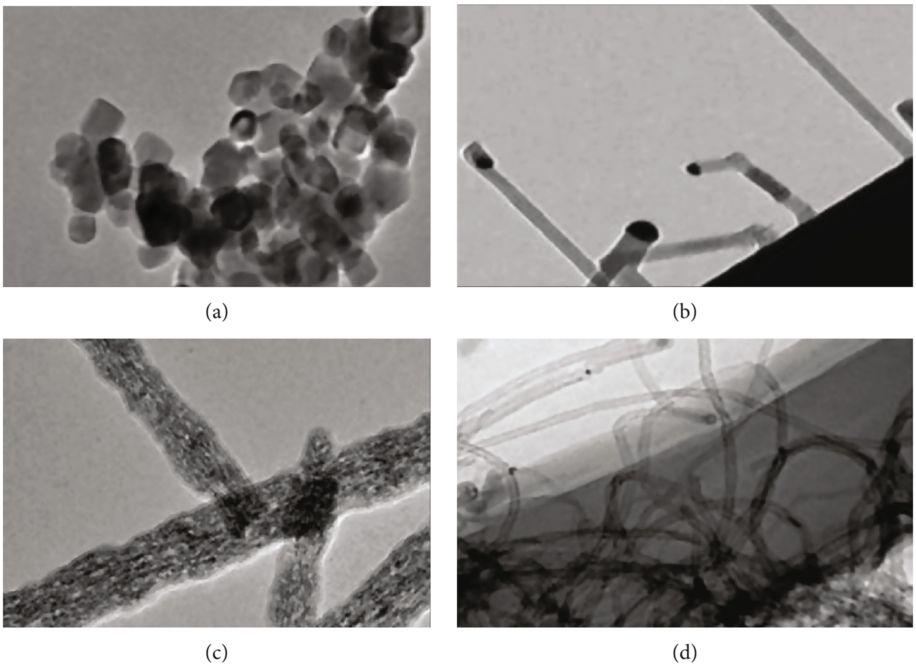


Figure 1: TEM image of (a) zinc oxide (ZnO) with 50 nm diameter [8], (b) silicon nanowires with 200 nm diameter [9], (c) titanium dioxide (TiO_2) nanofibers with 50 nm diameter [10], and (d) multiwalled-carbon nanotubes (MWCNT) with 15 nm diameter [11].

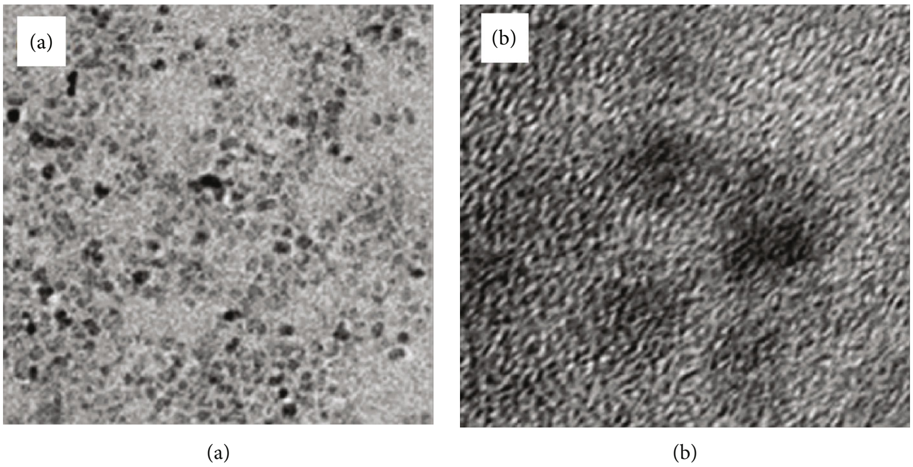


Figure 2: Morphology of (a) TiO_2 nanoparticles and (b) TiO_2 nanofluids [15].

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 nanofluids. 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_3O_4 and 20% concentrations for Al_2O_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.

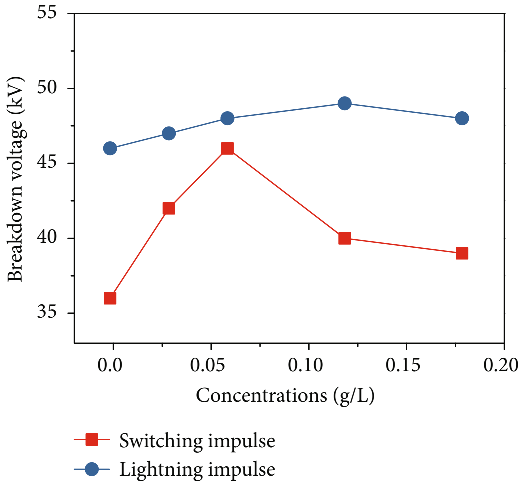


Figure 3: The impulse breakdown voltages of the TiO_2 nanofluid at various concentrations [31].

Furthermore, in another report, Peppas et al. [32] investigated the magnetic iron oxide nanocrystal (MION) powder in two conditions: with oleic acid surface modification and with an oleate-coated colloidal. In brief, the authors measured the breakdown voltage with a function of six weight percentages (0.004% to 0.014%). According to the results, a similar pattern was observed as found by other researchers, where the breakdown voltage tends to increase until 0.08% for the MION nanofluid with oleic acid and 0.012% for the oleate-coated MION nanofluid. The reduction of breakdown performance is mainly attributed to the agglomeration that exists in nanofluids at higher volume concentrations. However, Taro et al. found that SiO_2 nanofluids with a diameter of 30 nm with concentrations ranging from 0.1 to 1% volume fraction were successfully stable where no agglomeration and sedimentation issues were noticed [33]. It can be computed that a certain value of concentrations is impactful for the optimization of high lever power transformers and contributes to the mechanism that could improve electrical and insulation performance. Furthermore, methods on dispersing nanomaterials in liquid also play a significant role in order to produce a stable-uniform solution.

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].

Table 1: Methods used to produce nanofluids [35].

Name of method	Method of producing nanofluid
One-step method	Magnetron sputtering Direct evaporation Chemical precipitation Chemical vapor condensation
Two-step method	Stirrer Ultrasonic bath Ultrasonic disruptor High-pressure homogenizer

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 will be applied to the sample. However, there are differences in terms of effectiveness, efficiency, process capabilities, and stability between the dispersion techniques. The ultrasound sonication probe is much suitable for most of the study due to its capability to apply more energy density for small volumes of samples [47–49]. The homogeneity of nanofluids possibly depends on the time, 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

Table 2: Dispersion tools for nanofluids [46].

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 Can be difficult to clean; contamination likely
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 Cheap/affordable	Inefficient Rarely results in deagglomeration and is often employed in order to improve homogeneity of dispersion
High-speed homogenizer	Use of a rotor & stator generator probe; the rotor acts as a centrifugal pump to recirculate the liquid and suspends the solids through the generator	Suitable for large liquid samples up to 2500 mL	Potential metal contamination
High-pressure homogenizer	Shear and cavitation provided via increase in the velocity of pressurized liquid streams in micro channels	Highly efficient	Nanoparticle architecture can be altered; increase of temperature in the dispersion likely Expensive
Ultrasound sonication bath	Use ultrasound waves and cavitation in a bath	Cheap/affordable	Both formats less effective (less shear) compared to probe format
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	Probe tip disintegration can contaminate samples Can alter nanoparticle architecture; temperature increase (even for a few minutes) in dispersion highly likely

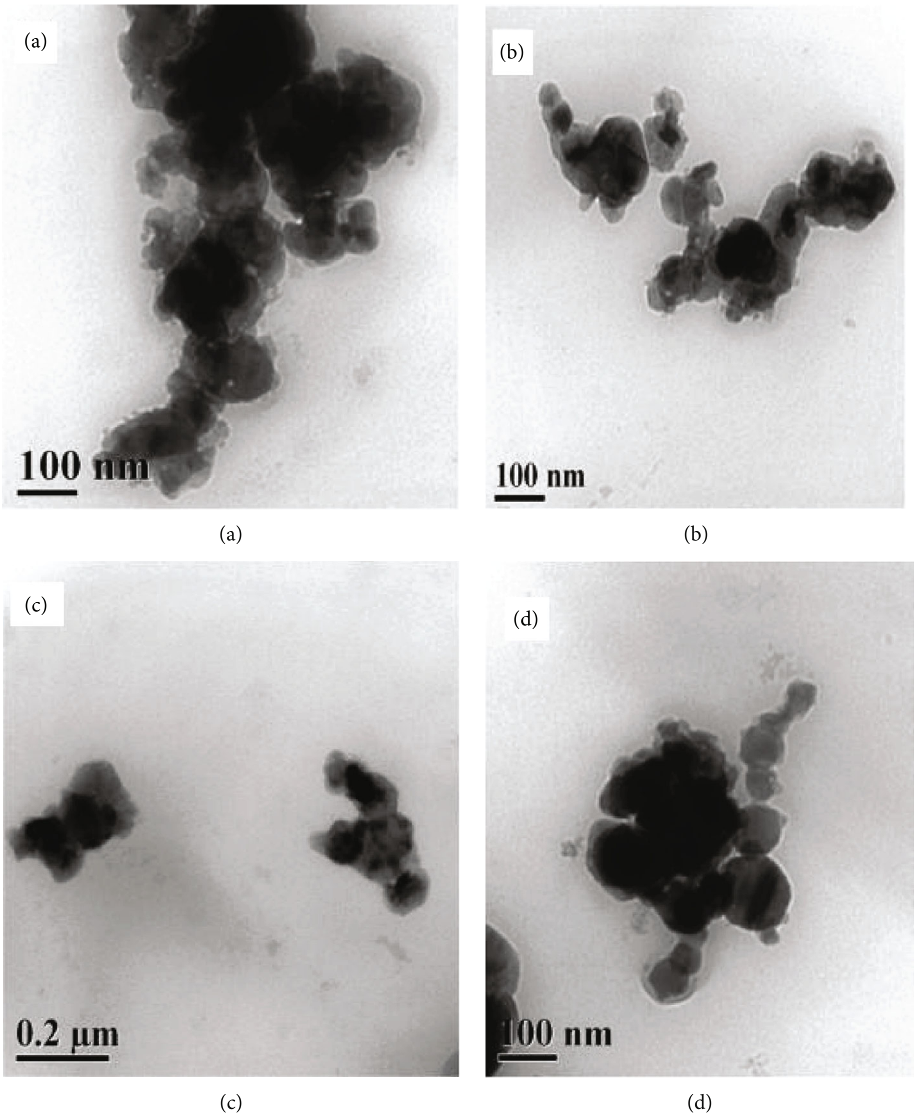
illustrated in Figure 4. Dynamic light scattering (DLS) has been used in the study to estimate the size of ZnO nanoparticles in ethylene glycol (EG) against the sonication duration as shown in Figure 5. It is seen that the nanoparticle cluster size decreases rapidly between 4 and 60 hours, and the cluster 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, Katiyar 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 SiO_2 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



(a) (b) (c) (d)

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

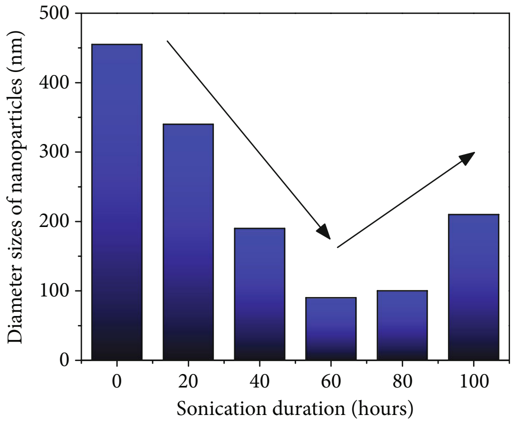


Figure 5: The cluster size of the ZnO nanofluid at different sonication durations based on Kole and Dey's investigation [52].

strongly dependent on the sample preparation, which plays a significant role in avoiding agglomeration and instability of the nanofluid.

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:

Table 3: Sonication method.

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 Silane coupling agent Z6011	30 minutes	2 hours
[66]	Fe_3O_4	Mineral oil	Hexadecyltrimethylammonium bromide	—	2 hours
[67]	Fe_2O_3 (50 nm) SiO_2 (12 nm)	FR3	Oleic acid	20 minutes	2 hours
[68]	SiO_2 (15 nm)	Synthetic oil, Therminol 66 (TH66)	Benzethonium chloride (BZC) Benzalkonium chloride (BAC) CTAB	—	50 minutes

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_2O_3), semiconductive nanoparticles: titanium dioxide (TiO_2) or cadmium sulphite (Cds), and nonconductive magnetic nanoparticle: iron(III) oxide (Fe_2O_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. 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_3O_4, 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_3O_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_2O_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_3O_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

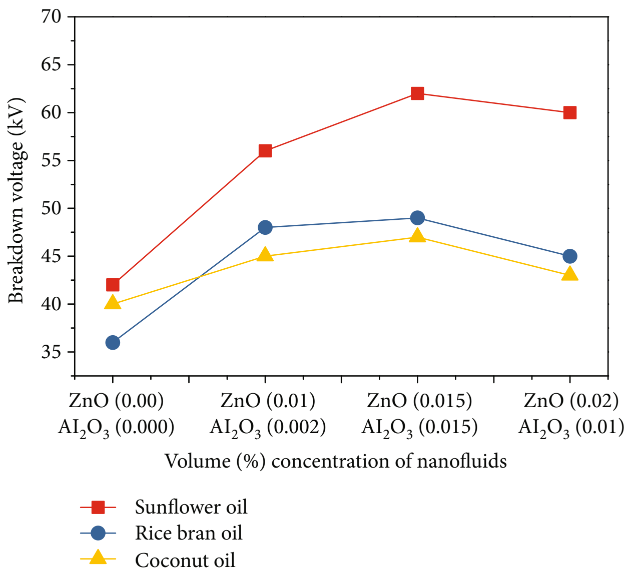


Figure 6: Electrical breakdown voltages of nanofluid-based natural ester oils (sunflower, rice bran, and coconut oil) [88].

Table 4: List of AC breakdown nanofluid-based mineral oils.

Ref	Nanomaterial	Diameter size (nm)	Improvement of breakdown (%)
[90]	ZrO_2	30	+202.60
[91]	TiO_2	50	+21.80
[92]	Al_2O_3	13	+11.50
[93]	Hybrid-barium titanate	50	+45.00
[72]	Ferrofluid (FF)	10	+25.53
	Tin oxide (TO)	50	+23.40
	SiO_2	8-20	+19.15
[61]	Anatase TiO_2	15-20	+88.00
	Rutile TiO_2	20-30	+64.00
[94]	CNT	<8	+73.70

Table 5: List of AC breakdown nanofluid based-natural ester oils.

Ref.	Nanomaterial	Diameter size (nm)	Improvement of breakdown (%)
[95]	$Ba_{0.85}Ca_{0.15}Zr_{0.1}Ti_{0.9}O_3$	<50	+20.00
[96]	SiO_2	836	+21.55
[97]	Al_2O_3	<50	+47.05
[98]	TiO_2	20	+25.00
[99]	Eggshell nanopowder	—	+38.33
[100]	Fe_3O_4	15-20	+42%
[101]	TiO_2	<21	+20.60
[102]	Fe_3O_4	30	+19.84
[103]	TiO_2	—	+44.00
	ZnO		+32.00
	CuO		+11.00

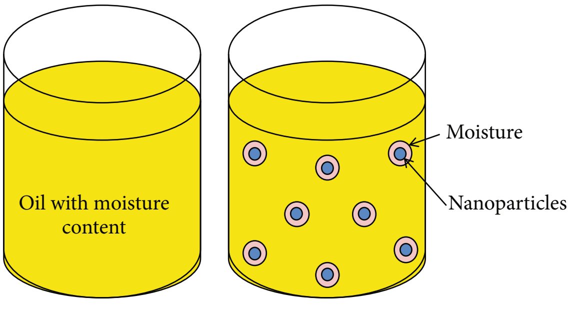
to trap the charges from the ionized oil molecules when exposed to the external electric field. However, Fontes et al. [105] contradict this opinion where a nanomaterial that disperses in mineral transformer oil by using a high-pressure homogenizer decreased substantially with increasing volumetric concentrations. Although these are conflicting arguments, in reference to most researchers' view from all over the world, most nanofluids could possibly enhance the electrical breakdown performance of mineral and natural ester oil at certain concentrations and condition.

It can be computed that the increment of electrical breakdown voltage mainly comes from two main aspects: moisture binding and charge trapping. The enhancement of transformer oil performance does depend not only on the intrinsic properties and interface regions formed between nanoparticles, but also on the potential mobility of charged particles in the nanofluid due to the orientation of the electric field. Streamer inception in the base oil is highly caused by the ability of nanoparticles to capture fast free electrons and convert them into slow-moving negatively charged particles.

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 withstanding 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 contribution 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 ($BaTiO_3$), and titanium dioxide (TiO_2) 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



(a) (b)

Figure 7: Moisture binding at nanoparticle surfaces for (a) mineral oil and (b) nanofluid.

Table 6: Positive and negative impulse breakdown results investigated by some researchers.

Ref.	Type of oil	Nanomaterial	Improvement of positive impulse (%)	Improvement of negative impulse (%)
[108]	MO	Fe_3O_4	+36.68	-14.79
[109]	MO	Aluminium nitride (AIN)	+50.86	+40.06
[110]	MO	Insulating metal oxide	+1.07	—
		Semiconductive metal oxide	+1.08	—
		Conductive metal oxide	+1.01	—
[111]	MO	Al_2O_3	+10.20	—
		Fe_3O_4	+8.20	—
		Si_3N_4	+7.56	—
		ZrO_2	+7.43	—
		AIN	+5.76	—
		TiO_2	+5.12	—
		SiC	+4.4	—
		ZnO	+3.4	—
		SiO_2	+2.9	—
[112]	NEO	TiO_2	+14.00	—
		ZnO	+21.00	
[102]	NEO	Fe_3O_4	+37.35	+11.81
[113]	MO	Fe_3O_4	+13.93	-18.31
		Al_2O_3	-11.61	-13.03
		ZnO	-3.35	-34.42
		SiO_2	-8.77	-0.09

MO: mineral oil; NEO: natural ester oil.

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 $BaTiO_3$ achieves compatible results compared to mineral oil. Other than Muangpratoo et al., Lv et al. [114] also studied on the positive and the negative impulse performance of Fe_3O_4-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]:

$$\tau = \frac{2\varepsilon_1 + \varepsilon_2}{2\sigma_1 + \sigma_2}, \tag{1}$$

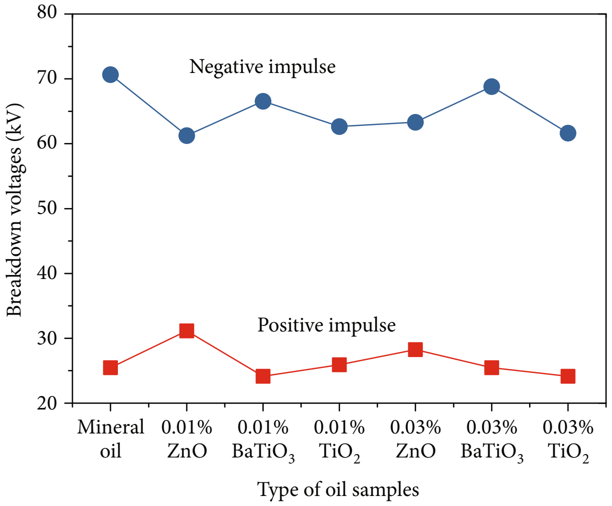


FIGURE 8: Positive and negative impulse breakdown voltages for ZnO, $BaTiO_3$, and TiO_2 nanofluids [63].

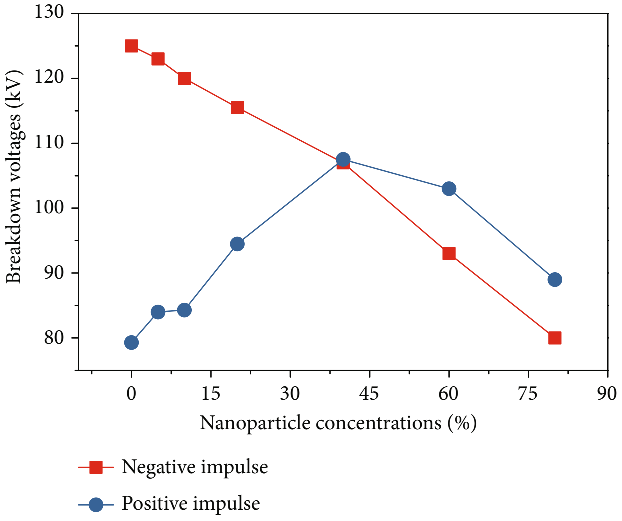


FIGURE 9: Positive and negative impulse breakdown voltage of Fe_3O_4 nanofluids [114].

where ε_1 is the permittivity of pure transformer oil, ε_2 is the permittivity of nanoparticles, σ_1 is the conductivities of pure oil, and σ_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 nanofluids 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.

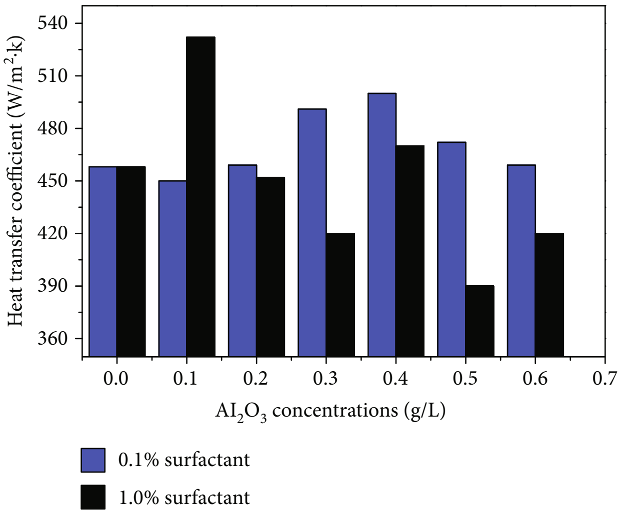


FIGURE 10: Heat transfer coefficient of nanofluids at different concentrations studied by Mansour and Elsaeed [118].

5.3. Thermal Properties. The research on oil-based nanofluids 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_2O_3 nanofluids 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 nanofluids can be calculated as follows:

$$h = \frac{q}{(T_i - T_o)}, \tag{2}$$

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_2O_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 Al_2O_3 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 Fe_3O_4 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 has 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: Al_2O_3, Pb_3O_4, and SiO_2 when dispersed in mineral oil, and found out that the Pb_3O_4 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 TiO_2 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 $10^{11}\Omega$ 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 TiO_2 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 TiO_2 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 adding 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 TiO_2 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 standard for evaluating the stability of nanofluids. In term of electrical conductivity, relative permittivity, and loss factor of nanofluids, some researchers obtained slightly different results comparing to the international standard requirement. These differences not only will affect the electrical stress distribution in transformer, but it also can have a huge implication towards the transformer structure [136, 137]. As there is a need for further clarification, more characterization and testing needs to be done for application of the findings in the industrial world.

7. Conclusion

Applications of nanotechnologies are expected to give impact to virtually every aspect of life and enable dramatic advances in electrical power systems including transformers. This paper reviews recent preparation and performance of nanofluid-based mineral and natural ester oils that have been studied by researchers from all over the world for transformer application. Research work on nanofluids as a high voltage electrical insulating oil has been challenging and provides great opportunities for industries and researchers in the future. Most of the studies proved that nanofluids which serve as a compromising insulation medium could be one of the alternatives for the occurrence of transformer failures. Although there are many significant features that have been reported, there are still many unknowns and improvisation methods that still need to be discovered. However, based on studies, the appropriate types of nanomaterial, amount of concentrations, proper methods and techniques of the synthesis process, and other aspects of nanofluid properties are crucial in order to ensure the optimized properties of nanofluids. Another difficulty encountered in producing nanofluids is nanomaterials' tendency to agglomerate into larger particles, which may result in the decrease of thermal conductivity. Hence, more comprehensive investigation and multidisciplinary research are required to solve the main issue of nanofluids, stability and deagglomeration issues, in the future.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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