

Review

A Critical Overview of the Impact of Nanoparticles in Ester Fluid for Power Transformers

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Abstract: This paper examines the impact of various nanoparticles on ester fluids with a special focus on their usage towards power transformers. The precautionary measures to be considered on the nanofluids such as preparation methodologies with an appropriate surfactant and its stability is well elucidated. The electrical double layer (EDL) formation around the nanoparticles on its diffusion in the insulating fluid is explained by its different layers away from the particle surface. The partial discharge of ester nanofluids with different detection methods is elaborated on its comparison with conventional IEC 60270 measurements. The field configurations on ester-nanofluids govern the breakdown mechanism with variations in the streamer patterns. The equation of relaxation time towards breakdown is valid only when it is lower than the initiation time for streamers. The flow charges induced at the solid/liquid interface inside transformers depends on the structure of the nanofluid and the condition of pressboard/paper insulation. The impact of different concentrations of nanoparticles on ester nanofluids observes a change in its flow behaviour affecting the streaming current. The permittivity of nanofluid depends on the polarization of nanoparticles where the Clausius-Mossotti equation governing this mechanism is explained towards ester-nanofluids. The viscosity of nanofluids observed no significant variation whereas the other physio-chemical properties such as flash point, interfacial tension, and oxidation stability improved depending on the type of nanoparticle. The addition of metal-oxide nanoparticles on ester fluids increases thermal conductivity with different models proposed based on the structure and shape of a nanoparticle. The impact of ageing on nanofluids observes an instability over a longer ageing duration with specific nanoparticles which should be better understood before implementing them in real-time power transformers.

Keywords: ester; nanofluids; stability; double layer; polarization; streamer; streaming current; oxidation; thermal ageing; fire point; heat dissipation



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1. Introduction

The power transformer is one of the important components involved in the transmission and distribution of reliable electric supply. The liquid-immersed power transformers are mostly used for high voltage applications compared to dry type and gas-filled transformers [1]. The mineral oil derived from petroleum-based resources was brought into commercial production towards transformers in the year 1899 [2] and its usage is adopted to date due to the lower cost involved in the extraction process. Depending on the viscosity of mineral oil, they are categorized into naphthenic and paraffinic oils. Among the above two types of oil, naphthenic-based oils are widely used for transformers compared to paraffinic oils due to their less viscous nature [3]. Apart from mineral oil, polychlorinated biphenyl (PCBs) and silicone oils [4,5] were introduced for transformer applications later in

the year 1932 and 1972 respectively. The PCBs provided better fire class properties and their non-flammable characteristics were suitable for power transformers. However, the PCBs disposal is a major hazard to environmental conditions and its attachment towards the soil can remain for many years causing further damage towards the health of the insulation engineers [6]. Silicone oils known as polydimethylsiloxane provided better stability on thermal stresses where its methyl group present in the molecular structure confines its flow behaviour inside the power transformers [7]. It was also found to be suitable for transformers but the researchers detected that silicone oils involved in the polymerization reaction during partial discharges (PD) leads to the formation of gel substance which was unavoidable [8]. Thus, the power engineers started considering mineral oil as the only resource available for transformer applications. The mineral oil involving the sulfur species in its chemical content was found to introduce a conductive copper sulfide (Cu_2S) formation in both winding and pressboard structures leading to transformer failure [9]. The on-load tap changing (OLTC) transformers used for regulating the output voltage based on the loading condition use a silver coating to prevent friction between the adjacent tap changers [10]. Over a longer operational lifetime, the coated silver particles diffuse into the insulating oil which can also lead to the formation of silver sulfide (Ag_2S) on the pressboard/paper insulation [11]. Comparing the effects of Cu_2S and Ag_2S on power transformers, the deterioration of liquid and solid insulation due to the former is more severe than the latter [12,13]. To overcome the above failure mechanisms involved with mineral oil inside power transformers, the alternate ester fluids are gaining more importance in the recent future. The guidelines of OECD 301 indicate a biodegradability of 95% with ester fluids compared to mineral oils [14].

The ester fluids are categorized into synthetic and natural esters based on their extraction process. Synthetic esters [15] are produced through the esterification of alcohols and acids that may be utilized in various kinds of applications with its primary utilization as a dielectric fluid in transformers. These fluids are ideal for cold regions and breathing systems where the fluid is exposed to oxygen from the air because of its exceptionally low pour point and good oxidation stability [16]. Natural esters [17] derived from renewable resources provide the optimum fit for transformer applications; nevertheless, unlike synthetic esters, their base oil characteristics cannot be drastically changed. Thus, a compromise must be made in order to obtain a natural ester dielectric fluid that maintains its liquid state at low temperatures, and a base oil with reduced oxidation stability is typically selected indicating that it is appropriate only for sealed transformers [18]. Natural esters are more suited to usage inside or in temperate climates since they have higher pour points than synthetic esters. Thus, the various electrical research groups have tried to postulate a separate IEEE standard [19,20] for the application of ester fluids and a committee has been formed recently to formulate a new IEEE Guide combining the effect of various dielectric fluids towards power transformer applications. The transformers' material compatibility (gaskets, seals, and paints) with alternative fluids should be considered before their installation into the power system network. The interior surfaces of the transformer tank are generally coated with an oil-resistant epoxy enamel to provide resistance towards moisture, UV-radiation, and abrasion resistance which is made compatible with mineral oils as per ASTM D3455 standard [21]. The coating used with the existing mineral oils should be compatible with the ester fluids since some of the materials can swell in the case of mineral oil and shrink with ester fluids. Furthermore, the tank enamels although it performs well under ambient temperature can wear out under hotspot temperatures with increased ageing [22]. The impregnation of insulating fluid with cellulosic pressboard is a non-linear process that is mostly dependent on the viscosity and surface tension of the fluid [23]. It is recommended that heating the ester fluids to $60\text{ }^\circ\text{C}$ can reduce the viscosity of ester fluid without modifying the surface tension thereby making its impregnation time similar to mineral oil at $20\text{ }^\circ\text{C}$.

The flow behaviour of insulating liquid depends on the viscosity with natural ester being higher viscous in nature than conventional mineral oil. This property of ester fluid

causes an increased charge separation at the solid/liquid interfaces [24]. Thus, special attention should be given to the flow speed of ester fluids due to its higher viscosity and static electrification phenomenon. In addition, the vacuuming of ester fluids must be conducted to avoid gassing and prevent excess foaming during installation [20]. The thermal performance of alternative fluids has been studied by Salama et al. [25] for varying loading conditions at different power factors. From the observations, it is inferred that synthetic ester provided an increased lifetime of transformer with its lower ageing than mineral oil compared to natural esters. The streamer behaviour of ester fluids subjected to lightning impulse voltage [26] has concluded that ester fluids provided more streamer branches compared to mineral oil. Further, it was inferred that the tolerance of ester fluids towards fast streamers was 40% lower than that of mineral oil. Yi et al. [27] investigated the creepage discharge on the pressboards impregnated with synthetic and natural ester under AC stresses concluding higher discharges at the negative half cycle of AC voltages. Moreover, at higher voltage stresses, an increased discharge density was more prominent in ester fluid due to its higher viscosity than mineral oil. The application of molecular sieves towards the drying of transformer insulation was found to have a significant difference between mineral oil and ester fluid [28].

The higher water solubility of ester fluids could impact the moisture effect towards the free-breathing transformer to be more serious. The silicone fluid and synthetic esters have been found to be successful with breathing conservator design whereas the lower oxidation stability of natural esters needs a modification when it is used with this design. Thus, a separate bladder or a membrane is to be fitted in the conservator tank to mitigate the air from modifying the viscosity of the fluid [29]. The accelerated thermal ageing of ester fluids [30] performed at 160 °C has observed a reduction in its antioxidants after 500 h with not much reduction in its breakdown voltage (BDV) compared to mineral oil. The discrepancies between the different ester fluids during ageing have been concluded by Gutiérrez et al. [31] with a requirement towards standardization on dissolved gas analysis (DGA). The stability of ester fluids was found to be good with various antioxidants [32] and the addition of different antioxidants increases its breakdown voltage, fire point, and viscosity with a lower ageing rate [33]. The zeolite addition improved the dielectric properties of synthetic esters [34] even after being subjected to thermal ageing which was concluded from its fluorescence spectroscopic analysis of the emission mechanism.

Now with the advancement of nanotechnology towards multiple disciplines [35], the impact of nanofillers on ester fluids is gaining more importance in power transformer applications. Initially, the particles of micron size were tested for their suspension towards transformer oil but it resulted in decreasing the dielectric strength and sedimentation of particles with poor stability [36]. Compared to microfluids, the higher interfacial area created by nanoparticles and the insulating fluid results in better dielectric behaviour, and thus nanoparticles are now being used in the electric power industry which is suitable for AC and DC power transmission systems [37]. Moreover, selecting a suitable nanoparticle to enhance the dielectric properties needs a lot of database information with more research on various nanoparticles towards transformers. The conductive, semi-conductive, and insulating nanoparticles are tested towards ester fluids to improve their specific dielectric properties for power transformers [38]. The conductive nanoparticles include zinc oxide (ZnO), iron oxides (Fe_2O_3 , Fe_3O_4), silicon carbide (SiC), semiconductive nanoparticles are titanium oxide (TiO_2), cupric oxide (CuO), copper oxide (Cu_2O) and insulating nanoparticles are silica (SiO_2), alumina (Al_2O_3) and boron nitride (BN). Recently, carbonic nanoparticles, such as graphene and fullerene, are also researched for their performance in power transformers [39].

With the aforementioned literature on insulating fluids, the main objective of the present survey is to provide an overview of the effect of different nanoparticles on ester fluids. The following objectives are explained in this current work: (i) Preparation of nanofluids with its stability; (ii) Partial discharge and breakdown mechanism; (iii) Impact of nanoparticles on flow electrification; (iv) Impact on dielectric permittivity

and dissipation factor; (v) Impact on physio-chemical properties; (vi) Effect of ageing towards ester-nanofluids.

2. Experimental Details

2.1. Preparation of Nanofluids

The nanofluids preparation is one of the precautionary steps to be considered before its implementation in power transformer applications. The preparation involves two different methods: the first one is the single-step process and the second one is the two-step method which is discussed in this section along with its stability analysis.

2.1.1. Single-Step Method

The production and distribution of the fluid's nanoparticles happen at the same time in a single-step method (Figure 1) which avoids the different processes such as drying, storage, shipping, and diffusion of nanoparticles [40]. This methodical procedure can produce nanoparticles with a uniform dispersion in the fluid where the submerged arc nanoparticle synthesis [41] is an effective way to be utilised for dielectric nanofluids. In order to melt and evaporate a metal rod in the specific region of arcing, an electric arc must be produced using an appropriate power source [42]. The nanofluids are produced by the condensation of vaporised metal with dilution in deionized water. The pulsed wire evaporation (PWE) method involving capacitors, a DC power source, and spark gap switches were also used for preparing nanofluids after their explosion with the required particle size depending on the inert gases [43]. However, the major issue is that only fluids with low vapour pressure are suitable for this technique. As a result, the single-step method minimizes the agglomeration of nanoparticles towards fluids and increases its stability [44]. However, since the production of nanofluids using a single-step method is not available on a large scale, along with a higher cost involved and probability of residual reactants to be present in the nanofluids which makes them suitable only for a smaller scale [45].

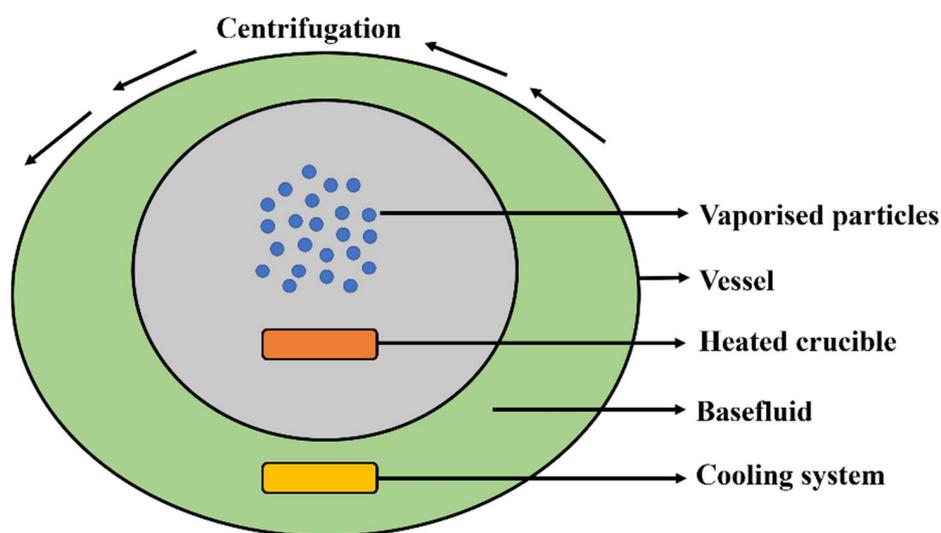


Figure 1. Single-step method for preparation of nanofluids.

2.1.2. Two-Step Method

The most typical approach for creating nanofluids is a two-step process as shown in Figure 2. In this procedure, nanoparticles are initially created as dry powders using techniques such as physical, chemical sol-gel, ball milling, and vapor phase methods [46]. The second processing stage will then involve dispersing the nanosized powder into a fluid using high-intensity magnetic force agitation with ultrasonication. Due to the fact that nanoparticle synthesis procedures have previously been scaled up to levels of commercial production, the two-step process is the most cost-effective way to generate nanofluids on a

wide scale [39]. Nanoparticles have the propensity to combine into larger particles due to their large surface area and surface activity [47]. The use of surfactants is a crucial strategy to increase the stability of nanoparticles in a fluid which also should be limited to certain concentrations due to reactions at high-temperature ranges.

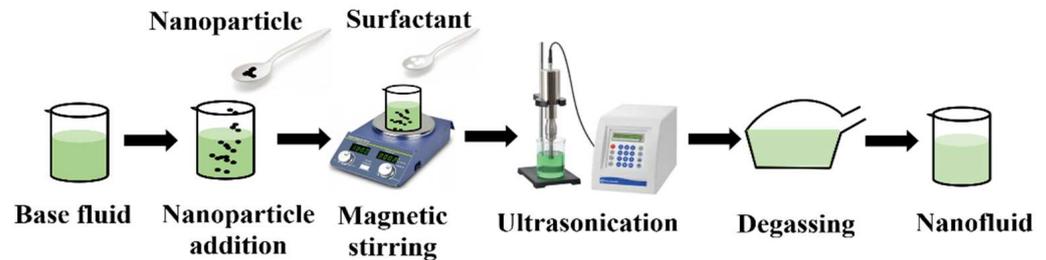


Figure 2. Two-step method for preparation of nanofluids.

There are different types of surfactants (cationic, anionic, and non-ionic) as shown in Figure 3 which are used with different types of nanoparticles on insulating liquid. The surface charge of the nanofluid depends on the isoelectric point of the nanoparticle (pH at which the nanoparticle carries no surface charge) and the pH of the base insulating fluid. The nanoparticle holds a positive charge when its isoelectric point is greater than 7 and it holds a negative charge when the isoelectric point is less than 7 [48]. Depending on the surface charge profile of the nanoparticle, suitable surfactants are to be chosen to improve the stability of the prepared nanofluid. The cetyl trimethyl ammonium bromide (CTAB) is a cationic surfactant with three methyl groups surrounded by the nitrogen ion which gets attached to the surface of the nanoparticle [49].

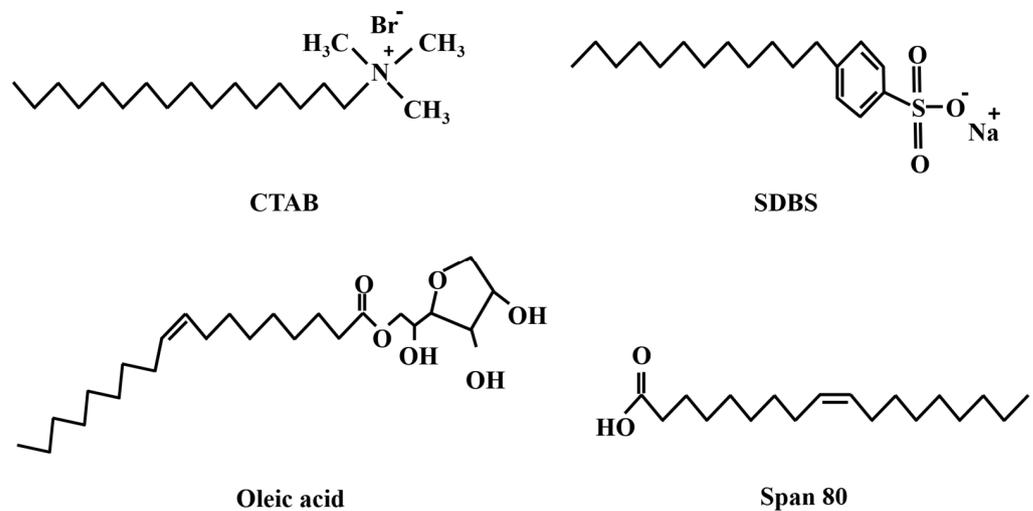


Figure 3. Surfactants used for transformer nanofluids.

Oleic acid is an anionic surfactant with hydroxyl groups on its head which gets attached to the tail of the nanoparticle [50]. Along with oleic acid, sodium dodecyl benzene sulfonate (SDBS) is also an anionic surfactant that is used for improving the stability of insulating nanofluids [49]. Span 80 is a non-ionic surfactant with an uncharged hydrophobic and hydrophilic layer on its surface [51]. Each of these surfactants should be used on the specific nanoparticle based on its surface charge resulting in the stability enhancement of prepared nanofluids. The surface modification of nanoparticles is also studied towards transformers where the surface properties are modified using physical and chemical methods thereby changing the nanoparticle crystal structure, surface behaviour, and increasing the repulsive forces [52]. The physical methods involve radiation treatment, ultrasonic

treatment, and plasma treatment whereas the chemical methods are esterification reaction, coupling agent method, and surface graft modification [53,54].

2.2. Stability of Nanofluids

The stability of nanofluids is an important aspect to be understood by the insulation engineers before deploying them for real-time application. The settling as well as its clogging towards the microchannel formation are caused by the agglomeration of nanoparticles decreasing its thermal conductivity and dielectric properties [55]. The exploration of stability is thus a crucial topic that affects the application-relevant properties of nanofluids, and it is important to research and evaluate the contributing elements to the dispersion stability of nanofluids. The methods for evaluating the stability of nanofluids, strategies for improving the stability of nanofluids, and mechanisms for maintaining nanofluid stability are all discussed in this section. There are different methods used by researchers worldwide for reporting on the stability of prepared nanofluids. The sedimentation process is one of the easiest methods which is used for its investigation of stability where its visual inspection on test tubes is mostly reported [40]. This method requires a longer time for its inspection. The centrifugation method [56] is also utilized where the silver nanofluids investigated with the polyvinylpyrrolidone (PVP) were inferred to improve the stability of nanofluids. Zeta potential analysis [42] is a major experiment (Figure 4) used for detecting the stability where the potential difference between the liquid medium and nanoparticle holding the stationary fluid layer is measured. Hence, electrical stabilization occurs in colloids with high zeta potentials, whereas flocculation or coagulation occurs in colloids with low zeta potentials.

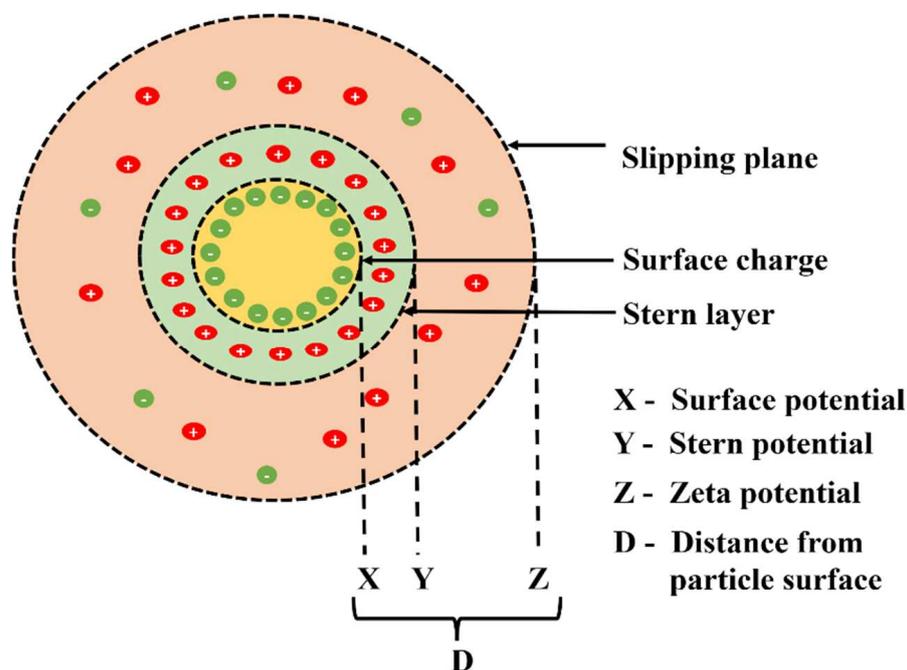


Figure 4. Electrical double layer of nanofluids.

There are ranges standardized for stability [41] which is around 25 mV between the highly charged nanoparticle surfaces with lower charged ones. The stability of nanofluids is concluded to be good when its zeta potential is between 40 mV to 60 mV. In some cases, a higher value of 60 mV represents an excellent stability of nanofluid towards the fluid. The Derjaguin-Landau-Verwey-Overbeek (DLVO) theory [57] is used to determine the interaction of charged particles in a dispersing medium. In accordance with this theory, the nanoparticle diffused in a fluid involves two forces: one is the electrostatic repulsive force and the other is the attractive van der Waals force. To prevent the nanoparticle in-

side the fluid from getting attracted towards the neighbouring nanoparticles, they should be separated from one another by a distance greater than the thickness of the electrical double layer (EDL). The above condition is possible when the repulsive forces are greater than the attractive forces which are provided by the addition of surfactants [58]. Apart from the above-mentioned methods towards stability identification, there is the 3ω method [59] which measures the stability based on the change in thermal conductivity over a wide concentration range with sedimentation time. Further, the spectroscopic analysis and transmission electron microscopic studies [60] can also be used to comment on the nanofluid stability.

3. Discussion

This section describes the different electrical and dielectric properties of ester nanofluids with their wide applications towards power transformers.

3.1. Partial Discharge

Partial discharge is an important effect noticed in the liquid-immersed transformer which gets initiated due to winding protuberances, weak metal points, and edge defects in the transformer tanks [61]. The different techniques of PD detection used for transformer application are shown in Figure 5. The voltage at which localized discharges gets initiated at the gaseous bubbles or void in the insulating fluid is termed partial discharge inception voltage (PDIV). The dielectric fluid should possess a higher PDIV thereby providing a better insulation performance inside the power transformers. There are different standards [62,63] postulated for quantifying PDIV based on the charge magnitude and repetitive pulses formed. In the later stages, the methods such as radio-frequency (RF) and acoustic emission (AE) methods were used for PD detection [64,65]. The researchers found that pulses formed during PD were emitting electromagnetic radiations in the frequency range of 0.3–3 GHz which was detectable using an ultra-high frequency (UHF) sensor [66]. These UHF sensors are mounted towards the transformer wall [67] and are continuously monitored by substation engineers in the control room for the detection of PD. Now along with UHF sensors, the fluorescent optical fibers [68] are investigated for PD in transformer insulation and its localization. There are fibers with different absorption wavelengths [69] available for various research applications which could be used along with transformer winding structures to record the rise in temperature as well as in identifying the partial discharges [70]. There is no specific standard for quantifying the effect of these discharges where the conventional PD measurements are being compared to current PD detection methods providing more sensitivity at a laboratory scale. Such novel methods should be incorporated into current requirements and formulated for their application towards real-time power transformers. The partial discharge of ester-based TiO_2 nanofluids along with CTAB surfactant was studied using a UHF sensor [71] and it was stated that 50 mg/L of TiO_2 with 1 mg/L of CTAB could increase the PDIV under AC and DC voltages. Mahidhar et al. [72] have used SiO_2 nanoparticles towards synthetic ester fluids and inferred that 0.05 g/L of SiO_2 with 0.00075 g/L of CTAB observed an increased PDIV under AC and DC voltages.

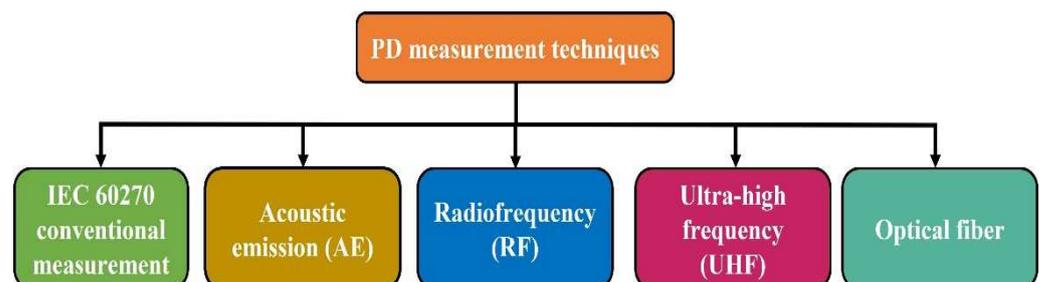


Figure 5. Methodologies for PD measurement in transformers.

The harmonic impact on the nanofluids has caused the PDIV to be lower than AC voltages indicating a higher dV/dt as a possible reason for its reduction. The effect of surfactants on the PDIV of synthetic ester-based SiO_2 nanofluids [73] has shown that Span 80 outperformed CTAB and Oleic acid with a higher PDIV at a lower concentration of $0.25 \mu\text{L/L}$ and increased stability. The aluminium nitride (AlN) nanoparticle towards synthetic ester [74] increases the PDIV by 44% under AC voltages. Moreover, the change in the PDIV observed under AC and DC voltages was negligible at an optimum concentration of 0.005%. Further, the impact of Fullerene and graphene towards synthetic ester was investigated by Khelifa et al. [39] with Oleic acid as a surfactant indicating a higher PDIV with C_{60} addition and reduction being noticed with graphene nanoparticles. The structural difference in C_{60} and graphene was concluded as a major reason for the change in its PD characteristics with both conducting nanoparticles. A similar research group has worked on the different nanoparticles (Fe_3O_4 , Al_2O_3 , and TiO_2) [75] indicating an increased PDIV and extinction voltage compared to synthetic ester along with a reduction in its charge magnitude. The ZrO_2 nanoparticles with synthetic ester [76] have shown a reduction in partial discharges with higher PDIV observed at 0.4 g/L . The nanofluids measured for PD indicated a less number of discharges compared to synthetic ester. The PD characteristics of ester nanofluids performed by various research groups use their unique sensor methods for their identification and thus making it difficult for a comparison. Hence, a committee should be formed for making standards on different sensor techniques for PD detection in transformers which could be useful information for power engineers to have an understanding of ester nanofluids.

3.2. Breakdown Voltage

The ester nanofluids-filled power transformers must withstand higher voltages when subjected to nominal AC and DC voltages along with transients such as lightning impulse (LI) and switching impulse (SI) voltages. The requirement of tolerance level by the insulating liquid increases with higher transmission voltage levels and thus demands a lot of work from transformer insulation designers to identify a suitable fluid matching the requirements. The ions dissociated in the nanofluids under the applied electric field causes the positive and negative ions in the nanoparticle to move in the same direction of the applied field, whereas the ions in the base fluids move towards the opposite electrodes. The higher mobility of electrons moves towards positive electrons leaving more positive ions in the fluid to be stationary. Thus, the free electrons are captured by the nanoparticle for its neutralization and a saturation limit is attained where the nanoparticle cannot trap further electrons. This mechanism of electron trapping by the nanoparticle is responsible for the streamer inhibition of nanofluids compared to base fluids [77]. The relaxation time (τ) needed for the polarization of nanoparticles under the applied electric field is given by,

$$\tau = \frac{2\varepsilon_{r_{nf}} + \varepsilon_{r_{np}}}{\sigma_{nf} + \sigma_{np}} \quad (1)$$

where $\varepsilon_{r_{nf}}$ and $\varepsilon_{r_{np}}$ are the relative permittivity of nanofluid and nanoparticle, σ_{nf} and σ_{np} are the conductivity of nanofluid and nanoparticle.

This equation formulated towards streamer mechanism holds good only when the relaxation time of nanoparticles is lower than the streamer initiation time. The movement of electrons in nanofluids are influenced by the polarized nanoparticles which then affects the potential distribution surrounding nanoparticles. Charge traps or potential wells may be created as a result of the electric field being distorted around the nanoparticle surface due to the change in the permittivity between the nanoparticle and base fluid. The addition of surfactant increases the nanoparticle radius which further increases the potential gradient resulting in deeper traps for attracting free electrons. Thus, the deeper traps involved in the nanofluid are responsible for its increased breakdown strength. In addition, the shallow trap theory [78] and hydrophilicity theory [79] impacts electron hopping and moisture affecting the propagation of streamers. The electrohydrodynamics

of ester fluid impacts the breakdown strength if there is a significant difference noticed in the conductivity and permittivity of nanoparticle and base fluid. Koutras et al. [80] have studied the potential well distribution around SiC and Al₂O₃ nanoparticles in ester fluid inferring higher traps in SiC due to its increased conductivity compared to Al₂O₃. Considering the above aspects, worldwide research groups have focussed on different nanoparticles towards ester fluids identifying their optimal condition [81] with better dielectric properties. The technical standards [82,83] have been postulated to understand such breakdown voltage under homogeneous electric field conditions. However, in a practical situation, the non-homogenous field is noted in the transformer [84] which should be investigated on ester nanofluids. The different field configurations reported in laboratory scale towards breakdown voltages are shown in Figure 6.

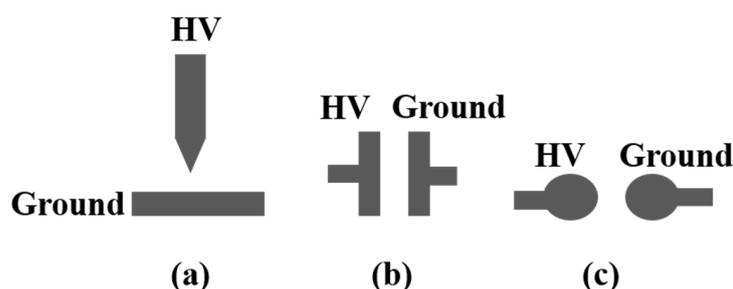


Figure 6. Field configurations used for breakdown studies with different configurations (a) Point-Plane, (b) Plane-Plane, (c) Sphere-Sphere.

Zhong et al. [85] studied the impact of TiO₂ nanoparticles on natural ester fluids towards the partial discharge and breakdown measurements. The AC breakdown voltage of prepared nanofluids was found to increase up to 1.3 times that of base ester fluids. It is inferred that TiO₂ nanoparticle increases the trap density which increases the transport of charges thereby preventing the accumulation of charges. The dispersion of Fe₃O₄ nanoparticles in natural ester fluids [86] has observed an increase of 50% in the breakdown voltage compared to base fluids and its magnitude was higher than its effect with ZnO and SiO₂ nanoparticles. The magnetite nanoparticles [87] have also observed an improved breakdown voltage on both synthetic and natural ester fluids with a requirement of concentration above 0.3% w/V. Khaled et al. [88] performed the DC breakdown voltage of natural esters with Al₂O₃, SiO₂, and Fe₃O₄ nanoparticles and concluded that 0.05 g/L of concentration was required for improving BDV irrespective of nanoparticles. An increase in the BDV was around 9% with Al₂O₃, 10.6% with Fe₃O₄, and a significant reduction with SiO₂ nanoparticles was noticed for different concentrations. Farade et al. [89] investigated the cotton seed oil towards hexagonal boron nitride (h-BN) nanoparticles observing an improvement in the impulse breakdown voltage by 5% with its optimal weight percentage to be around 0.1 wt%. A similar increase in the impulse breakdown of ester fluids is noticed with C₆₀ nanoparticle [90] at 0.1 g/L with an increase of 8.2% whereas the highest AC breakdown voltage was noticed at 0.4 g/L with a 7.8% increase compared to base ester fluid. Further, the graphene oxide [91] have also been tested towards natural esters with increase of 15% and 17% observed in the AC and impulse BDV. Apart from the nominal voltage profiles discussed towards ester nanofluids, it is also necessary to verify the lightning impulse voltages on prepared nanofluids before implementing them towards power transformers. Koutras et al. [92] examined the impact of TiO₂ nanoparticles on natural ester fluid and observed an increase of 12.94% in LI BDV. This gives an indication that TiO₂ not only traps the electrons with a nominal voltage profile but also from the streamers developed during the transient overvoltages. The addition of C₆₀ to natural ester fluids observed an increment of 8.2% in LI BDV with 0.1 g/L [90] and concentrations higher than this range exceeds the percolation threshold limit leading to the tunnelling mechanism. The SiC nanoparticle on ester fluids [93] increases the LI BDV to 9.8% with 0.004% (w/w) and it is inferred that surface charges on the nanoparticle produces a potential well trapping

the electrons in the streamers requiring a higher electric field to bridge the gap. Potivejkul et al. [94] investigated the negative LI voltages on ester fluid with 0.03% concentration of ZnO indicating a 21% increase in its LI BDV compared to base ester fluid. Emara et al. [95] observed an enhancement of 15.15% in LI BDV of a natural ester with 0.01% (*w/w*) of MgO nanoparticles. The Al₂O₃ nanoparticle with a concentration of 0.004% *w/w* in ester fluids observed increased LI voltages under both positive and negative polarities by 28.5% and 1.52% respectively [80]. It is concluded that the Al₂O₃ nanoparticle narrows the gap spacing between the electrodes which is responsible for increased LI BDV. A minimal increase of 5.38% is only noticed on LI BDV with the influence of BN nanoparticle (0.1 wt%) of natural ester fluid [89]. Beroual et al. [96] studied the impact of Fe₃O₄, Al₂O₃, and SiO₂ nanoparticles on both natural and synthetic ester fluids under a quasi-uniform field. The synthetic esters observed the highest LI voltage with an increase of 25.6% with Fe₃O₄ (0.05 g/L), 18.3% with Al₂O₃ (0.3 g/L), and 22% with SiO₂ (0.3 g/L). Similarly, the natural esters observed an increase of 7.5% Fe₃O₄ (0.2 g/L), 16.8% with Al₂O₃ (0.05 g/L), and 13% with SiO₂ (0.2 g/L) towards LI BDV. Each nanoparticle accumulates electrons on its surface forming a double layer and slowing the streamer development which above a certain concentration gets saturated and is unable to trap further leading to a breakdown. The results postulated with different nanoparticles towards esters under homogenous and non-homogenous field conditions for multiple voltage profiles (AC, DC, LI) are to be compared and considered before their implementation towards power transformers.

3.3. Flow Electrification

The flow electrification phenomenon is a major hazard that occurs in liquid-immersed power transformers. This mechanism was first reported in the 1980s [97] where fluid used for heat transport inside the transformer leads to charge formation at the solid insulation which then causes the flashover. Both the liquid and solid insulation are neutral at their initial stages, but once the fluid flow is circulated inside the power transformer, the physical and chemical interaction between the two mediums results in the electrostatic charge formation explained with an electrical double layer formation (EDL) [98]. It is important to understand the flow electrification of insulating fluids before it is applied to a power transformer where different methods such as planar flow, centrifugal flow, and Ministatic tester are experimented with on a laboratory scale [99]. The CIGRE report [100] suggests the reduction of flow charges by reducing the surface tension of the insulating fluid. Harvey et al. [101] have studied the charge distribution between the solid and liquid interfaces based on the relation between the Debye length and diffusive sublayer thickness. The mechanism illustrating the charge separation between the pressboard and insulating liquid is shown in Figure 7.

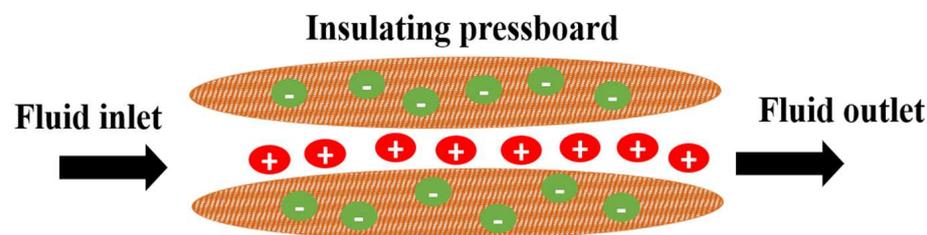


Figure 7. Mechanism of charge separation at pressboard spacers in a transformer.

The EDL consists of a fixed layer and a diffuse layer where the former is the region nearer to solid pressboard insulation and the latter confines the region of charges diffused by the liquid. The cellulosic pressboard/paper insulation holds a hydrogen ion in its external structure which absorbs the negative ions towards its surface diffusing the positive ions to be carried by the liquid. In contrast, the metallic and liquid interfaces follow the opposite trend compared to the pressboard and liquid interfaces, and it is eliminated through the grounding of transformer tanks. The ester nanofluids are now studied towards flow electri-

fication aspects by various high voltage researchers worldwide. Amalanathan et al. [71] investigated the TiO₂ nanoparticle on natural ester fluids towards flow electrification and inferred a higher streaming current with nanofluids compared to base ester fluids. The impact of CTAB surfactant also experimented where the nanofluids involving surfactant observed a higher current compared to nanofluids without surfactant. The diffusion of more charges from the surfactant and nanoparticle was found to be the reason for the higher charging tendency with nanofluids. It was also concluded that the conductivity of nanofluids impacts the flow electrification higher than viscosity. Amizhtan et al. [73] studied the impact of different surfactants (CTAB, Oleic acid, and Span 80) with SiO₂ nanoparticles on the electro-rheological aspects of synthetic ester fluids. The streaming current was lower for ester fluids with Span 80 as a surfactant compared to CTAB and Oleic acid indicating that non-ionic surfactants are preferable for reduced charge formation. Similar surfactants and nanoparticles have also been studied towards natural ester fluids [102] and the CTAB surfactant observed a lower streaming current than base fluids, and with the impact of Span 80 and Oleic acid. The authors have also used machine learning techniques of Long Short-Term Memory (LSTM) which provided better accuracy on its prediction towards streaming current from the rheological parameters compared to Artificial Neural Network (ANN). The electrification of AlN nanoparticles towards synthetic ester fluids was assessed by Anju et al. [74] for different concentrations inferring a low current for the range of 0.0025% to 0.005%. These limits were identified to be optimal levels of AlN nanoparticles on ester fluids for streaming phenomenon and higher concentrations above these limits observe increased ionic mobility. Zdanowski [103] studied the effect of fullerene on both natural and synthetic ester fluids observing the streaming current with the impact of flow velocities. It was concluded that C₆₀ acts as a better inhibition on the streaming current towards ester fluids with its higher reduction noticed in the concentration of 200 mg/L. A model for streaming electrification of ester-based TiO₂ nanofluids [104] has also been elaborated where the interfacial zone explains the mechanism behind the increased current of nanofluids involving surfactants. The benzotriazole additive (BTA) [71,105] which is used as a passivator towards the sulfide formation also reduces the streaming current of ester nanofluid with a requirement of higher concentration towards nanofluid prepared with the addition of surfactant compared to base ester fluids.

3.4. Dielectric Permittivity and Dissipation Factor

The liquid-immersed power transformer filled with ester fluids ($\epsilon_r = 3.2$) has a higher permittivity than mineral oil ($\epsilon_r = 2.2$) where the change in permittivity between the liquid and solid insulation should be as low as possible to reduce the tangential stress which is being satisfied by the ester fluids [106]. The dielectric measurements are performed with test cells containing three terminals (high voltage, ground, and guard ring) as per IEC 60247 standards [107] with temperatures ranging up to 100 °C. In the application of an electric field, the ions present in the nanoparticle dissociate and distributes equally around the surface of the particle. Polarization is a term that describes the ability on the separation of charges in a nanoparticle and permittivity is confined to the polarizability of the material towards the applied electric field. The real part of the permittivity defines the polarizability and the imaginary part indicates the dielectric losses with both parameters being a function of frequency. The insulating fluids become more agitated at a higher range of temperatures which reduces its ability to orientate towards the applied electric field, thereby causing a reduction in its permittivity [108]. Maxwell-Garnett [109] equation is used for determining the permittivity of nanofluids as shown below:

$$\frac{\epsilon_{r_{nf}} - \epsilon_{r_f}}{\epsilon_{r_{nf}} + 2\epsilon_{r_f}} = \phi \left\{ \frac{\epsilon_{r_{np}} - \epsilon_{r_f}}{\epsilon_{r_{np}} + 2\epsilon_{r_f}} \right\} \quad (2)$$

where ϕ is the volume fraction of diffused nanoparticle and ϵ_{r_f} indicates the permittivity of the base fluid.

Since this equation is dependent only on the concentration and permittivity without considering any polarization, it holds good only for higher concentrations of nanoparticles and not for lower concentrations as used for power transformers [110]. Thus, the Clausius-Mossotti (C-M) equation [111] was formulated for nanofluids which considers the different polarization mechanisms such as oil molecule's polarization, nanoparticle's inner polarization, and polarization exhibited towards the orientation of nanoparticle (Figure 8).

$$\frac{\epsilon_{r_{nf}} - 1}{\epsilon_{r_{nf}} + 2} = \frac{1}{3\epsilon_0} \times \{N_1\alpha_1 + N_2\alpha_2 + N_2\alpha_3\} \quad (3)$$

where N_1 and N_2 are the number of molecules present in the base fluid and nanoparticles per unit volume of nanofluids, $\alpha_1, \alpha_2, \alpha_3$ are the polarizability of base fluid, nanoparticle, and nanoparticle's orientation, ϵ_0 is the permittivity of the vacuum.

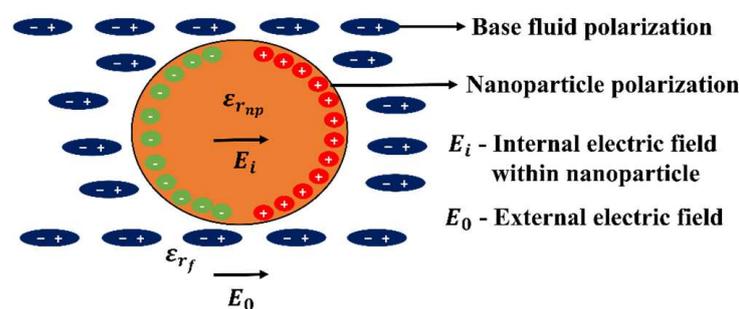


Figure 8. Polarization of base fluid and nanoparticle in nanofluids.

Farade et al. [112] have adopted the C-M equation towards ester-based Al_2O_3 nanofluids describing the different polarization towards the relative permittivity. Hussain et al. [113] understood the dielectric performance of iron phosphide on ester fluids indicating a higher permittivity with its specific description of the polarization of magnetic nanoparticles. Li et al. [114] studied the dispersion of Fe_3O_4 nanoparticles towards rapeseed oil concluding a better dielectric behaviour. The higher permittivity of Fe_3O_4 nanoparticles causes an increased dielectric constant of rapeseed oil on prepared nanofluids. The dissipation factor of nanofluids was lower with nanofluids at lower frequencies due to its increased volume resistivity than base fluid. On comparing the effect of TiO_2 and Fe_3O_4 nanoparticles on natural ester fluid, the dielectric loss was found to be lower than base fluid with the addition of TiO_2 , whereas, at a concentration higher than 1.0 g/L, the conductive nature of Fe_3O_4 nanoparticle increases the mobility of ions [115].

A drastic reduction in the dielectric loss has been noticed in the methyl ester with TiO_2 and Al_2O_3 nanoparticles [116] for the concentration ranging from 0.2 wt% to 1 wt%. At higher concentrations, these nanoparticles cause the trapping of electrons with less mobility between the nearby nanoparticles which is responsible for its reduced loss factor. The AlN nanoparticle increases both the permittivity and dissipation factor of synthetic ester fluid [74] with its optimal concentration found to be around 0.0025%. The fullerene nanoparticle caused no significant change in the permittivity of both natural and synthetic ester fluids, whereas its optimal concentration towards ester could decrease the dissipation factor [117]. The oleate-coated Fe_2O_3 nanocrystals on natural ester fluid observed a minimal change in its dissipation factor with frequency at ambient temperature and its increase was similar to base fluid even at higher temperatures [118]. The polarization and depolarization current (PDC) of natural ester fluid with 0.01% of TiO_2 and 0.03% of ZnO nanoparticle indicated an increase in its conductivity that affects its insulation performance but can trap the electrons towards its surfaces [119]. Thomas et al. [120] understood the impact of doping nano $\text{CaCu}_3\text{Ti}_4\text{O}_{12}$ (CCTO) on synthetic ester fluid indicating a decrease in the loss factor with increasing weight percentage (0.005 vol%) and an increased dielectric permittivity was observed at 0.0025 vol%. The higher dielectric constant of nano-CCTO has been found to be the reason for its increased permittivity towards ester fluids. The impact

of $\text{Ba}_{0.85}\text{Ca}_{0.15}\text{Zr}_{0.1}\text{Ti}_{0.9}\text{O}_3$ (BCZT) was also found to increase the permittivity at 90 °C containing 0.01 wt% along with a corresponding increase in the loss tangent of synthetic ester [121]. Thus, the impact of nanoparticles on ester fluids should be understood for its dielectric permittivity and loss factor at varying frequencies and temperatures.

3.5. Physio-Chemical Properties

The insulating liquid undergoes multiple reactions such as oxidation and hydrolysis which impacts the formation of free-radical and accelerated ageing. The condition assessment of the fluid can potentially benefit from a fuller insight into the physicochemical transformations taking place during operation. This section goes through various techniques that can be used to analyse these changes in the insulating fluid.

3.5.1. Viscosity

The cooling efficiency of power transformers during their typical working regime and, consequently, their temperature rise, are determined by the various thermal parameters among which the dominant being the viscosity of insulating fluids. Further, the flow conditions within the transformer impact the static electrification where the nanofluids follows flow patterns different from base fluids. The ASTM D341 standard [122] was used for kinematic viscosity measurement with a change in temperature. Nowadays, researchers measure the dynamic viscosity using Anton-Paar modular compact rheometer with different configurations (cone-plate, double-gap cell) [123,124]. The database on the improvement in the viscosity of various nanoparticles towards ester fluids is shown in Table 1.

Table 1. The viscosity of ester-based nanofluids.

S. No	Authors	Base Fluid and Nanoparticle	Comments
1.	Wanatasanappan et al. [125]	NE (soybean, coconut, and palm oil) + Al_2O_3 - TiO_2	At an ambient temperature with 0.6 wt%, the increased viscosity observed in coconut oil, soyabean oil, and palm oil was around 15.7%, 6.7%, and 10.9%.
2.	Olmo et al. [126]	NE + TiO_2	A 7.2% increase is noticed in viscosity at higher concentrations of TiO_2
3.	Shill et al. [127]	SE + SiO_2	A 12.5% increase is observed at 0.06 w/V%
4.	Ramaian et al. [128]	NE (sunflower oil, rice bran, corn oil) + hybrid ZnO - Al_2O_3	A moderate change in the viscosity observed at room temperature and 80 °C.
5.	Raj et al. [129]	NE + Al_2O_3	Reduction in viscosity to around 66% is observed at 30 °C and 90 °C.
6.	Szcześniak et al. [130]	NE + C_{60}	A minimal increase in viscosity of nanofluids after ageing compared to the base fluid.
7.	Nadolny et al. [131]	SE + TiO_2 + Span 20	The change in viscosity was higher for nanofluids at 25 °C which became similar to ester fluids at 80 °C.
8.	Amalanathan et al. [71]	NE + TiO_2 + CTAB	The nanofluids with surfactant showed an increased viscosity at 30 °C which was overlapped with ester fluids at 65 °C.
9.	Khan et al. [132]	NE + GO and SE + GO	The SE nanofluids with GO showed lower viscosity compared to NE nanofluids with GO at different temperatures.
10.	Mohamad et al. [133]	NE + Fe_3O_4	The change in viscosity observed for nanofluids at 40 °C was less than 0.5% which was reduced at 60 °C to 0.2%.

3.5.2. Oxidation Stability

The insulating fluids are significantly influenced by their oxidation stability where both the naturally occurring oxygen and its intake from the environment outside are possible in the fluid. The chemical structure of natural ester fluid involving a glycerol backbone is more susceptible to oxidation whereas synthetic esters start to oxidize very slowly at temperatures greater than 125 °C [24,29] based on the saturated fatty acid without the production of sludges. The double bonds between the carbon structures are the main sites of oxidation reactions. The lower oxidation stability of natural ester fluids makes them suitable only for sealed power transformers with nitrogen as its head space [134]. The various antioxidants are now being tested on ester fluids [32] for improving oxidation stability. The C₆₀ nanoparticle preventing the reaction of lipid oxidation provides improved oxidation stability towards natural ester fluids [130]. The synthetic ester fluid indicated oxidation at lower temperatures, whereas, upon its addition of cadmium sulfide (CdS) has observed higher oxidation stability [135]. Sunil et al. [136] investigated the thermal stability of rice-bran oil observing an increase of 25% in oxidation with the addition of CaO nanoparticles. Ranjan et al. [137] studied the impact of TiO₂/gC₃N₄ nano-additive on vegetable oil indicating an increased oxidative onset temperature of 165 °C. The reason for this improvement in oxidation stability was related to the mending behaviour of nitrides and oxides on the unsaturated bonds present in the ester fluids.

3.5.3. Flash Point and Fire Point

The fire hazards in transformers are one of the major safety concerns to be understood since it can create a complete blackout of the power network. The localized hotspots within the transformer can cause an elevated temperature of 160 °C damaging both the solid and liquid insulants [138]. The ester fluid comes under a higher thermal class K than mineral oil [24] with thermal class O providing more advantage in reducing the ageing rate of cellulosic pressboard insulation. Further, the maximum top hotspot temperature limit for ester fluids with normal and emergency loading is higher than mineral oil [139]. From the above information, now with the diffusion of different nanoparticles on ester fluids, it is required to analyze the characteristic changes in the thermal class properties. Madavan et al. [140] compared the effect of different nanoparticles (Fe₃O₄, Al₂O₃, and BN) on natural ester concluding an improved fire class properties than base fluid. The synthetic ester fluid examined with CaCu₃Ti₄O₁₂ (CCTO) inferred a low flash point at small volume concentrations whereas to the contradict, at higher vol% an increased flash point was observed [141]. Prasath et al. [142] investigated the effect of TiO₂ nanoparticles on ester fluid observing an enhancement of 8.5% in its fire point. The addition of 0.015% of ZnO and Al₂O₃ nanoparticles to sunflower oil observed a higher flammability characteristic than base oil [128]. Oparanti et al. [143] studied the effect of tungsten oxide (WO₃) and SiO₂ nanoparticles on neem oil inferring an increased flash point by 8.75% and 5.71%. The impact of GO nanoparticles on soyabean oil increased the flash point by 27.27% with 0.005 g/L [144]. The marula oil with the addition of 0.75 g/L of Al₂O₃ enhanced the fire point by 12.41 °C [122]. Raymon et al. [145] studied the impact of conductive, semi-conductive, and magnetic nanoparticles on both the flash point and fire point of natural ester. The conductive nanoparticle (Al₂O₃) on ester fluid indicated an increment of 16% in fire point with semi-conductive nanoparticles (TiO₂, CdS) observing up to 10%. Additionally, there was no improvement in the fire class properties of ester fluids with the addition of Fe₂O₃ nanoparticles.

3.5.4. Interfacial Tension

The impurities in the insulating liquid move under the charging attraction of water at interfaces, producing a corresponding tensile force, which is an approximate measure of interfacial tension [24]. Increased contamination in the fluid owing to its deterioration causes a decline in the IFT denoting a higher concentration of polar impurities. There are standards [146,147] formulated providing recommendations for testing the IFT of insu-

lating fluids. Because of their fundamentally different chemical structure from mineral oils, natural ester fluids have a lower IFT than mineral oils. The uncertainty in the fluid behaviour is observed when the IFT reaches below 22 mN/m and its replacements are required at less than 15 mN/m [148]. The vegetable oil with h-BN nanoparticle observed an increased IFT compared to its base oil throughout the ageing duration [149]. The increased concentration of $\text{CaCu}_3\text{Ti}_4\text{O}_{12}$ on synthetic ester fluid [120] observed a reduced IFT indicating its higher affinity to polar solvents. Moreover, the optimal concentration of 0.001 vol% was providing a higher IFT among the different concentrations. Siddique et al. [144] studied different blends of soyabean oil with various concentrations of nanoparticles and observed a higher IFT at 0.003 g/L. The IFT of a natural ester with fullerene nanoparticles (250 mg/L, 500 mg/L) was higher than the base fluid before and after ageing process [130]. The natural ester with h-BN nanoparticle observed a higher IFT compared to its base fluid but was found to be lesser than mineral oil-based nanofluids [109]. The molecular structure of ester fluid involving more fatty acids is concluded as a reason for its reduced IFT.

3.5.5. Thermal Conductivity

The insulating fluid for transformers has to be designed for its cooling function with its necessary thermal characteristics to maintain its operating temperature within acceptable bounds. The higher thermal conductivity of solid metals compared to fluid led to the dispersion of metal oxide nanoparticles. The change in the thermal conductivity on nano-dispersion has been explained by the Brownian motion, clustering of nanoparticles, heat transfer between the nanoparticle, and thermophoretic effect [150]. The thermal comparator, transient techniques, and steady-state methods are the most widely used experimental measurement for the thermal conductivity of nanofluids [151]. The different models proposed for the thermal conductivity of nanofluids are shown in Table 2.

Table 2. Proposed models used for thermal conductivity of nanofluids.

S. No	Proposed Models	Equation of Model
1.	Maxwell model [152]	$\frac{k_{eff}}{k_{fl}} = 1 + \frac{3(\alpha-1)\phi}{(\alpha+2)-(\alpha-1)\phi} \quad (4)$ <p>where k_{eff} and k_{fl} is the thermal conductivity of nanofluid and base fluid, ϕ is the volume fraction of dispersed nanoparticles, α represents the ratio between the thermal conductivity of nanoparticle and base fluid. This model holds good only for spherical nanoparticles and upto the order of ϕ^1.</p>
2.	Hamilton and Crosser model [153]	$\frac{k_{eff}}{k_{fl}} = 1 + \frac{\alpha+(n-1)-(n-1)(1-\alpha)\phi}{\alpha+(n-1)+(1-\alpha)\phi} \quad (5)$ <p>where $n = \frac{3}{\psi}$ is the empirical shape factor and ψ denotes the sphericity. Sphericity is the ratio of the surface area of a sphere holding the same volume as the nanoparticle to the surface area of the nanoparticle. This model applies to both spherical and non-spherical nanoparticles.</p>
3.	Jeffery Model [154]	$\frac{k_{eff}}{k_{fl}} = 1 + 3\beta\phi + \phi^2 \left\{ 3\beta^2 + \frac{3\beta^2}{4} + \frac{9\beta^2(\alpha+2)}{16(2\alpha+3)} + \frac{3\beta^4}{26} + \dots \right\} \quad (6)$ <p>where $\beta = \frac{(\alpha-1)}{(\alpha-2)}$. This model holds good for spherical nanoparticles with its limitation increased to the order of ϕ^2.</p>
4.	Davis Model [154]	$\frac{k_{eff}}{k_{fl}} = 1 + \frac{3(\alpha-1)}{(\alpha+2)-(\alpha-1)\phi} \{ \phi + f(\alpha)\phi^2 + 0\phi^3 \} \quad (7)$ <p>where $f(\alpha) = 2.5$ for $\alpha = 10$ and $f(\alpha) = 0.5$ for $\alpha = \infty$.</p>
5.	Bruggeman model [155]	$\phi \left(\frac{k_{np}-k_{eff}}{k_{np}-2k_{eff}} \right) + (1-\phi) \left(\frac{k_{fl}-k_{eff}}{k_{fl}+2k_{eff}} \right) = 0 \quad (8)$ <p>where k_{np} is the thermal conductivity of nanoparticles. Applicable for uniformly dispersed spherical and randomly distributed nanoparticles.</p>

The increase in the concentration of BN nanoparticles up to 0.1 wt% [156] has inferred better thermal conductivity with a reduction of 4.21% observed in its comparison with the natural ester fluid. The Al_2O_3 nanoparticles on natural ester fluids have inferred an

improved thermal conductivity with an increase in its concentration from 0.02 wt% to 0.1 wt% [157]. The higher concentration of nanoparticles has caused an increase in the surface area which provides efficient heat transfer. The increased percentage absorbed in ester-based Al_2O_3 nanofluids was 14.6% higher than in mineral oil-based Al_2O_3 nanofluids. The addition of TiO_2 nanoparticles to natural ester fluids did not change the thermal characteristics even at various concentration levels [126]. The semi-conductive nanoparticles (CdS, Co_3O_4) tested on synthetic ester fluid observed a lower heat dissipation with better thermal stability inferred in both air and nitrogen medium [158]. The different types of natural ester fluids (palm oil, coconut oil, soyabean oil) were tested with an equal proportion of Al_2O_3 - TiO_2 dispersed in the concentration range of 0.2 wt% to 0.6 wt% [125]. Among the nanofluids, the palm oil-based hybrid nanofluids observed an increment of 125.3% in thermal conductivity compared to soybean and coconut oil which inferred only an increase of 18.5% and 27.1% with respect to its base fluid. The cottonseed oil (CSO) on its dispersion with h-BN nanoparticles observed an improved thermal conductivity compared to base fluid with its validation performed on thermal measurements [89]. The heat dissipation factor was much higher with nanofluids which were related to the transport of phonon between the nanoparticles and its interaction with the neighboring nanoparticles.

3.6. Impact of Ageing on Ester-Nanofluids

The impact of a higher electric field along with the temperature rise experienced in power transformers during loading conditions can lead to a chemical reaction in both the solid and liquid insulants [159]. Thus, the effect of varying temperature conditions on ester nanofluids are to be known under laboratory conditions. Figure 9 shows the precautionary measures to be followed before performing ageing tests. Among the different stress conditions observed inside transformers, thermal stress impacts the insulation at a higher rate than electrical and chemical stress [160]. Considering the above statement, now the accelerated thermal ageing test [161,162] of nanofluids are understood to simulate the transformer on a small scale with its materials of pressboard insulation and copper winding. The ASTM D1934 and IEC 62332-2 [163,164] are the standards that discuss the ageing methodologies to be followed for an insulating fluid towards transformers. Additionally, the impact of ageing medium [165] on insulation along with moisture level impacts the transformer insulation.

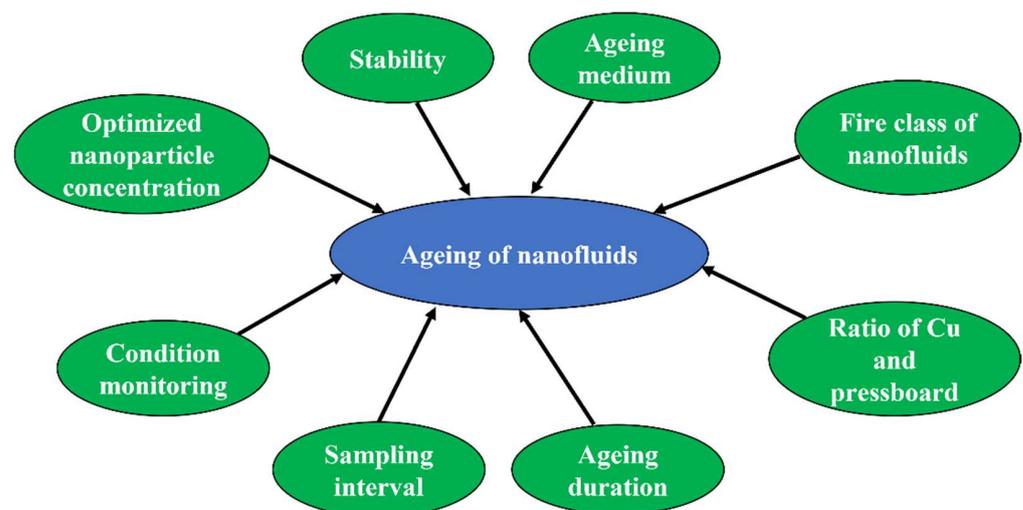


Figure 9. Precautionary steps for the ageing of nanofluids.

Maharana et al. [149] performed oxidative ageing tests on natural ester fluid with hexagonal boron nitride (h-BN) nanoparticles at 115 °C for 500 h. The surface-modified h-BN also studied on natural ester fluid increases the particle size as well as lowers the stability at higher temperature conditions compared to its influence without structural

modification. Further, the enhancement in AC BDV with ester nanofluids were observed to be higher than mineral oil at different ageing durations. Koutras et al. [166] studied the impact of TiO₂ and SiC nanoparticles on natural ester with varying concentrations (0.004–0.016% *w/w*) at an elevated temperature of 90 °C. The authors observed a decrease in the stability with ageing time for TiO₂-based nanofluids while the SiC nanoparticles improved the stability under ambient temperature and thermal ageing durations. The trap modelling further confirmed that ester fluids with SiC nanoparticles have higher deep traps than TiO₂ nanoparticles. Jacob et al. [167] investigated the natural ester fluids with Al₂O₃ nanoparticles towards its behaviour on cellulose with thermal ageing at 130 °C. It is inferred that 0.02 wt% of Al₂O₃ nanoparticles in ester fluid observed a higher resistance of cellulose towards ageing and concluded these nanofluids to be a suitable alternative for transformers. The impact of ZnO and TiO₂ nanoparticles on ester fluids [168] was conducted for thermal ageing at 150 °C where the ZnO-based nanofluids indicated a higher particle size at the end of ageing time (312 h) confirming the beginning of agglomeration with ageing duration. Nevertheless, a higher BDV was noticed in both nanofluids but with increased loss factor and conductivity. The graphene oxide (GO) on ester fluids [132] was aged at 130 °C for a period of 60 days indicating better tensile strength with retention in the crystal structure of its pressboard insulation compared to base ester fluids. The GO-based ester fluids provided a better stable dispersion than TiO₂ based ester fluids [144]. The electrical and thermal stressing of ester-based TiO₂ nanofluids [169] caused a reduction in the streaming current due to the dissolution of negative ions from oxygen atoms in TiO₂ nanoparticles. The impulse stressing of nanofluids caused a negative streaming current compared to base fluids due to depletion in its EDL whereas surfactant-based nanofluids observed a positive streaming current. However, the effect of thermal stress caused a reduction in nanofluids with and without surfactant. Further, the reclamation of these nanofluids performed using activated bentonite did not observe a marginal change in the magnitude of current concluding that depletion of EDL cannot reduce the streaming current as compared to base ester fluids. In addition, the thermal stability of ester fluids with GO nanoparticles is higher than TiO₂ nanoparticles which was due to less oxidation stability and a higher ratio of surface to volume in the former compared to the latter. The addition of fullerene nanoparticles towards synthetic ester fluid [131] observed an increase in heat transfer coefficient with not much change noticed on the addition of Span 20 as a surfactant. Thus, the different nanoparticles towards ageing conditions on ester fluids should be verified for its stability, electro-thermal, and other physio-chemical properties before loading them into real-time applications.

4. Current Trends in Ester-Nanofluids

The nanoparticle diffusion in ester fluids improves the specific dielectric properties such as breakdown voltage, thermal, fire point, and oxidation properties in the power transformers. The metal oxide nanoparticles (TiO₂, SiO₂) on ester fluids retards the electrons involved in the initiation of the discharge process improving the breakdown voltage. The Al₂O₃ and BN nanoparticles could be a suitable choice for improving the thermal conductivity of ester fluids with lower concentration levels. The GO nanoparticles provide the highest percentage increase in the fire point of ester fluids which could be considered for transformers nearer to load centers. The oxidative onset temperature of ester fluids with CaO and CdS nanoparticles increases which can delay the formation of peroxides responsible for the ageing phenomenon. The streaming phenomenon of ester nanofluids shows an increased current magnitude with pressboard interfaces which should be reduced using suitable additives (BTA, C₆₀) with a maximum concentration limited to 100 ppm. The stability of ester nanofluids varies with different nanoparticles during the ageing process which should be monitored continuously by the power insulation engineers. A negligible change in the viscosity of ester fluids is noted with different nanoparticles, thereby requiring no specific modifications in the existing cooling tubes involved with the ester-filled transformers.

5. Future Perspective and Conclusions

The following outcomes have been postulated on ester nanofluids for its application towards power transformers:

1. The effect of nominal voltage profiles of AC and DC voltages are widely presented on ester nanofluids. Nevertheless, now with the development of the HVDC transmission network and implementation of distributed power generation such as solar and wind, the impact of different harmonics and switching impulse overvoltages on both partial discharges and breakdown voltage is to be understood.
2. The impact of different nano-fillers on ester fluids should be optimized for its better electrical and dielectric properties for power transformers creating a complete database of information for the power engineers. The identification of accurate concentration of nanoparticles and surfactant on ester fluids can be performed through optimization techniques such as Response surface methodology, Genetic algorithm, or through hybrid methods available for engineering problems.
3. The metal-oxide nanoparticle is mostly used on ester fluids for improving the properties of ester fluids. However, the effect of magnetic field inside the transformers can modify the performance of these ester nanofluids with its orientation causing the insulation failure. Hence, a lot more research is required on the nanofluid's characteristics with the impact of the magnetic field.
4. The flow charges of the nanofluid are governed by the interfacial zone of the nanoparticle and surfactant on the base fluid. The interaction of different nanoparticles at the pressboard interfaces can differ modifying its charge formation. Further, the flow pattern of different nanofluids is to be clearly understood which can help in avoiding the static charges formed during the fluid filling in transformers.
5. The stability of ester-fluids towards thermal ageing is still unclear where the highly stable nanofluids at the start of power transformers can lead to sedimentation after a longer operational time. Thus, it is necessary to identify a nanoparticle that can provide better stability throughout its lifetime inside the transformers.

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