Electrical and thermal properties of insulating oil-based nanofluids: a comprehensive overview

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Abstract: Nanofluids, formed by adding nanoscale particles to insulating oil, are stable and homogeneous suspensions that present advanced performance of electrical insulation and heat dissipation. This study shows a comprehensive literature review based on the related results of nano-modified insulating oils (both mineral and vegetable insulating oils) to analyse the preparation methods, stability, dielectric spectroscopy, thermal conductivity, breakdown characteristics under AC and DC voltage, the thermal aging performance of nanofluids and oil-paper interaction. Then theoretical models have been introduced to explain the electrical mechanism of nanofluids. In addition, future research is proposed for nanofluids which would be low cost, highly stable and practically applicable to the power transformers.

1 Introduction

With the rapid development of the power system, voltage level and transmission capacity are rising which not only also reduces the safety and reliability of equipment. Oil-paper insulation as a more mature insulation technology has been widely used in the power equipment. Traditionally, mineral oils are widely used in power transformers due to excellent electrical characteristics. However, mineral insulating oils may easily lead to fire or even explosion accident in transformers due to the presence of polycyclic aromatic hydrocarbons in them, which do not satisfy the requirements of fire and safety. Mineral insulating oil being derived from petroleum products is a non-renewable resource and it is thought to be hazardous to the environment. In recent years, vegetable insulating oil, which is an environmentally friendly liquid dielectric, has been drawn attention as a potential alternative to traditional mineral oil for power transformers [1]. However, as the service time increases, the oil-paper insulation is exposed to more and more serious integrated aging problems, especially thermal aging because of severe electric, mechanical and thermal stresses and some other multiple physical factors [2].

Nanotechnology provides an effective way to improve the thermal and electrical performance of the transformers. As shown in Fig. 1, statistics show recently the transformer oil-based nanofluids are focused by researchers worldwide, meanwhile, magnetite ($\text{Fe}_3\text{O}_4$) and titanium dioxide ($\text{TiO}_2$) nanoparticles are widely used by researchers. Insulating oil-based nanofluid was first proposed by Siginer et al. in 1995 in order to improve the heat dissipation of insulation oil [3]. Choi et al. investigated that the thermal conductivity enhanced up to 8% by the addition of nano-alumina (nano-ALN) with 0.5 vol% in mineral oils and the overall thermal efficiency increased to 20% [4]. Subsequent studies have shown that aluminium oxide ($\text{Al}_2\text{O}_3$), silicon dioxide ($\text{SiO}_2$), silicon carbide (SiC), hexagonal boron nitride (h-BN), graphene and other nanoparticles can improve the thermal conductivity of insulating oils and hence provide more and better choices for transformer insulation applications [5–11].

In 2000, Segal et al. found that positive lightning impulse breakdown voltage (BDV) of nano-modified mineral oil enhanced up to 50% as compared to pure oil [12]. Segal investigated the colloidal fluids behaviour in power transformers and found that magnetic $\text{Fe}_3\text{O}_4$ do not bind with cellulosic fibres and they are relatively free to move in and out of the cellulose fibres and paperboard without being adsorbed, while the aging characteristics of nano-oil–paper composite system were much better than that of pure oil–paper insulation system. Then, a series of studies have been carried out on the insulation performance of nano insulating oil. The AC and DC breakdown characteristics of nano-oil, the
characteristics of lightning impulse, partial discharge characteristics, resistance to moisture and aging properties were found significantly higher than that of pure oil [13–15]. In recent years, the base oil of nanofluid fluid is also transformed from mineral oil to vegetable insulating oil [5, 16, 17].

This study reviews the numerous properties of different insulation oil-based nanofluids. First, preparation of stable nanofluids was introduced and stability mechanism was analysed. Second, numerous electrical properties of various nanofluids were compared and the mechanism of electrical performance enhancement was explained in detail. What is more, aging characteristics, colloid interaction with cellulose and thermal conductivity properties of nanofluids were discussed in detail.

2 Stable nanofluids preparation and stability measurement methods

2.1 Preparation of stable nanofluids

Two methods for stable nanofluid preparation exist: one-step method [18] and two-step method [19, 20]. One-step method: in which the preparation and dispersion of nanoparticles in insulating oil are executed at the same time that can save the time of storage, drying, and transportation of nanoparticles [21]. Reduced agglomeration of nanoparticles and improved stability of nano-oil are the advantages of using one step method. Bönennmann et al. prepared the mineral oil-based nano-Ag via one-step method [22]. However, agglomeration and sedimentation occurred after 1 month with a volume concentration of 0.011 and 0.3%. In the two-step method, first the nanoparticles are prepared followed by their surface treatment, and then magnetic stirring, ultrasonic dispersion, and ball milling are performed on surface-treated nanoparticles for better dispersion of nanoparticles in insulating oils [4, 23, 24].

2.2 Methods of stability measurement

Long-term stability and well dispersion of nanoparticles into insulating oil is the basis of its enhanced applications. There are many methods to evaluate the stability of nanofluids, some of them are shown in Fig. 2. First, sedimentation and centrifugation techniques are the simplest and used by many researchers [26–33]. Stability of the nanofluids is usually observed for more than 1 month under the same environment and persistent physical conditions or centrifuged for more than 10 h at high rotation speed without sedimentation. Secondly, zeta potential analysis, which is an important tool to evaluate the stability of colloid, has been widely used [34–38]. If the zeta potential of nanofluids is >40 mV, it is considered to be a stable nanofluid. Third, spectral absorbance analysis is also an effective method to determine the stability of nanofluids [39–43]. Since the concentration of nanoparticles and absorbance intensity are in a linear relationship, researchers used dispersion characteristics of nanofluids after sedimentation more than 24 h. Du et al. measured the dynamic light scattering of surface-modified TiO₂ nanoparticles in mineral oil and the results have shown that the size distribution in nanofluid was basically unchanged after 18 months, which proves that the nano-modified oil has good stability [44].

2.3 Enhancement of stability for nanofluids

The surfactants used for nanoparticles provide a bridge between liquid and solid phases and also this is an efficient way to enhance the stability of nanofluids. For a base fluid with mineral oil or vegetable insulating oil, the nanoparticles are usually modified by the lipophilic group that shows a highly stable dispersion in insulating oil. Currently, widely used surfactants are mainly oleic acid [4, 23, 24, 45–47], stearic acid or silicone oil [48] and cetyltrimethylammonium bromide [25]. Shen et al. prepared the modified ZnO nanoparticles via oleic acid molecules and modified the nano-ZnO surface by stirring and heating at 170°C for 24 h [45]. Li et al. were the first to prepare the modified Fe₃O₄ nanoparticles by the high temperature decomposition method with oleic acid modification [49] and obtained four different sized Fe₃O₄ nanoparticles by the decomposition method at high temperature and varying reaction time as shown in Fig. 3.

2.4 Stability mechanisms of nanofluids

If the nano-insulating oil has poor stability, the nanoparticles will agglomerate due to the surface energy and interface energy and no longer be stable, thereby affecting the dielectric and insulating properties of the nano-insulating oil. Nanoparticles dispersed in the base fluid will be subjected to various forces together, including van der Waals force, electrostatic force, solvation power, gravity, buoyancy etc. [50], and the dispersion stability is closely related to their physical and chemical properties. Derjaguin, Verway, Landau, and Overbeek (DVLO) theory indicated that stability of nanofluids is collectively determined by van der Waals attractive forces and electrical double layer repulsive forces [51, 52]. It suggests that if the repulsive forces are higher than the attractive forces, the nanofluid will be stable. With the nanoparticles without or with a very low concentration of surfactant, aggregation due to collisions or sedimentation due to gravity will be observed. However, with the excess of surfactant, as shown in Fig. 4, an additional steric repulsive force between each of the nanoparticles will be generated due to the double chain around the surface of nanoparticles [4]. Thirdly, electrostatic stabilisation is another mechanism to enhance repulsive forces for nanoparticles according to the DVLO theory. Hence, the agglomeration of nanoparticles is inhibited for these reasons and the stabilisation of nanofluids is ensured.
3 Electrical properties of nanofluids

3.1 Dielectric properties

Nano-materials, composed of a certain type of crystal, show superior physical and chemical properties, such as small size effect, volume effect and quantum tunnelling effect [53, 54]. Addition of nanoparticles will inevitably lead to a significant change in the dielectric properties of nanofluids [55].

Sartoratto et al. added surface modified Fe₃O₄ magnetic nanoparticles into mineral insulating oil and the results show that the addition of nanoparticles greatly increased the dielectric loss factor, electrical resistivity, and the imaginary part of dielectric constant, as indicated in Table 1. Specially, the relative permittivity remains constant until the volume fraction of nanoparticles reaches 0.016 in Table 1 [56]. When the volume fraction of nano-Fe₂O₃ is 0.8%, the dielectric loss factor of nanofluids is 0.1868, which is 51 times higher than that of pure oil (0.0036). Moreover, magnetic nanoparticles reduce the volume resistivity, hence they might adversely be applied in the electrical field for nanofluid applications. The influence of frequency in the dielectric properties of nano-oil was investigated by Merges et al., who reported that Fe₃O₄-based nanofluids showed higher relative permittivity in the frequency range of 10⁻¹ × 10⁶ Hz and dielectric loss factor is also increased in the frequency range of 10⁻¹ × 10⁷ Hz [57]. Du et al. investigated the effect of temperature on dielectric properties of nanofluids as shown in Fig. 5. The semi-conductive Fe₃O₄ nanoparticles have decreased the electrical resistivity and increased the dissipation factor in different temperature ranges of the oil.

Table 1 Dielectric properties of pure mineral oil and nanofluids [56]

| Volume fraction, % | Electrical resistivity, \(\times10^{10}\) Ωm | Dielectric loss factor, tan δ | Relative permittivity (real part) | Imaginary part of dielectric constant |
|--------------------|---------------------------------|-------------------------------|----------------------------------|-------------------------------------|
| 0.0000             | 36.0                            | 0.00366                       | 2.1                              | 0.00769                             |
| 0.8000             | 0.0021                          | 2.389                         | 8.8                              | 21.023                              |
| 0.0160             | 0.73                            | 0.399                         | 2.1                              | 0.628                               |
| 0.0080             | 1.75                            | 0.1868                        | 2.1                              | 0.3923                              |
| 0.0040             | 2.5                             | 0.1274                        | 2.1                              | 0.2676                              |

Fig. 3 Transmission electron microscopy (TEM) and high resolution TEM images of monodispersed Fe₃O₄ nanoparticles at different reaction times [49]

(a) TEM image of modified Fe₃O₄ nanoparticles, (b) High resolution TEM image at 12 h, (c) High resolution TEM image at 24 h, (d) High resolution TEM image at 48 h, (e) High resolution TEM image at 72 h

Fig. 4 Steric and electrostatic stabilisation [25]

(a)-(d) Steric stabilisation at low coverage, full coverage and excess amount of surfactant, (d) Electrostatic stabilisation

However, insulated BN nanoparticles increased the electrical resistivity and decreased the dissipation factor, which is a beneficial dielectric property [58]. Li et al. investigated the dielectric properties of vegetable oil-based Fe₃O₄ nanofluid [23, 59]. They found that the dielectric loss factor of nano-oil is much lower than that of pure oil when the frequency is <10 Hz and also found that the volume resistivity of nanofluids was higher than that of pure vegetable oil when the frequency was >100 Hz. From Fig. 6, which shows the real part of the dielectric constant of nanofluids, it can be seen that smaller the size of nanoparticles, higher would be the dielectric properties and vice versa especially at the frequency range of 10⁻²–1 Hz. In addition, Table 2 listed the dielectric strengths such as AC, DC BDV, and impulse voltage of different nanofluids with different nanoparticles. Most of the studies focused on AC BDV, and the researches on DC BDV and positive impulse voltage are still lacking. In the list, the mineral-oil based nanofluid with the greatest improvement in AC and DC BDV and positive impulse voltage is the mineral-oil based Fe₃O₄ (diameter of Fe₃O₄ nanoparticle is about 10 nm; nearly spherical). As for vegetable oil, the vegetable oil-based nanofluid with the greatest improvement in AC BDV and positive impulse voltage is the vegetable oil-based Fe₃O₄ (diameter of Fe₃O₄ nanoparticle is 6.8–24.4 nm; nearly spherical). What is more, it is seen that most of the nanoparticles are nearly spherical, seldom is there any other shapes studied. Lv et al. studied the morphology such as the size and shape of nanoparticle that affects the dielectric properties, and they found that the positive impulse BDV and the conductivity of...
nanofluids with rod-like nanoparticles of TiO$_2$ increased 23 and 60.7%, respectively, compared to that of TiO$_2$ nanospheres [62].

### 3.2 AC and DC BDV characteristic

The traditional ‘bridge theory’ considers solid particles to be a source of great damage to insulation properties for insulating oils. These ‘impurity’ particles can distort the electric field and hence it is easy to form a discharge path, resulting in the breakdown of the insulating oil. However, nano-sized particles (TiO$_2$, Fe$_3$O$_4$, BN, SiO$_2$) added to nanofluids happen to destroy their dielectric strength, but on the other hand, help to enhance the insulation properties [18, 48, 58, 60, 75]. Nazari et al. reported that the AC BDV of mineral oil-based Fe$_3$O$_4$ nanofluids exhibited better performance than that of pure oil, after applying impulse current [18]. Thus, magnetic nanoparticles, which act as free electrons snapper, reduce the ionisation process of free electrons. Segal et al. used magnetic nanoparticles dispersed in mineral oil with moisture content <5 ppm [65] and found that nanoparticles did not change the AC BDV. However, as the moisture content increases any further (>10 ppm) in the oil, the AC BDV of nano-oil was increased than that of pure oil. Zhou et al. found that DC BDV of nano-modified mineral oil and pure oil is basically the same at relatively shorter gap distance, but with the increase of the gap distance, BDV of modified oil significantly increased compared with the pure oil [76]. Fig. 7 shows the breakdown property of mineral oil and mineral oil-based nanofluids under AC and DC voltage with different gap distance. Peter et al. found that the magnetic fluids with the volume concentration of <0.01% will have better dielectric properties than that of pure mineral oil [75]. An overly higher volume concentration of nanoparticles will lead to aggregation and strongly influence the dielectric breakdown strength of mineral oil. Chiesa et al. found that conductive Fe$_3$O$_4$ nanoparticles (electrical conductivity is $1 \times 10^4$ S/m) can improve the BDV of insulating oil, but the low electrical conductivity of SiC nanoparticles ($1 \times 10^2$ S/m) cannot improve insulation.

### Table 2 Enhancement of breakdown strength for different nanofluids

| Dielectric liquid         | AC Positive impulse voltage | Shape of nanoparticles |
|---------------------------|-----------------------------|------------------------|
| mineral oil-based TiO$_2$ [60, 61] | 27% (0.02 wt.%) | 23.6% (0.075 vol %) | sphere |
| mineral oil-based TiO$_2$ [62] | — | 55.5% (0.075 vol%) | rods |
| mineral oil-based Fe$_3$O$_4$ [63–65] | 42.8% | 21.4% (0.25 vol%) | 82.5% | — |
| mineral oil-based Fe$_2$O$_3$ [56] | 12.8% (0.016 vol%) | — | — | — |
| mineral oil-based SiO$_2$ [66] | 17% (0.074 vol%) | — | — | — |
| mineral oil-based Al$_2$O$_3$ [67] | reduction | — | — | — |
| mineral oil-based ZnO [68, 69] | 8.3% (0.0005 vol%) | — | — | — |
| mineral oil-based SiC [57] | reduction | — | — | — |
| mineral oil-based BN [58] | 28.6% (0.1 wt.%) | 20% (0.1 wt.%) | — | nearly spherical |
| mineral oil-based C$_60$ [69] | 34% (0.1%) | — | — | — |
| mineral oil-based AlN [70] | reduction | — | — | — |
| vegetable oil-based Fe$_3$O$_4$ [59, 71] | 63% (0.03 wt.%) | 37.4% | nearly spherical |
| vegetable oil-based TiO$_2$ [72] | 31% (0.00625 vol%) | — | — | — |
| vegetable oil-based BN [73, 74] | 31% (0.1 wt.%) | 13% (0.1 wt.%) | — | — |

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performance [56]. The influence of an external magnetic field on the dielectric BDV of nano-oil was investigated by Lee et al. [77]. The results show that the dielectric BDV of nano-oil with the external magnetic field was 30% higher than that without the external magnetic field. The dielectric strength and endurance aging test of vegetable oil-based nanofluids were investigated by Peppas et al. [78]. According to the results of BDV as indicated in Fig. 8, the maximum BDV is achieved at 0.008% wt./wt. (77.7 kV) with commercial Fe₃O₄ powder and 0.012% wt./wt. (77.8 kV) for nanofluids with oleate-coated colloidal Fe₃O₄. However, with the further addition of nano-Fe₃O₄, the BDV was significantly reduced. At even higher concentrations, the nanofluid turns out to be a semi-conductive liquid. This is probably due to the decreasing interparticle distance of the nano-Fe₃O₄ which, above a threshold value, start forming conductive paths. Fig. 9 shows that the nanofluids with oleate-coated colloidal Fe₃O₄ have high breakdown strength after 200 times endurance test.

3.3 Lightning impulse breakdown voltages

The characteristics of the impulse BDV are usually thought to be a key performance indicator of insulating materials, particularly for oil-paper insulation. Segal et al. have shown that the positive lightning impulse BDV of mineral oil-based ferrofluids was enhanced by 50% than that of pure oil under the needle to sphere electric impulse as reflected in Table 3 [65]. The development speed of the streamer is slower than pure oil and this phenomenon becomes more obvious when the gap distance is increased. However, the negative lightning impulse BDV under needle to sphere electric impulse is not that obvious. Du et al. found that the volume fraction of 0.075% of the TiO₂-transformer oil has a
positive impact on BDV and the BDV of nano oil increased by 23.6% and development rate of streamer decreased by 34.8% as compared to pure oil [61]. Positive and negative lightning impulse BDV of vegetable oil-based nano-Fe$_2$O$_3$ filler was increased by 37 and 12%, respectively [23]. It was first ever time to find that Fe$_2$O$_3$ nanoparticles improve the negative lightning impulse voltage and the main reason was analysed to be the huge differences between molecular structures of vegetable oil and the mineral oil.

The research on the breakdown process of insulating oils mainly focuses on the streamer development at the pre-breakdown phase [62, 79–83]. The liquid dielectric produces a weak discharge channel under the action of local high field strength and a ‘tree-like’ shape is generated in a very short time under external energy injection [84–86]. Lv et al. analysed the positive streamer patterns in mineral oil-based TiO$_2$ and Fe$_3$O$_4$ nanofluids [87–89].

### 3.4 Electrical mechanism

#### 3.4.1 Fast electronic capture model

In the latest decade, a large number of studies focused on the streamer development of nanofluids. Hwang et al. from Massachusetts Institute of Technology simulate the development process of streamers in nanofluids [90, 91]. Nanoparticles were polarised in short time under the action of the electric field, which they projected from the capture electron theory of conducting nanoparticles as illustrated in Fig. 10. The positive and negative ions produced by the polarisation of nanoparticles are uniformly distributed on the surface of nanoparticles along the direction of the electric field. At the same time, ions and electrons produced by the ionisation of nano-oil under an external electric field moved towards negative and positive electrodes, respectively. Since electron mobility ($\mu_e = 1 \times 10^{-4} \text{m}^2 \text{V}^{-1} \text{s}^{-1}$) is much larger than positive ion mobility ($\mu_p = 1 \times 10^{-9} \text{m}^2 \text{V}^{-1} \text{s}^{-1}$), electrons move rapidly along the direction of the electric field to the upper surface of positively charged nanoparticles, while the ions can approximately be considered to be stationary and not moving in a very short time interval. Electrons will be ‘captured’ by nanoparticles during the course of their motion which would tend to neutralise ions on the surface of nanoparticles and would immediately be re-distributed on the surface of the nanoparticles. This process is quite-like charging the surface of nanoparticles. As the charge reaches saturation, the whole of nanoparticles would become negatively charged and will not capture electrons any more. Thus, nanoparticles reduce the charge density and inhibit the streamer development in the nano-oil, resulting in improvement of the BDV.

The time of capturing electrons by nanoparticles in the transformer oil can be calculated as

$$\tau = \frac{2\varepsilon_1 + \varepsilon_2}{\sigma_1 + \sigma_e}.$$  

where $\varepsilon_1$ and $\varepsilon_2$ are relative dielectric constants of nanofluids and nanoparticles, respectively, $\sigma_1$ and $\sigma_e$ are the electrical conductivities of nanofluids and nanoparticles, respectively.

The relaxation time constant of nanoparticles ($\tau$) represents the speed of the polarisation process of nanoparticles under an applied electric field. Since the streamer development process in nanofluids is usually in microseconds, the relaxation time of nanoparticles is considered to be less than a microsecond. Therefore, the surface of nanoparticles can capture free electrons and inhibit the development of the streamer. On the other hand, if the polarisation relaxation time of nanoparticles is greater than the development time of the streamer, the streamer will not be affected and the breakdown performance of the insulating oil will not be improved.

According to the charge continuity equation and the Gaussian equation, Hwang further proposed the control equation for the development streamer of nano-oil as (see (2)) , $E$ is the electrical field, $\rho_p$, $\rho_n$, $\rho_e$, and $\rho_{np}$ are the densities of positive ions, negative ions, electrons, and charged particles, respectively. Also, $\mu_p$, $\mu_n$, $\mu_e$, and $\mu_{np}$ are the velocities of the above four kinds of particles, respectively, $\varepsilon$ is the relative dielectric constant of insulating oil. $G_i$ is the degree of dissociation of the oil-molecules due to the electric the field. $\tau$ is the time of adsorption of electrons for the neutral particles. $R_{np}$ is the binding constant for positive and negative ions and $R_{pe}$ is the binding constant for positive ions and electrons. $1 - H(\rho_{np, \text{sat}} - \rho_{np})$ describes the upper limit of nanoparticles to capture electrons.

\[
\begin{align*}
\nabla \cdot (\varepsilon \mathbf{E}) &= \rho_p + \rho_n + \rho_{np}, \\
\frac{\partial \rho_p}{\partial t} + \nabla \cdot (\rho_p \mathbf{u}_p) &= \rho_e \frac{\mu_e R_{pe}}{\varepsilon} + \rho_p \frac{\mu_p R_{np}}{\varepsilon}, \\
\frac{\partial \rho_n}{\partial t} + \nabla \cdot (\rho_n \mathbf{u}_n) &= -G_e \frac{\mu_e R_{pe}}{\varepsilon} + \rho_p \frac{\mu_p R_{np}}{\varepsilon} - \frac{\rho_e \mu_e}{\tau_e} \left[1 - H(\rho_{np, \text{sat}} - \rho_{np})\right], \\
\frac{\partial \rho_e}{\partial t} + \nabla \cdot (\rho_e \mathbf{u}_e) &= -\frac{\rho_p \mu_p R_{np}}{\varepsilon} + \rho_e \frac{\mu_e R_{pe}}{\varepsilon} - \frac{\rho_e \mu_e}{\tau_e} \left[1 - H(\rho_{np, \text{sat}} - \rho_{np})\right].
\end{align*}
\]
The streamer development of nano-insulating oil was simulated by the Cosmo finite element analysis method with the above equations, and the results are shown in Fig. 11. It can be seen from these figures that the space charge density of the nano-mineral insulating oil is obviously reduced compared with the ordinary insulating oil, and main charge gathering is near the electrode, which indicates that nanoparticles ‘capture’ free charge in the mineral insulating oil under the electric field. At the same time, in the direction of the needle-sphere electrode, electronegative particles increase obviously at the initial stage due to the electron adsorption at the nanoparticle surface and reach the maximum number of electrons adsorbed by the nanoparticles. Through the simulation of charge density of nano-insulating oil at different relaxation time, the maximum value of the adsorbed electrons of the nanoparticles is gradually shifted in the direction of the needle-ball electrode with the increase of the relaxation time of the nanoparticles.

However, Chiesaa et al. investigated the breakdown performance of different nano-insulating oils [57]. They found nano-SiC cannot improve the breakdown strength while the relaxation time \( \tau = 1.1 \times 10^{-12} \) s was much smaller than the time of the streamer developed. It has shown that there is some limitation to nanofluids by comparing the relaxation time with the development of the streamer.

3.4.2 ‘potential well’ model: In the dielectric liquids, there exist some chemical effects such as C=O, C=C, C–O bond etc., as the ‘trapping’ generated by carrier polarisation under the electric field, increases the dielectric BDV [92–94]. In 2007, Takada et al. further extended the research theory and proposed the deep trap theory of the space charge characteristics of nanocomposites [95]. The deep trap theory gives the impression that the nanoparticles can distort the electric field around its surface and form a charge trap on the surface of the nanoparticles due to the difference of relative permittivity between nanoparticles and dielectric liquid. The spherical coordinate system is shown in Fig. 12, in which the
The depth of the traps formed by the nanoparticles is about 5 eV, which is much larger than the trap depth of LDPE itself (0.45 eV). Thus, it can capture the carriers injected into the electrodes and improve the electric field distribution within the dielectric resulting in improvement of dielectric breakdown performance.

3.4.3 Shallow trap theory: To some extent, the deep trap theory explains that the addition of nanoparticles can enhance the breakdown performance of insulating oil. According to the deep trap theory, if the depth of traps generated by the nanoparticles in the electric field is greater than the depth of the trap of the dielectric itself, insulation properties will be improved. Conversely, there is no improvement. However, the same literature reported that deep traps generated in the electric field by ZnO, SiO2 nanoparticles were less than that of the pure insulating oil. It also improved the breakdown strength of insulating oil and is not applicable to the deep trap theory.

Du et al. investigated the modification mechanism of TiO2 nanoparticles by pulse electroacoustic (PEA) tests and thermally stimulated current (TSC) tests [72, 96]. Addition of TiO2 nanoparticles can significantly improve the dissipation rate of space charge in insulating oil and suppress the distortion of space electric field and can also improve the BDV of oil. Yu et al. measured the TSC of Fe3O4 nanofluids as shown in Fig. 14, the current peak value of nanofluids is about two times that of mineral oil [89].

The depth of trapping of mineral oil and nanofluids was 0.345 and 0.340 eV, respectively. It shows that the shallow trap density of nanofluids is much larger than that of mineral oil. They believe that the high-density shallow traps are likely to capture the fast electrons in nanofluids and could change into slow electrons, meanwhile forming a local negative space charge. Thus, the space charge density was reduced and resulted in more electric field distribution by the Kerr electro-optic technique [97]. Since the nanoparticles enhance the trap density of nanofluids, free electrons will be trapped and released in the process of movement and can hinder the migration of electrons. Thus, reducing the rate of streamer in the oil and improving its breakdown strength.

4 Aging characteristics

Aging of insulation material is the result of the combined effect of electrical, thermal, mechanical, environmental and other factors, and the insulation damage caused by the aging of the insulating material is the main reason for the insulation fault in the transformers. With the nanoparticles (CaCu3Ti4O12, TiO2, C60 etc.) addition in insulating oil, the aging characteristics of nanofluids will improve some of the electrical properties [98–104]. Segal et al. first investigated the accelerated aging test of nano-oil [105]. Insulation cardboard, silicon steel sheet, copper and other solid insulation materials were mixed with fresh mineral oil and nanofluid, respectively, and accelerated aging was performed for 12 weeks at 185°C. The result of BDV is shown in Table 4, and it was found that nanofluids appeared to be superior to fresh oil in anti-aging property [105]. Du et al. measured the effect of TiO2 nanoparticles on the electrical properties of mineral insulating oils with different aging levels [106, 107]. It was found that the BDV of the mineral insulating oil after aging by adding TiO2 nanoparticles was increased to the level before aging, the lightning striking voltage was increased by 30–40% and the local starting discharge voltage increased by 12%, and the same conclusion has been certified by Chen et al. [99]. Fig. 15 compares the partial discharge inception voltage of aged oil-based nanofluids and mineral oil at 130°C.

\[
V(r, \varphi) = \frac{\alpha E_0(r)}{4\pi} \left( \frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2 + \varepsilon_1} \right) \cos \varphi \sin \theta.
\]

where \(E_0\) is the field strength, \(r\) is the distance from the centre of the nanoparticles and \(a\) is the radius of the nanoparticle. From the results of the nano-polarisation model, we can see that the distribution of the surface potential of nanoparticles is also related to their size. Nanoparticle surfactants, which increase the effective radius of the nanoparticle, tend to increase the trap depth of the nanoparticles [49]. Subsequently, the potential well was deepened and the breakdown characteristics were enhanced.

Takada calculates the trap depth in the nano-MgO modified low-density polyethylene (LDPE) composite dielectric based on this model. As shown in Fig. 13, the maximum depth of the trap is on the surface of the nanoparticle under the external electric field. The depth of the traps formed by the nanoparticles is about 5 eV, which is much larger than the trap depth of LDPE itself (0.45 eV). Thus, it can capture the carriers injected into the electrodes and improve the electric field distribution within the dielectric resulting in improvement of dielectric breakdown performance.

**Fig. 13 Cross-sectional view (left) and 3D view (right) of trapping depth distribution of nanoparticle [95]**

**Fig. 14 TSC curve of Fe3O4 nanofluids and pure transformer oil [89]**

\[
V(r, \varphi) = \frac{\alpha E_0(r)}{4\pi} \left( \frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2 + \varepsilon_1} \right) \cos \varphi \sin \theta \int_0^\theta \int_0^\varphi \sin^2 \theta \cos \varphi \sin \theta \cos (\varphi - \varphi') d\varphi d\theta.
\]

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The experimental results signify that the addition of nanoparticles can improve the anti-aging performance of insulating oil. Compared to pure insulating oil, the oil-based nanofluids have shown numerous excellent performance such as AC breakdown strength, lightning impulse BDVs, and partial discharge inception voltage. Yu et al. found that TiO$_2$ nanoparticles induced the space charge decay in aged nano-oil [108]. As shown in Fig. 16, the maximum space charge around anode in nano-oil is higher than that of aged pure oil. The decay rate of space charge in nano-oil is increased by 1.57 times of that in aged pure oil at first 8 s, which indicated that the space charge rapidly transports through the nanofluids by TiO$_2$ nanoparticles. At the same time, they tested the TSC to analyse the trap characteristics of aged oil as illustrated in Fig. 16. It can be seen that the current peak of nano-oil shifted from 310 to 295°C (pure oil), which is related to the trap energy level. Also, Fig. 17 indicated that shallower trap levels are generated with nanoparticles addition.

### 5 Colloid interaction with cellulose

Oil-paper insulation is widely used in the electrical insulation equipment which strengthens the pressboard mechanically, well accords with electrical equipment in all the aspects of electrical, mechanical, thermal and other requirements of the insulation system. Therefore, a single study of the performance of nano-oil cannot satisfy the requirements of the actual applications. Segal et al. investigated the interaction between nano-oil and insulating pressboard [12]. They found the nanoparticles could flow into the paperboard with the process nanofluid-impregnated pressboard (NP). It influences the electrical properties of the insulating pressboard due to the nanoparticles residing in the pressboard. Through scanning electron microscopy (SEM) images of oil-impregnated pressboard (OP) and NP in Fig. 18, it can be clearly seen that nanoparticles are completely distributed in the core of pressboard. Fig. 19 shows the internal charge and electric field distribution of OP and NP by PEA, which indicates that the internal electric field of NP is more uniform than that of OP [109, 110]. The more uniform electric field and higher charge transportation rate of nanoparticles in pressboard make DC and AC BDV higher.

Roman et al. investigated magnetic nanoparticles effect on the thermal degradation of oil-paper insulation [111] and found that magnetic nanofluids impregnated pressboard offer much more resistance to moisture than that pressboard impregnated by pure mineral oil. In addition, nanofluids maintain stable within 800 h of thermal aging at 90°C. The long-hour stability under high temperature indicates ultra-long term stability of nanofluid under normal conditions (25°C).

### Table 4 BDV of aged mineral oil and nanofluids

| Simple ID    | AC strength, kV | Positive | Impulse withstand, kV |
|--------------|-----------------|----------|-----------------------|
| aged nanofluids | 43.1            | 127      | 119                   |
| fresh nanofluids | 47.5            | 145      | 143                   |
| aged oil carrier   | 32.0            | 81       | 129                   |
| fresh oil carrier  | 48.9            | 93       | 157                   |

![Fig. 15 Partial discharge inception voltage of aged oil-based nanofluids and mineral oil [106]](image1)

![Fig. 16 Space charge accumulation and decay characteristics of (up) aged pure mineral oil and (down) nano-oil [108]](image2)
In power transformers, the insulating liquid dielectric plays its role not only in insulation but also in heat dissipation. The internal heat source of the oil-immersed transformer is mainly generated by core losses and winding losses, and the losses transform into heat, resulting in the increased temperature of the oil [112, 113]. The improved insulation and heat transfer performance are beneficial to the miniaturisation of high-power transformers.

Transformer oil-based nanofluids being new insulating dielectrics, and researchers are mainly concerned about their thermal performance. The addition of nanoparticles can greatly improve the thermal conductivity of base fluid [58, 114–117]. Chiesa investigated the effects of four kinds of nanoparticles (Al$_2$O$_3$, SiO$_2$, SiC, Fe$_3$O$_4$) on the thermal conductivity of mineral insulating oil and polyalphaolefin (PAO) [57]. As shown in Fig. 20, the thermal conductivity of nano-oil increases with the nanoparticles volume fraction. As the nano-SiC fraction is 1 vol.%, the thermal conductivity of mineral insulating oil and PAO insulating oil is increased by 5 and 10%, respectively. For 2D nanoparticles, h-BN and graphene could greatly enhance the thermal conductivity of mineral oil at a low mass fraction.

With the increase of temperature, the thermal conductivity of h-BN nano-oil with 0.1 wt.% can be increased to 75% (323 K), and graphene nano-oil increased to 9.5% with 0.01 wt.% as depicted in Fig. 21.

Choi et al. found that AlN nanoparticles can enhance the thermal conductivity of transformer oil by 8% and overall heat transfer coefficient by 20% at 0.5 vol.% [4]. Peppas et al. investigated the thermal response of the nanofluids [78]. From the results shown in Fig. 22, it is clear that heat transfer increases when nanoparticles concentration is increased. Both heating and cooling are observed to be 45% faster at 0.012% w/w concentration.

Nanoparticles dispersed in the insulating oil will form an adsorption layer on their surface. The physical and chemical properties of the adsorption layer are different for different nanoparticles and base oil, which plays a key role in improving the thermal conductivity of liquids, serves as a bridge for the heat exchange between nanoparticles and insulating oil [119]. It can be concluded that thicker the layer, the more obvious the enhancement in thermal conductivity will be. The effect of the nano-adsorbent layer seems more obvious [120].

Moreover, the agglomeration of nanoparticles in the nanofluids will reduce the effective contact area between the adsorption layer and the base fluids, which is not favourable to the enhancement of the thermal conductivity [121–123]. The Brownian motion also affects the thermal conductivity of nanofluids. The motion of nanoparticles itself and convection caused by Brownian motion will obviously improve the thermal conductivity [123–125].
Conclusion

Nanofluid as a new type of insulating material for transformers is a new development prospect to traditional oil–paper insulation system. On the one hand, it can significantly improve the insulation performance of the oil and on the other hand, it can enhance the thermal performance of the transformer. Thus, enhances the effective service life and operation safety of oil–paper insulation system in electrical equipment. This study is basically based on the research of nano-oil and oil–paper insulation systems in recent years and summarises the insulation and heat transfer characteristics of nano-oil. At the same time, the modification mechanism of nanoparticles is also analysed. However, nano-oil and nano-oil paper system being a new area, yet needs to be researched more, whether its theoretical explanation or thermal conductivity mechanism or the insulation characteristics have a lot of problems that need to be explored.

i. Selection of nanomaterials. The present research shows the effect of different nanoparticles on the thermal conductivity of the transformer oil and overall heat transfer efficiency is very different, especially the graphene, which shows a significant improvement in the oil properties. However, transformer oil as an insulating dielectric for long-term operation of the transformer, its insulation properties (electrical characteristics and anti-aging) and stability (nanoparticle agglomeration degree and settlement rate) are important factors that affect the performance of nano-oil. Therefore, the choice of nanoparticles to satisfy the transformers’ needs is worth to be researched.

ii. Preparation of low cost and high-performance nanoparticles. Most of the recent research has used a two-step method to prepare nanoparticles and then disperse them in transformer oil. This method requires a higher production cost. How to improve the preparation process of nanoparticles with high efficiently and low cost will be important research in the future.

iii. Effect of nanoparticles on electrical resistivity and dielectric loss. The present research shows usually conductive nanoparticles reduce the electrical resistivity and increase the dielectric loss. The higher dielectric loss will result in heating of the transformer. Particularly, vegetable insulating oil, which itself has a higher dielectric loss than mineral oil, dielectric loss needs to be reduced and electrical conductivity should be increased. How to reduce the negative effect of nanoparticles on conductivity and dielectric loss of nanoparticles and nanofluids, needs to be investigated further.

iv. Effect of nanoparticles on oil–paper insulation system. However, the influence of nanoparticles on oil–paper insulation system is relatively lower. The addition of the nanoparticles will affect the dielectric constant of oil and paper, which has a greater impact on the distribution of the...
Acknowledgments

Asadi, A., Asadi, M., Rezaniakolaei, A.

Liao, R., Liang, S., Yang, L.

Liang, N., Liao, R., Xiang, M.

Sun, P., Sima, W., Zhang, D., et al.

Primo, V.A., Garcia, B., Albarracin, R.: ‘Improvement of transformer liquid nano-TiO$_2$ and investigation of its breakdown and dielectric properties’, IEEE Trans. Dielectr. Electr. Insul., 2015, 22, (5), pp. 1800–1806.

Perreira, I., Ziehliska, A., Ferreira, N.R.: ‘Optimization of in-line oil-loaded solid liquid nanoparticles using experimental design and long-term stability studies with a new centrifugal sedimentation method’, Int. J. Pharm., 2018, 549, (1), pp. 261–270.

Langevin, D., Loozano, O., Seielstad, A., et al.: ‘Inter-laboratory comparison of nanoparticle size measurements using dynamic light scattering and differential centrifugal sedimentation’, Nanomaterials, 2018, 30, pp. 13–21.

Xia, W., Zhao, J., Wu, Y.: ‘Analysis of oil-in-water based lubricants with varying mass fractions of oil and TiO$_2$ nanoparticles’, Wear, 2018, 396–397, pp. 162–171.

Wang, Z., Liao, Z., Yan, Y.: ‘Dispersion and sedimentation of titanium dioxide nanoparticles in freshwater algae and daphnia aquatic culture media in the presence of arsene’, J. Exp. Nanosci., 2018, 13, (1), pp. 119–129.

Tao, P., Shu, L., Zhang, J., et al.: ‘Silicone oil-based solar-thermal fluids dispersed with PDSM-modified Fe$_3$O$_4$ graphene hybrid nanoparticles’, Prog. Nat. Sci. Mater. Int., 2018, 28, (5), pp. 554–562.

Singh, A.K., Raykar, V.S.: ‘Microwave synthesis of silver nanoparticles with polyvinylpyrrolidone (PVP) and their transport properties’, Colloid Polym. Sci., 2008, 286, (14), pp. 1667–1673.

Li, D., Kaner, R.B.: ‘Processable stabilizer-free polyaniline nanoparticle aqueous colloids’, Chem. Commun., 2005, (26), pp. 3286–3288.

Zhu, H., Zhang, C., Tang, Y., et al.: ‘Preparation and thermal conductivity of suspensions of graphite nanoparticles’, Carbon, 2007, 45, (1), pp. 226–228.

Zhu, D., Li, X., Wang, N., et al.: ‘Dispersion behavior and thermal conductivity characteristics of Al$_2$O$_3$–H$_2$O nanofluids’, Curr. Appl. Phys., 2009, 9, (1), pp. 131–139.

Kim, H.J., Bae, C., Oune, J.: ‘Characteristic stability of bare Au-water nanofluids fabricated by pulsed laser ablation in liquids’, Opt. Lasers Eng., 2009, 47, (5), pp. 532–538.

Wang, X., Li, X., Wang, S.: ‘Effect of pH and SDBS on the stability and thermal conductivity of nanofluids’, Energy Fuels, 2009, 23, (5), pp. 2684–2689.

Misam, T., Alonso, U., Fernández, A.M., et al.: ‘Analysis of the stability behaviour of colloids obtained from different smectic clays’, Appl. Geochem., 2019, 92, pp. 180–187.

Jeong, O., Shin, M.: ‘Preparation and stability of resistant starch nanoparticles, using acid hydrolysis and cross-linking of waxy rice starch’, Food Chem., 2018, 256, pp. 77–84.

Huang, J., Wang, X., Long, Q., et al.: ‘Influence of pH on the stability characteristics of nanofluids’, 2009 Symp on Photomics and Optoelectronics, Wuhan, China, 2009, pp. 1–4.

Farahmandjou, M., Seht, S.A., Parhizgar, S.S., et al.: ‘Stability investigation of colloidal Fe$_3$O$_4$ nanoparticle systems by spectrophotometer analysis’, Chin. Phys. Lett., 2009, 26, (2), p. 27501.

Gimeno-Furio, A., Navarrete, N., Martínez-Cuenca, R., et al.: ‘Influence of high temperature exposure on the thermal and optical properties of thermal oil-based solar nanofluids’, Sol. Energy Mater. Sol. Cells, 2018, 185, pp. 1062–1071.

Karhikeyan, A., Coulombe, S., Kitzberg, A.M., et al.: ‘Interaction of oxygen functionalized multi-wall carbon nanotube nanoparticles with copper’, Carbon, 2018, 130, pp. 201–209.

Yadav, N., Jaral, R.K., Rao, U.M.: ‘Characterization of mineral oil based Fe$_3$O$_4$ nanofluid for application in oil filled transformers’, Int. J. Electr. Eng. Energ., 2018, 10, (2), pp. 338–349.

Du, J., Li, Y., Li, S., et al.: ‘Effect of water adsorption at nanoparticle–oil interface on charge transport in high humidity transformer oil–nanofluid’, Colloids Surf. A Physicochem. Eng. Aspects, 2012, 415, pp. 153–158.

Shen, L.P., Wang, H., Dong, M., et al.: ‘Solvothermal synthesis and electrical conductivity model for the zinc oxide-insulated oil nanofluid’, Phys. Lett. A, 2012, 376, (10), pp. 1054–1056.

Tao, C., Wang, B., Barber, G.C., et al.: ‘Tribochemical behaviour of SnO$_2$ nanoparticles as an oil additive on brass’, Lubr. Sci., 2018, 30, (5), pp. 247–255.

Ghasemi, R., Fazlali, A., Mohammadi, A.H.: ‘Effects of TiO$_2$ nanoparticles and oleic acid surfactant on the rheological behaviour of engine lubricant oil’, J. Mol. Liq., 2018, 268, pp. 925–930.

Du, Y., Li, Y., Wang, F., et al.: ‘Effect of TiO$_2$ nanoparticles on the breakdown strength of transformer oil’, 2010 IEEE Int. Symp. on Electrical Insulation, San Diego, CA, USA, 2010, pp. 1–3.

Li, J., Du, B., Wang, F., et al.: ‘The effect of nanoparticle surfactant polarization on trapping depth of vegetable insulating oil-based nanofluids’, Phys. Lett. A, 2016, 380, (4), pp. 604–608.

Trahr, W.J.: ‘The influence of pulp potential in sulphide flotation’, 1984.

Popa, I., Gillies, G., Papastavrou, G., et al.: ‘Attractive and repulsive electrostatic forces between oppositely charged latex particles in the presence of anionic linear polyelectrolytes’, J. Phys. Chem. B, 2010, 114, (9), pp. 3170–3177.

Misam, T., Adell, A.: ‘On the applicability of DLVO theory to the prediction of clay colloids stability’, J. Colloid Interface Sci., 2000, 230, (1), pp. 150–156.
Yao, W., Huang, Z., Li, J., et al.: ‘Effect of nanoparticles on transformer propagation breakdown and breakdown of vegetable oil-pressboard interface in non-uniform field’, Appl. Phys. Lett., 2016, 108, (8), p. 85205.

Wang, T., Tao, F., Wei, et al.: ‘Influence mechanisms of pulse duration on transformer oil breakdown characteristics’, 2018 12th Int. Conf. on the Properties and Applications of Dielectric Materials (ICPADM), Xi’an, China, 2018, pp. 1098–1101.

Li, Y., Wen, J.Y., Liang, Y., et al.: ‘Streamer discharge propagation and branching characteristics in transformer oil under AC voltage: partial discharge and lightning impulse voltage’, IEEE Trans. Dielectr. Electr. Insul., 2017, 24, (3), pp. 746–886.

Xiong, Q., Nikiforov, A.Y., Lu, X.P., et al.: ‘A branching streamer propagation argon plasma plume’, IEEE Plasma Sci., 2011, 39, (11), pp. 2094–2095.

Lv, Y., Ge, Y., Du, Q., et al.: ‘Fractal analysis of positive streamer patterns in transformer oil-based TiO2 nanofluid’, IEEE Trans. Plasma Sci., 2015, 43, (7), pp. 1704–1709.

Lv, C.Y., Ge, Y., Li, C., et al.: ‘Effect of TiO2 nanoparticles on streamer propagation in transformer oil under lightning impulse voltage’, IEEE Trans. Dielectr. Electr. Insul., 2016, 23, (4), pp. 2110–2115.

Lv, Y., Wang, Q., Zhou, Y., et al.: ‘Effect of Fe3O4 nanoparticles on positive streamer propagation in transformer oil’, AIP Adv., 2016, 6, (3), p. 35110.

Hwang, J.G., O’Sullivan, F., Zahn, M., et al.: ‘Modeling of streamer propagation in transformer oil-based nanofluids’. 2008 Annual Report Conf. on Electrical Insulation and Dielectric Phenomena, 2008, pp. 361–366.

Hwang, J.G., Zahn, M., O’Sullivan, F.: ‘Effect of nanoparticles charging on streamer development in transformer oil-based nanofluids’, J. Appl. Phys., 2010, 107, (1), p. 14310.

O’Sullivan, F.M.: ‘A model for the initiation and propagation of electrical streamers in transformer oil and transformer oil based nanofluids’, (Massachusetts Institute of Technology, Boston, MA, USA, 2007).

Menner, M., Quirké, N.: ‘Molecular modeling of electron trapping in polymer insulators’, J. Chem. Phys., 2000, 113, (1), pp. 369–376.

Zhang, C., Cui, W., Bao, K., et al.: ‘Effects of trap characteristics on streamer propagation in dielectric liquid’. 2017 IEEE 19th Int. Conf. on Dielectric Liquids (ICDL), Manchester, United Kingdom, 2017, pp. 1–4

Takada, T., Hayase, Y., Tanaka, Y., et al.: ‘Space charge trapping in electrical potential well caused by permanent and induced dipoles for LDPE/MgO nanocomposites’, IEEE Trans. Dielectr. Electr. Insul., 2008, 15, (1), pp. 152–160.

Du, Y., Lv, Y., Li, C., et al.: ‘Effect of semiconductive nanoparticles on insulating performances of transformer oil’, IEEE Trans. Dielectr. Electr. Insul., 2012, 19, (3), pp. 770–776.

Yang, Q., Yu, F., Sima, W., et al.: ‘Space charge inhibition effect of nano-Fe3O4 on improvement of impulse breakdown voltage of transformer oil based on improved Kerr optic measurements’, AIP Adv., 2015, 5, (9), p. 92707.

Rafiq, M., Wang, W., Ma, K., et al.: ‘Insulating and aging properties of transformer oil-based TiO2 nanofluids’. 2014 IEEE Conf. on Electrical Insulation and Dielectric Phenomena (CEIDP), Des Moines, USA, 2014, pp. 457–461.

Mu-tian, C., Yue-fan, D., Yu-zhen, L., et al.: ‘Effect of nanoparticles on the dielectric strength of aged transformer oil’. 2018 Annual Report Conf. on Electrical Insulation and Dielectric Phenomena, Toyohashi, Japan, 2017, pp. 1–4

Zmarz, D., Dobry, D.: ‘Analysis of properties of aged mineral oil doped with C60 fullerene’, IEEE Trans. Dielectr. Electr. Insul., 2014, 21, (3), pp. 1119–1126.

Aksamit, P., Zmarny, D., Boczar, T., et al.: ‘Aging properties of fullerene doped transformer oils’. 2016 IEEE Int. Symp. on Electrical Insulation, San Diego, CA, USA, 2010, pp. 1–4.

Rajan, N., Prasath, R.T.R., Roy, N.K.: ‘Aging performance of mineral oil using ZnO nanofluids’, Int. J. Innov. Eng. Technol., 2016, 6, (3), pp. 155–162.

Prasath, R.T.R., Thomas, P., Cruz, A.P., et al.: ‘Aging analysis of mineral insulating oils using CTCO nanofluids’. 2015 Int. Conf. on Energy, Power and Environment Towards Sustainable Growth (ICEPE), Shillong, India, 2015, pp. 1–7.

Segal, V., Nattrass, D., Raj, K., et al.: ‘Accelerated thermal aging of petroleum-based ferrofluids’, J. Magn. Magn. Mater., 1999, 201, (1), pp. 70–76.

Lv, Y.Z., Du, Y.F., et al.: ‘Nanoparticle effect on electrical properties of aged mineral oil based nanofluids’, CIGRE, 2012, D1–106.

Yue-fan, D., Yu-zhen, L., Jian-quan, Z., et al.: ‘Effect of using ZnO nanofluids’, J. Nanomater., 2016, D1–106.

Lee, J.-C., Seo, H.-S., Kim, Y.-J.: ‘The increased dielectric breakdown voltage of transformer oil-based nanofluids by an external magnetic field’, Int. J. Therm. Sci., 2012, 62, pp. 29–33.

Peppas, G.D., Boudrinatros, A., Chalatsalampakis, V.P., et al.: ‘Ultrastable natural ester-based nanofluids for high voltage insulation applications’, ACS Appl. Mater. Interfaces, 2016, 8, (38), pp. 25202–25209.

Porto, R., ‘Prediction of breakdown voltage of transformer oil from predischARGE phenomena’, IEEE Trans. Dielectr. Electr. Insul., 2003, 10, (6), pp. 933–941.

Butcher, M., Neuber, A.A., Cevallos, M.D., et al.: ‘Conduction and breakdown mechanisms in transformer oil’, IEEE Trans. Plasma Sci., 2006, 34, (2), pp. 467–475.
[110] Du, Y., Li, Y., Li, C., et al.: ‘Effect of nanoparticles on charge transport in nanofluid-impregnated pressboard’, J. Appl. Phys., 2012, 111, (12), p. 124322

[111] Cimbula, R., Backo, S., Krúželák, L., et al.: ‘Thermal degradation of transformer pressboard impregnated with magnetic nanofluid based on transformer oil’, 2017 18th Int. Scientific Conf. on Electric Power Engineering (EPE), Kouty nad Desnou, Czech Republic, 2017, pp. 1–5

[112] Tang, W.H., Wu, Q.H., Richardson, Z.J.: ‘Equivalent heat circuit based power transformer thermal model’, IEE Proc.—Electric Power Appl., 2002, 149, (2), pp. 87–92

[113] Khare, V., Khare, C.J.: ‘Aspects of transformer in electricity generation: a review’, J. Adv. Mach., 2018, 3, (2), pp. 1–33

[114] Du, B.X., Li, X.L., Xiao, M.: ‘High thermal conductivity transformer oil filled with BN nanoparticles’, IEEE Trans. Dielectr. Electr. Insul., 2015, 22, (2), pp. 851–858

[115] Xuan, Y., Li, Q.: ‘Heat transfer enhancement of nanofluids’, Int. J. Heat Fluid Flow, 2000, 21, (1), pp. 58–64

[116] Wang, X.-Q., Majumdar, A.S.: ‘Heat transfer characteristics of nanofluids: a review’, Int. J. Therm. Sci., 2007, 46, (1), pp. 1–19

[117] Sairar, R., Leong, K.Y., Mohammad, H.A.: ‘A review on applications and challenges of nanofluids’, Renew. Sustain. Energy Rev., 2011, 15, (3), pp. 1646–1668

[118] Taha-Tijerina, J., Narayanan, T.N., Gao, G., et al.: ‘Electrically insulating thermal nano-oxides using 2D fillers’, ACS Nano, 2012, 6, (2), pp. 1214–1220

[119] Tillman, P., Hill, J.M.: ‘Determination of nanolayer thickness for a nanofluid’, Int. Commun. Heat Mass Transf., 2007, 34, (4), pp. 399–407

[120] Xie, H., Fujii, M., Zhang, X.: ‘Effect of interfacial nanolayer on the effective thermal conductivity of nanoparticle-fluid mixture’, Int. J. Heat Mass Transf., 2005, 48, (14), pp. 2926–2932

[121] Gharagozloo, P.E., Goodson, K.E.: ‘Temperature-dependent aggregation and diffusion in nanofluids’, Int. J. Heat Mass Transf., 2011, 54, (4), pp. 797–806

[122] Hong, J., Kim, D.: ‘Effects of aggregation on the thermal conductivity of alumina/water nanofluids’, Thermochim. Acta, 2012, 542, pp. 28–32

[123] Ghasemi, B., Aminossadati, S.M.: ‘Brownian motion of nanoparticles in a triangular enclosure with natural convection’, Int. J. Therm. Sci., 2010, 49, (6), pp. 931–940

[124] Li, J., Kleinstreuer, C.: ‘Thermal performance of nanofluid flow in microchannels’, Int. J. Heat Fluid Flow, 2008, 29, (4), pp. 1221–1232

[125] Daviran, S., Kazarian, A., Tahmooressi, H., et al.: ‘Evaluation of clustering role versus Brownian motion effect on the heat conduction in nanofluids: a novel approach’, Int. J. Heat Mass Transf., 2017, 108, pp. 822–829