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State-of-Art in Nano-Based Dielectric Oil: A Review

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ABSTRACT Dielectric fluids or commonly oils serve as the protection of any power utility components, which make it selection crucial for utility. Due to its significance, consistent research has been performed and new insulants have been introduced for power utilities to attain better, reliable, and a longer lifespan than the former one. Nanotechnology-based insulating liquids are still under research but show the potential to achieve the objective of smart and futuristic insulation. This paper provides the critical review for the development of insulating liquid and promising results shown by the nanoparticles dispersed fluid termed nanofluids. The state-of-the-art research illustration includes synthesis, experimental investigation, and dielectric and physio-mechanical characterization of nanofluids. The enhancements in the characteristics of nanofluids are elucidated along with its possible mechanisms and shortcomings.

INDEX TERMS Liquid dielectric, nanofluids, mineral oil, natural oil, nanoparticles, dielectric response, breakdown characteristics.

I. INTRODUCTION

The steady and never meeting demand of electricity is a continuous challenge for the researchers to improve the power generation/distribution on a more substantial gauge and enhanced capitals. Reliable operation of the transformer (i.e. the fundamental component of power transmission and distribution systems) is of the utmost importance [1], and around one-third of the transformer failures are provoked by the insulation failure [2]. The insulating oil outlines the usability, performance, and aging of transformer [3] for expediting the development of the insulating medium. For the accomplishment of futuristic insulating oil, conventional transformer oils are treated with nanotechnology for significant cost savings and enhanced dielectric properties [4].

Nanofluid (NF) is newly evolving product of nanotechnology-in application of dielectric fluid and coolant, engineered by stably dispersing the colloidal particles, which typically sized in the order of nm into the traditional base fluids with the support of surfactants [5], [6]. The addition of nanoparticles enhance the heat transfer performance of transformer oil along with the improvement in the dielectric performance [7]. Choi and Eastman [8] put forward the concept of nanofluid in 1995 comprising the base liquid and uniform dispersion of nanoparticles in it. Choi [9] described multi-benefits of nanofluids such as aggrandized surface area, better dispersion stability, significant heat flow rate and higher breakdown strength as a huge advantage for the modern industrialized applications over the conventional fluids.

The literature reviews on nanofluids published by the previous authors are mostly confined to nanofluids as thermal fluid or coolant. Its synthesis [11], [12], characterization [11]–[14], mechanism [14]–[16], applications [6], [11]–13], and future challenges [6], [7], [10] undoubtly stand out as the next-level heat exchanger. The individual nanoparticle (NP) based review has also been published [16]. The whole past work was limited to water, ethylene glycol, pump oil, etc. as base fluid, which are conventional conductive medium and a single review of nanofluid as an enhanced insulant has been discussed. Lv *et al.* [4] illustrated the electrical properties of limited nano-based insulating oils with the lack of stability analysis, and the role of surfactants and the environmental influence.

This paper aims to provide the state-of-art literature reviews on the nanofluids in the dielectric application which is significantly demanded. The recent progress and evolutionary impact of NPs over the conventional dielectric liquids along with the study of the NFs stability, surfactant enactment and dielectric influence in presence of physio-mechanical characteristics are reviewed in this paper.

II. HISTORY

Narrow applications of gaseous dielectric have led to the abundant applications of liquid dielectrics globally in traditional power utility components [17]–[19], transmission components [20]–[22], protection schemes [22], [23], advanced power electronic thermal management [24], etc. The mineral oil obtained from petroleum with ideal insulating characteristics [3], [25], [26] is a well-known commercial dielectric liquid since the 19th century and probably shall ensure its market continuously [27]. Halogenated hydrocarbons based oil [28] for special applications were introduced in 1930, but due to its biohazards [29], its uses were prohibited soon to preserve ecosystem and also its alternative has been developed. Liquid insulation with its bifunctional characteristics are mandatory from huge power transformer to μ-electronics heat sink. Its development originates from various synthetic and natural liquid dielectrics consisting of synthetic hydrocarbons [30]–[32], silicone oils [33]–[36], synthetic esters [37]–[39], vegetable oils [40]–[43], and hybrid oil as classified on the basis of applications in Figure 1. The specific applications of a dielectric liquid overridden by the intermixing of different oil to obtain the specific properties of insulant have been evaluated for over a decade[44]–[48].

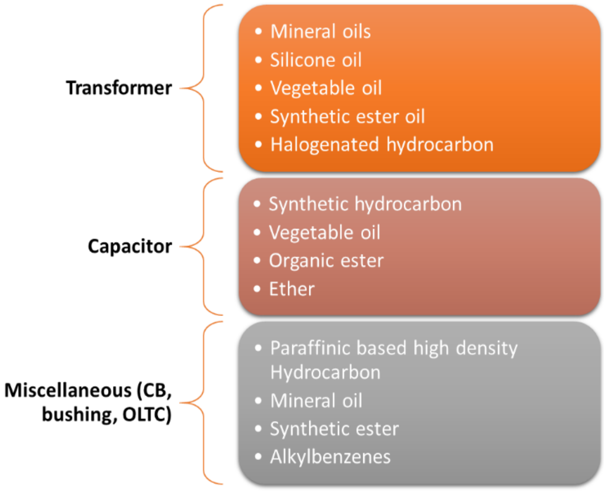

FIGURE 1. Classification of dielectric fluid or insulating oil on the basis of applications. The selection of insulating oil depends on application requirement and commerce of implementation.

The principle of Superconductivity is utilized in various power applications like cables and transformers insulation with the critical requirement of steady temperature. Costly liquid nitrogen and other cryogenic liquids with their superior dielectric strength are making their place as coolant and insulant in the power equipment [49]–[53]. However, much work is needed to exploit the nanofluids potential to the fullest.

A. INTRODUCTION TO NANOFILLERS

The process of performance enhancement of the dielectric liquid has been researched for over the decades. Many chemicals have been used as additives in the dielectric fluid to inhibit, passivate, reduce pour-point or scavenge the electrons present in the dielectric fluid [25], [54]. The chemicals such as 2,6-ditertiary-butyl paracresol and 2,6-ditertiary-butyl phenol with concentrations less than 0.1% of mass in fluid act as the antioxidant to improve the expected insulation age [48], [49].

Afore nanotechnology, dielectric enhancement of the base fluid tried with the dispersion of micron-sized colloids in the fluid [52] which results into significant deterioration in dielectric characteristics of the suspension, as the micron sized particle are considered as the electron trapping sites which hasten streamer development due to the local field enhancement. Another shortcoming associated with microparticle is the higher density when compared to suspension [53]. The objective of efficient cooling, better dielectric strength, miniaturization and better efficiency of the transformer are likely to be achieved by nanofluids [54]. The term nanofluid has been introduced by Choi [9] and upon his experimental work, the results showed better, and stable thermal heat exchanging property as compared to micron-sized particles. For over the decades, nanofluid, as new thermal exchanger medium is still in the state of research [55], [56]. Until, Segal [57] observed the enhancement in breakdown strength due to magnetic nanoparticle addition in transformer oil along with the improved thermal characteristics. Afterward, many magnetic [58]–[64], conductive [65]–[75], semiconductive [67], [76]–[86], insulated [87]–[90] natured nanoparticles are dispersed in different dielectric liquids to achieve improved dielectric properties without compromising physio-thermal properties. The dispersion stability [91]–[93], influence of the moisture [83], [87], [94]–[98], temperature, role of surfactant [71], [99] and nanoparticle's surface modification [84] are also researched. However, the development of nanofluids are still hindered by several factors such as the lack of agreement between results, poor characterization of suspensions, and the lack of theoretical understanding of the mechanism.

III. PREPARATION

Nanofluids are not basically twofold solid-liquid mixtures considering the fact that there are several hindrances and chucks while preparing an efficient nanofluid. The stability of nanofluids as well as uniform dispersion of nanoparticles are essential while preparing nanofluids [97]. Nanofluids usually suffer from agglomeration and clusters formation due to high attractive/repulsive force between nanoparticles, thereby resulting in instability and falls off under gravity over the duration of time [100]. To overcome such obstacles, a uniform dispersion of monosized nanoparticles are required before they coagulate [101]. The elusive preparation of nanofluid has been categorized into two methods namely as one-step and two-step physical and chemical processes [15].

One-step process involves simultaneous synthesis and dispersion of nanoparticles into the base fluid i.e., the practices of drying, storage, and transportation of the nanoparticles are escaped, resulting in minimization of agglomeration and enhanced stable nano-based oil [11]. For example, silver nanoparticle, when synthesized by one-step process adopts mineral oil by disintegrating silver lactate into the mineral oil, which remained well dispersed roughly for a month [74]. The single step preparation method produces the nanofluids with less range of particle size that limited the chances of aggregation [102]. The drawback of one-step process is the formation of residues in the nanofluid due to the incomplete reaction or stabilization [15] and its incompatibility with base fluids which have lower vapor pressure.

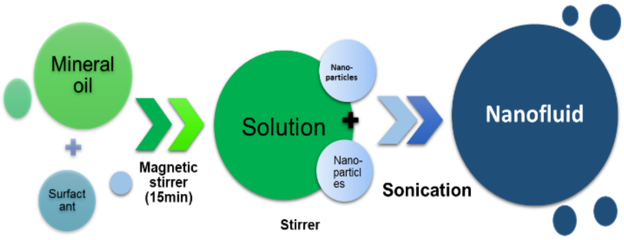

FIGURE 2. Two-step method for the preparation of nanofluid or nano-insulating oil.

Two-step process involves two-phase process: preparation of nanofillers such as nanotubes, nanoparticles which are usually in the form of powder, and dispersion of nanofillers into the base fluid using techniques like magnetic stirring, ultrasonication, etc. as shown by Figure 2 [64]. Fontes *et al.* [65] prepared nanofluid by dispersing multiwall carbon nanotubes (MWCNT) and diamond in mineral oil by two-step process. The addition of dispersant during preparation enhances the stability of nanofluid. Lee and Kim [103] firstly used oleic acid as a surfactant by mixing it with the mineral oil upon the application of magnetic stirrer and then dispersed magnetic nanoparticles into the oleic acid solution by using ultra-sonication. Atiya *et al.* [84] used Cetyl Trimethyl Ammonium Bromide (CTAB), which is a cationic surfactant, to enhance the stabilization of nanofluid prepared by two step method, where Titanium oxide nanoparticle dispersion in mineral oil. The advantage of two-step process is the possibility of preparing nanofluid on the large scale. The only significant flaw with two-step process is the nanoparticle's high surface energy, which creates the nanofluid unstable [104].

A. ROLE OF SURFACTANT

The size of nanoparticles and its nature influence the solution formation which usually results into coagulation or fall off under gravity. The surfactants are stabilizing reagents, mixed in liquid to provide the benefit of controlled particle–particle interactions and stable dispersion of nanoparticles in fluids for long lifespan [15], [105]–[107]. Sartoratto *et al.* [59] observed that the addition of oleic acid into transformer oil with the dispersion of iron oxide nanoparticles sustain colloidal form at room temperature over 2 years. The synthesis of stable mineral oil-based silica nanofluid by two-step preparation method entails base fluids (Diala S3ZXIG mineral oil), SiO_2 nanoparticles, Surfactant sorbitan monooleate and coupling agent Z6011 [94]. Improved TiO_2 based nano-oil synthesis constitutes highly refined mineral oil as Base oil, TiO_2 nanoparticle (size $\sim$ 100 nm), cetyl trimethyl ammonium bromide (CTAB) as cationic surfactant [84]. Mansour *et al.* [99], observed the deterioration in the stability of nano-based oil and uniform dispersion of nanoparticles with the excess amount of surfactant due to the formation of double chain of surfactant around nanoparticles. Many researchers work highlighted in Table 1 that comprises of np size and surfactant utilized for NFs based on nanoparticle features, base fluids, zeta potential (pH), NF preparation steps, and mass fraction along with brief summary and findings.

Zeta potential (ζ) is a property that provides the nanoparticles affinity to agglomerate or de-agglomerate during dispersion in the base liquid and ease the surface modification process to achieve improved dispersion stability [108]. The higher zeta potential reduces the stability of NF by increasing the agglomeration rate. The zeta potential of nanoparticles dispersion in oil is calculated by Helmholtz–Smoluchowski equation [109] given below.

$$\zeta = \mu U/\varepsilon \tag{1}$$

where, U is the electrophoretic mobility, and μ and ε are the viscosity and the dielectric constant of the liquid respectively.

Steric stabilization is acquired by the reduction of agglomeration of nanoparticles by reduction of the active surface of nanoparticles with support of the surfactant. The thresholds have been set by optimizing the surfactant concentration not to completely inactivate the surface of nanoparticles. Whereas, E*lectrostatic stabilization* is attained by charging the surface of nanoparticles with the same polarity. Charges are firstly formed on the inner surface of the nanoparticles at the interface with oil. Then, a layer of oppositely charged ions, called counter ions or co-ions counterbalances these charges. According to Derjaguin-Landau-Verwey-Overbeek (DLVO) theory [111], the total interaction between two nanoparticles is the combination of van der Waals attraction force and electrostatic repulsion force. Minimum interaction between the nanoparticles or no overlapping is acquired by the separation between nanoparticles larger than the combined thickness of their electric double layers. The surfactant is mixed with the insulating oil to provide stable interaction between the nanoparticles and oil, which can be explained by two different stabilization processes as shown in Figure 3 [110].

IV. MEASUREMENT

Insulating oil diagnosis is complex and essential for the consistent, optimized and efficient operation of power utilities; numerous electric, non-electric characterizations, and condition monitoring tests (online/offline test) execute on the dielectric over the course from its pre-installation to lifespan [112]. The fundamental source of insulation failure in a system involves dissection of defective insulation [27].

Features extraction from oil-based diagnosis is a complex process and involves numerous parameters of fluids tests

TABLE 1. Variation in nanoparticle size used for preparation of Nano-based oil.

Nanoparticle	Base oil	Particle Size (nm)	Surfactant	Comments
Fe_3O_4	Mineral oil	10		- AC (60 Hz) breakdown, impulse breakdown, Partial Discharge, Resistivity characteristics are observed [57] - Dielectric characteristics under the influence of magnetic field [58]
	Transformer oil	10.6	Oleic acid	DC dielectric breakdown under influence Magnetic field[114]
	Mineral oil, Synthetic ester oil, THESO	10	Oleic acid	DC breakdown and impulse breakdown with both polarity[115]
	Mineral oil	10	Oleic acid	Dielectric strength enhancement explained with electron scavenging mechanism [116]
	Mineral oil	10.2	Oleic acid	Influence observed in dielectric strength in NFs with orientation of magnetic and electric field [117-118]
	Mineral oil	7.4	Oleic, dodecanoic, or decanoic acids	Enhancement in dielectric and breakdown strength with dispersion of nanoparticles [59]
	Vegetable oil	30	Oleic acid	Surface modified nanoparticles effects the dielectric characteristics of fluids is explained by physical characteristics analysis[73]
	Natural ester oil	30	Oleic acid	Influence of nanoparticles over natural ester oil is explained with charge relaxation theory[119]
	Mineral oil, Isoparaffinic polyalphaolefin (PAO)	<100	Span	Comparative study of different nanoparticles with breakdown strength implementing non-destructive test [120]
	Mineral oil	8.5	Oleic acid	dielectric properties, dielectric losses, breakdown strength, and Partial discharges measured for the NFs [62]
	Transformer oil	20		Enhanced thermal characteristics of nano-based transformer oil along with better dielectric strength is observed [87]
	Transformer oil	10	Oleic acid	The enhanced dielectric properties of conductive nanoparticle -oil was explained with charge accumulation hypothesis [121]
	Fr3 vegetable oil	13.4	Oleic acid	Role of surfactant and surface modification effect was described[122]
TiO_2	Transformer oil (paraffinic)	20		The enhanced dielectric characteristics of semiconductive nano-based fluid is explained with shallow trap theory[123], the influenced of humidity on NFs was illustrated [67]
	Mineral oil	20	Stearic acid	Charge dynamics and potential distribution on nanoparticles was model[121]
	Mineral oil	<20		AC, DC and lightning impulse breakdown voltage, partial discharge (PD) characteristics was determined for various NFs[85]
	Transformer oil	<20	Oleic acid	AC and impulse breakdown characteristics of NFs was influenced with aging [81]
	Mineral oil	<100	CTAB	The surface modification of nanoparticles and dispersion stability of nano particle in oil is described[84]
	Paraffin oil	100		Relative dielectric constant and dielectric loss of NFs is observed and analyzed with variation in frequency[69]
Al_2O_3	Mineral oil	<50		Comparative study of various nano-based oil via positive and negative impulse breakdown Strength [86]
	Paraffin oil	50		Relative dielectric constant and dielectric loss of inter mixed nanoparticles in fluid observed and analyzed with variation in frequency[69]
	Mineral oil, Isoparaffinic polyalphaolefin (PAO)	<80	Span	Comparative study of different nanoparticles with breakdown strength implementing non-destructive test [120]
	Mineral based transformer oil	10	Span 80	Streamer theory for enhancement in dielectric property of dielectric based fluid[121]
	Transformer oil	13	Oleic acid	Illustrate negative influence of addition of excessive surfactant in nanofluids [124]
	Transformer oil	23,80,100	Oleic acid	Influence in breakdown strength of NFs with variation with temperature and moisture[96]
SiO_2	Mineral oil	15	Silane coupling agent z6011	Hydrophilic nature of SiO_2 shows the positive effects of dielectric characteristics of NFs in presence of moisture[94, 125]
	Mineral oil	5-20		Enhanced Dielectric strength shown by NF under divergent field[66]
	Synthetic oil	15	Benzalkonium chloride	Effects of surfactant mass on the thermal and dielectric properties of NFs[107]
SiC	Mineral oil, Isoparaffinic polyalphaolefin (PAO)	<80	Span	Comparative study of different nanoparticles with breakdown strength implementing non-destructive test [120]
BN	Transformer oil (paraffinic based)	50		Variation of Dielectric and thermal characteristics of NFs with NPs amount and temperature is observed [87, 90]
	Vegetable oil	50		Dielectric, breakdown and thermal characteristics of vegetable oil based NFs was observed and explain with charge trap model.[89]
ZnO	Insulating oil	22	Oleic acid	Variation in electric conductivity with mass fraction and temperatures is observed[126]
	Transformer oil	40, 80	Oleic acid	The influence of nanostructures concentration, morphology, permittivity and size on the breakdown strength of NFs examined[96]
GO	Mineral Oil (commercial product)	12		Comparative study of Dielectric strength of NFs under divergent field [66]
	Mineral oil	100, 300		First time prepared NFs shown better dielectric breakdown strength and thermal characteristics and modelled.[127]
CNT	Mineral oil	20, 10		
AlN	Mineral oil	40	Oleic acid	AlN based NFs experimented to obtain dielectric breakdown, partial discharge, and for various concentration of nanoparticles[70]
Fullerene	Mineral oil	1		Partial discharge parameters of NFs measure and analyzed.[125]
CeO_2	Mineral oil	6-8		AC and impulse breakdown strength of the NF was analyzed[128]
MgO	Transformer oil	15	Oleic acid	Comparative study of different nanoparticles based Oil via analyzing breakdown strength with variation in concentration, temperature and moisture [96]
Bi2O3		15		
ZrO2		40, 70		

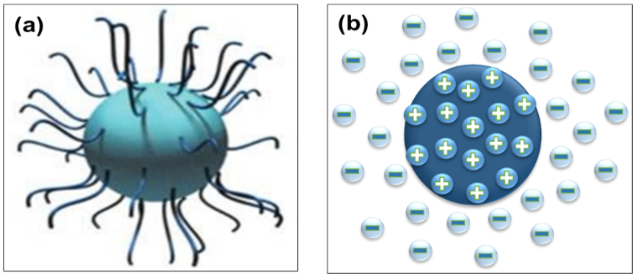

FIGURE 3. (a) Steric stabilization; (b) Electrostatic stabilization.

which can be broadly categories in the sub-functional group on the basis of timeline as [113]:

1. Characterization: to identify the oil and particle profile
2. Dielectric analysis: to determine insulation characteristics and dielectric coordination.
3. Degradation: to provide information regarding failure, breakdown, and faults.
4. Aging: to provide the lifespan of oil

Nano-based oil pre-preparation process depends on its application and desired properties which significantly determine by particle and oil characterization and manufacturing and treatment process.

A. CHARACTERIZATION

When the nanoparticles are added to the base oil, the affinity towards agglomeration is quite common for the dispersant since the solution may posess the hydrophillic/hydrophobic nature. Therefore, the measurement and analysis of nanoparticles must be performed before and after intermixing of dispersant, as the possibility of the enhancement in electrical properties may not always be feasible [114]. The sizes of Fe_3O_4 nanoparticles in vegetable oil, nanodiamond particles in oil, and TiO_2 nanoparticles based NF have been measured by the laser particle size analyzer [67], [73], [115], Zetasizer [53].

Particles profile and distribution, impact of surfactant, dispersion stability of NFs over temperature range have been analyzed by using techniques such as Transmission Electron Microscopy (TEM) [73], [84], [96], [116], [117], Scanning Electron Microscopy (SEM) [87], [118], [120], Thermogravimetric analysis (TGA) [73], [121], [122], Fourier Transform Infrared Spectroscopy [59], [73], [91], dynamic light scattering (DLS) [94], [123], X-ray diffraction (XRD) [53], and differential thermal analysis (DTA) measurements [73], [123].

Zeta potential is a physical property that is attained by nanoparticle during dispersion in the fluid in the form of surface charge providing an affinity of agglomeration in nanoparticles and dispersion stability [73]. The measurements of zeta potential for different NFs have been performed by an electrophoretic light scattering (ELS) particle counter [124], or by an electrophoresis apparatus [67].

Zeta potential of TiO_2 based NF have been measured by conventional method for calculating drift velocity of nanoparticle in an electric field [84].

Nano-based oil is analyzed by using various tests based on different parameters and are compared with conventional insulating oil characteristics [4].

The tests ranges from the conventional breakdown test [97] to non-breakdown test [125], depending upon the necessity. The parameters of the oil are determined by relative measuring equipment or experimental setup as per national and international standards enlisted below in Table 2.

TABLE 2. Standards for measuring characteristics of insulating liquids.

Characteristics	Test Method Standard
Breakdown Voltage	IEC 60156, IEC 60296, IEC 60897, ASTM D1816-12, ASTM D877-M13, ASTM D 3300 – 12, IS 6792:1992, IS – 11697 : 1986
Relative Permittivity	IEC 60247, ASTM D-150-98, ASTM D924-15
Dissipation Factor	IEC 60247, IEC 61620, ASTM D924-15, ASTM D-150-98, IS 6262:1971, IS 16086 :2013
Volume Resistivity	IEC 60247, ASTM D1169-11, IS 6103:1971
Partial Discharges	IEC TR 61294, IEC 60270, ASTM D1868- 13
Aging	ASTM D1934-95, IEC Publication 354, ANSI 057.92 1981, IEEE Std 756
Moisture content	ASTM E203-16, ASTM D1533-12, IEC 60814
Appearance	IEC 61099, ISO 2211, ASTM D1500-12, ASTM D1524-15
Density	ISO 3675, ASTM D1298
Thermal Conductivity	ASTM D2717 -95
Kinematic Viscosity	ISO 3104, ASTM D445-15a, IEC 61868, IS 16084, IS 1448 - Part 25: 1970
Flash Point / Fire point	ISO 2719, ISO 2592, ASTM D92-16, IS 1448 - Part 21: 1970
Interfacial tension	ISO 6295, ASTM D971
Acid value	IEC 62021-1, IEC 60296, IEC 61125, ISO 660, ASTM D974 – 14e2, ASTM D664

B. DIELECTRIC ANALYSIS

The application of the insulating oil over the vast range of power utilities emphasize on the advancement in the dielectric and heat exchange characteristics of dielectric liquid which further leads to the innovation of nanofluids [12]. Dielectric status of insulating oil covers breakdown strength, dissipation factor, dielectric permittivity, partial discharge and resistivity to provide the dielectric safety margin of insulation under the normal operating conditions and faults [130].

Breakdown Strength of the nano-based oils need to be measured for the regulation of its operability and capability to act as the electrical insulation. Breakdown strength of oil is measured under different conditions like AC, DC and impulse voltage to analysis behavior under different operating conditions. The *AC breakdown voltage* measurements of the nanofluids need to be accomplished in accordance with international standard [131]–[134]. The conventional AC breakdown tester have been utilized on nanofluids such as ferrofluids [57], [59], [61] and silica based nanofluid [94]. The breakdown measurement with varying Electrode specification (i.e. shapes, gap) [116], [118], [135] and different electrode material (i.e. copper [87], stainless steel [136] has been performed. The advancement of HVDC in power transmission results into the evaluation of the DC breakdown strength of transformer oil as per standards [131], [133]. The DC breakdown strength dependence on the electrode profile and magnetic field have been illustrated for magnetic nanoparticles based oil [114], [117], [118], [137] and for non-magnetic nanoparticles [85], [115]. Behavioral response of nanofluids under switching and lighting impulse scenario have been analyzed as per standard IEC 60897 [138], ASTM D 3300-85 [139], and IS–11697:1986 [140] by various author [57], [73], [123].

Dielectric response of insulating materials is characterized by relative permittivity, dissipation factor, and electrical resistivity. Dielectric response of insulation signifies the polarization of substance in existence of additives (nanofillers), quantified by dielectric permittivity and dissipation constant [141]. The measurement of relative permittivity of insulating oil has been performed for ZnO [142], TiO_2 [78], [87], [90], insulated and magnetic nanoparticle-based oil [73], [143], nano-based vegetable oil and ZrO_2 based nanofluid [144]–[146]. The complex components of dielectric permittivity and dissipation factor of the paraffin oil with nano-additives (TiO_2, Al_2O_3) have been measured over varying frequency [69], [82]. Permittivity and loss factor of magnetic fluid in presence of magnetic field have been quantified [62]. The resistivity and dissipation factor of magnetic fluid have been measured via a equipment based on IEC 60247 standard [144] by applying 500 kV (DC) and 2000 kV (AC, 60Hz) respectively [59]. The volume resistivity of nano-modified vegetable oil [73], [143] and BN or Fe_2O_3 modified insulating oil has been analyzed over frequency [87]. The resistivity influence on nanoparticle of silica aerosol on castor oil can be a measurement of DC conduction current [147], [148].

C. DEGRADATION AND AGING

The performance and efficiency of nanofillers based insulating oil are evaluated by other electrical including Aging, Partial discharge, Moisture content, Electric Conductivity measurement in accordance with the international standards as given in Table 2.

Partial discharge (PD), as a nondestructive test for nanofluid testing are performed for the identification of the PD parameters like PD inception voltage (PDIV) [149], PD duration, PD rise time, total discharge magnitude, current impulse. PD phenomenon for silica, fullerene in mineral oil [125], ZrO_2 nano mixed enamel [136], magnetic nanofluid [62] determined by the time-resolved experimental set-up as per IEC 60270 [150]. PDIV measurement of TiO_2 based NF [90], [111] and Magnetite, Graphene oxide and Silicone oxide based NFs [116], [117] have been measured by using PD detector. The moisture is an undesirable content in any insulation system and therefore, its miniaturization and quantification are necessary for better operation. The moisture content and thermal influence in SiO_2, Al_2O_3, TiO_2, and Fe_2O_3 based NFs have been measured moisture and temperature meter [57], [66], [77], [79], [83], [94]–[96], [151], [155]–[157].

For the vast applications, the insulating oils should serve as insulant as well as coolant and better heat transfer capability is demanded from nanofluid as futuristic oil. Thermal conductivity is a measure of fluid's heat transfer capability based on techniques such as transient hot-wire method [87], [120], [124], [160], the 3ω method [161], the thermal constants analyzer method [107], the cylindrical cell method [162], the temperature oscillation method, and the thermal comparator method [163]. The NFs thermal conductivity measured using conventional [94], [97], and non-conventional (i.e. infrared thermal imager [53]) [90], [107], [164], and automatic thermal conductivity measuring system [70].

The viscosity plays a key role in the heat transfer property of insulating liquid and is measured for different nanofluids [91], [94], [95], [107], [159], [160], [165]. Transformer oils have flash point that reduces with nanofluid, as the ignition and the safe operating temperature range is also been determined [159], [166].

The condition monitoring of any power utilities contains the quantitative analysis of insulation degradation and aging due to continuous operating stress. The condition monitoring of nanofluids requires dielectric as well as mechanical testing over the times and most of the time utilized artificial aging [97].

V. CHARACTERISTICS OF NANOFLUIDS

A. BREAKDOWN CHARACTERISTIC

Each liquid known as insulant must inherit the capability to withstanding power frequency AC voltage as well as unwanted lightning and switching impulse voltage appear during operating conditions of power system. Newly developed nano based oil shows extraordinary enhanced dielectric strength when compared with its base oil. The levels of enhancement measured with different voltage magnitude and waveform (such as AC, DC or impulse) as well as nanoparticles. Initially, conventional breakdown strength testing or power frequency tests have been performed on NFs for quality assessment, then its withstand capability in the presence of contaminants, moisture and other atmospheric conditions has been measured [167]. The breakdown measurements are categories into three section as discuss above are common testing performed on different nanoparticles based nanofluids. Enhancement (k_j) can be measured in term of ratio of nanofluids and base oil as shown in equation 2.

$$k_j = \frac{Breakdown\ voltage\ (kV)\ \ of\ \ NF\ with\ varying\ np\ conc.}{Breakdown\ voltage\ of\ \ base\ oil} \tag{2}$$

where, j = 1,2,3 for AC/power frequency breakdown test; 2 for DC breakdown test and 3 for impulse breakdown test respectively. The experimental data is derived from various research published in papers are analyze to process it to compare the quality and performance of nanofluids graphically to improve the understandability. The k_1 shows the change in power frequency or AC breakdown strength of nanofluid as compared to base oil with change in nanoparticle concentration, all conclusively observed graphed in Figure 4.

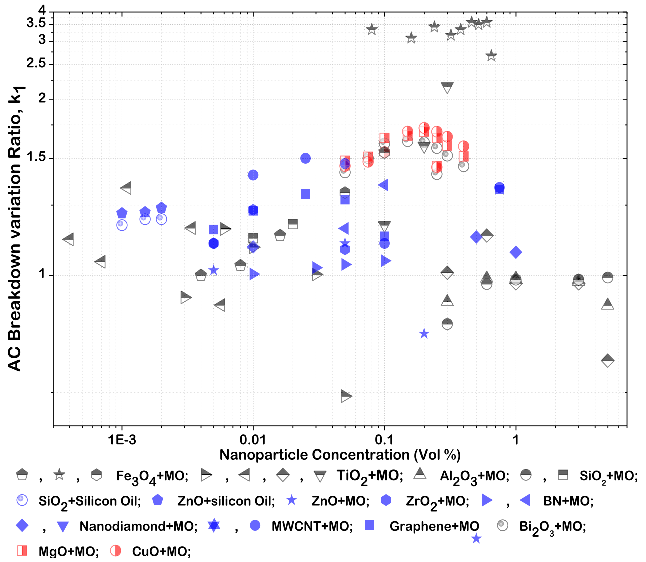

FIGURE 4. The ratio of AC breakdown strength of nanofluid with respect to AC breakdown strength of base fluid is defined as AC breakdown variation ratio, k_1. The changes in k_1 with variation in concentration of nanoparticles [53], [57], [59], [61], [62], [66], [76], [78], [79], [81], [83], [90], [119], [123], [127], [143], [157], [159], [160], [169]–[172].

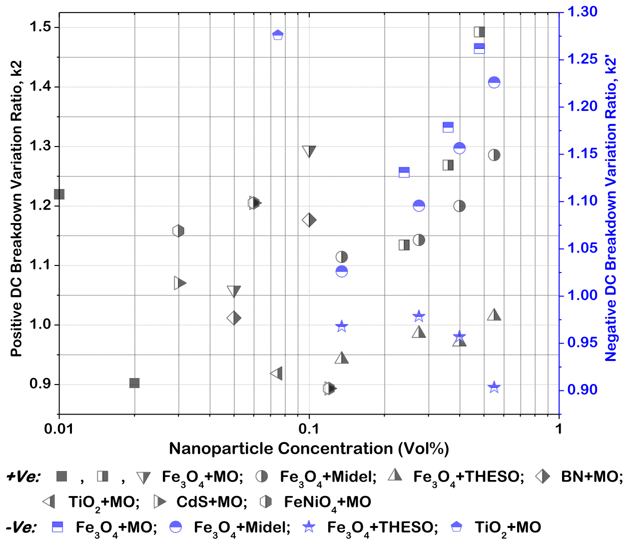

FIGURE 5. The changes in k_2 and $k_{2'}$ with variation in concentration of nanoparticles. The ratio of positive and negative DC breakdown strength of nanofluid to the base fluid is defined as positive and negative DC breakdown variation ratio, k_2 and $k_{2'}$, respectively [66], [114], [115], [117], [118], [173], [174].

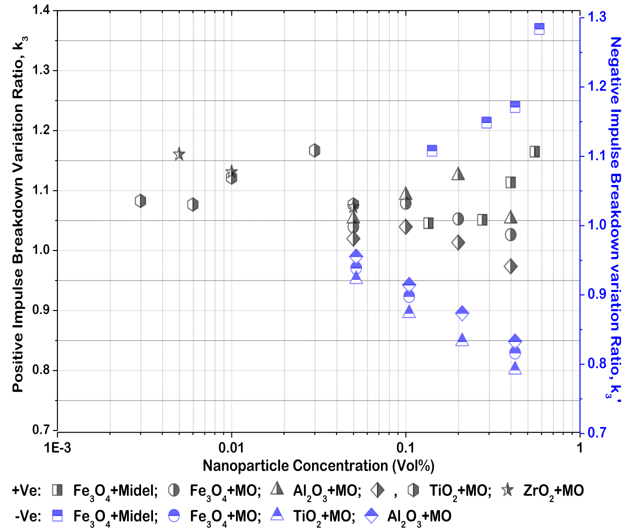

FIGURE 6. The variation in k_3 and k_3' with variation in concentration of nanoparticles. The ratio of positive and negative impulse breakdown strength of nanofluid to the base fluid is defined as variation ratio, k3 and k3′ respectively [81], [83], [86], [121], [123], [143], [159], [172].

The k_2 signifies alteration in DC breakdown strength of nanofluid with respect to its base oil with increasing nanoparticle concentration, all observation categorically (i.e. positive and negative) plotted in Figure 5. Similarly, impulse breakdown strength enhancements are signifying by k_3, and plot in Figure 6. The maximum enhancement observed with different type of nanoparticles mixed with dielectric liquids to its base oil have been discuss with time line in this section and also illustrate graphically.

The firstly prepared magnetic colloid (or ferrofluid) as an insulating oil showed the improvement in AC as well as impulse breakdown strength in the exposure of environment [57] and over a range of magnetization [168]. AC [60] and DC impulse [117], [118] dielectric breakdown of ferrofluid over electrode separation with orientations of magnetic field under electric field, optimized result was found at 0.01% ($I_s = 3$mT). Sartoratto *et al.* [59] illustrated only AC breakdown characteristics of different concentration of magnetic nanoparticles in nanofluid when treated with the best surfactant out of available surfactant on the basis of stability. O'Sullivan [169] and Hwang *et al.* [170], [171] explained the enhanced and improved performance of transformer oil based nanofluid by modeling a relationship between streamer propagation and relaxation time of nanoparticles. Herchl *et al.* [62] covered the breakdown distribution function using mathematical techniques over magnetic-based transformer oil. Chiesa and Das [120] failed the streamer theory [171] by using nanoparticles with lower relaxation time and showed enhancement in breakdown strength of NF by a non-destructive breakdown test. Kudelcik *et al.* [114] illustrated the improvement in DC breakdown strength till 1% vol conc. of magnetic nanoparticle-based transformer oil, which deteriorated for the higher concentration of nanoparticles and also showed the negative influence of magnetic field on NF. The Semiconductive nanoparticle (TiO_2) based NFs increased both for AC as well as lightning breakdown strength to a non-similar saturation concentration [81], [83].

A comparative study shows that chemically treated TiO_2 nanoparticle dispersion in transformer oil withstand higher voltage even in the presence of moisture as compared to untreated TiO_2 based transformer oil [76], [79]. The introduction of nanotechnology in biodegradable vegetable oil increased AC as well as impulse breakdown strength from 49.9 to 59.8 kV and from 83.59 to 93.74 kV as shown in Figure 4 and Figure 6 respectively [143]. Fe_2O_3 based natural ester oil improves the breakdown strength to 20% as compared to the base fluid [119] while TiO_2 based ester oil improves to 30% [77]. Du *et al.* [123] justified the mechanism of enhanced AC and lightning breakdown strength of semiconductive-based transformer oil by shallow trap density and charge transportation.

Given *et al.* [115] showed the comparative study of the influence of magnetic nanoparticle on mineral oil, Midel 7131 oil, and THESO oil resulting into the higher enhancement in positive DC and negative DC breakdown test for mineral and Midel 7131 as shown in Figure 5. Impulse test is performed only on nano-based Midel oil showing positive results. AC, lightning, and 1% probability breakdown of TiO_2 based Transformer oil was 6∼26%, 23∼34%, and 22∼58% higher than base oil respectively [172].

Lv *et al.* [157] prepared new transformer oil based on SiO_2 and Al_2O_3, which enhanced the breakdown strength of base fluid at an optimum concentration and deteriorated at some concentration due to the agglomeration. Nanofluid-impregnated pressboard (NP) showed higher AC and DC breakdown voltage as compared to oil impregnated pressboard (OP) [173], [174]. ZrO_2 and TiO_2 based insulating oil showed maximum AC breakdown voltage increment and lightning breakdown voltage at 0.01%wt and 0.005%wt [159]. The negative influence on the increment of surfactant in NF on its breakdown characteristics has been discussed by Mansour *et al.* [99].

Lee *et al.* [61] showed that the magnetic-based insulating oil when treated with an optimum amount of surfactant raised the breakdown voltage to 3.3 times of base oil for concentration ($\Phi < 0.65\%$) and showed negative effect at the higher concentration. The high water content hardly influenced on TiO_2 [67], [151] and SiO_2 [95] based transformer oil when compared to the transformer oil, and yielded better breakdown strength. Lee and Kim [103] showed that the magnetic-based transformer oil gave breakdown strength double as compared to pure oil, which further enhanced 30% more under magnetic field. Li *et al.* [73] observed that the vegetable oil based nanofluid gave 20% greater AC breakdown voltage and enhanced lightning voltage. Hanai *et al.* [78] showed that the AC breakdown enhancement for shaped TiO_2 and ZnO based oil. The aged transformer oil breakdown strength enhanced using stable and uniform dispersion of TiO_2 [80]–[82]. Dehkordi [175] compared the breakdown strength of TiO_2 based NF over the time with pure oil [80] under temperature variation.

Atiya *et al.* [84] showed 27 % enhancement of insulating oil with the stable TiO_2 nanoparticle. Du and Li [90] improved the breakdown strength with new insulated BN nanoparticle in transformer oil but with lower performance when compared to magnetic-based NF [87] with temperature range according to bubble theory. Cavallini *et al.* [66] illustrated AC as well as DC (both positive and negative) characteristics of magnetic, silica, and graphene oxide based nanofluids under uniform and divergent field to determine the superior NF.

The dielectric strength of transformer oil declined with the amount of multi-walled carbon nanotube (MWCNT) and nano-diamond dispersion in the oil, [160] while slightly increased in breakdown strength by nano-diamond has also been observed [53]. The minimum influence on breakdown strength of silicone oil has been observed with the dispersion of ZnO and SiO_2 [166]. Sima *et al.* [121] and Wang *et al.* [86] illustrated the impulse breakdown strength of conductive, semiconductive, and dielectric nanoparticles dispersion in oil. Dhar *et al.* [127] showed the percentile enhancement in the breakdown strength of graphene and carbon nanotube-based oil with varying size and concentration and comparative study with the prediction model.

Ibrahim *et al.* [71] showed the enhancement in breakdown strength with CdS (cadmium sulphide), Ferrous nickel oxide (Fe_2NiO_4), and its mixture with a probability distribution. Li *et al.* [122] showed AC breakdown voltage of Fe_3O_4 based vegetable oil increased by 24.5% with the variation in nanoparticles size and influence of surfactant thickness over nanoparticles are also discussed. Peppas *et al.* [176] used three different electrode configurations under divergent and uniform electric field to study the statistical distribution (normal, Weibull, Gumbel and generalized extreme value (GEV) distribution) of AC breakdown strength probability of the nanoparticle-based mineral and ester oil. Aluminum nitride (AlN) based transformer oil gave the positive lightning impulse and AC breakdown voltage amplified around 50% and declined to 20-30% than the pure transformer oil [70]. The AC Breakdown voltage of Magnetic-based oil after impulse testing showed lesser value as compared to initial AC breakdown voltage and optimum result with 0.3% concentration [63].

The breakdown strength of the oil grows with insertion of nanoparticles upto certain limit but sustainability cannot be ensured with nanoparticle coagulating nature over a period of time.

B. DIELECTRIC PROPERTY

The dielectric properties (permittivity, loss factor) of magnetic-based NFs show significant sensitivity for the magnetic field and electric field and their orientation at threshold frequency [62]. The outline of variation of dielectric characteristics includes dissipation factor, relative permittivity, and resistivity with respect to the mass fraction of diverse NPs has been illustrated in Figure 7, 8 and 9 respectively. TiO_2 modified transformer oil doesn't show change in relative permittivity and resistivity [83].

The better resistivity and permittivity have been attained for nano-modified transformer oil [143]. The viscosity and dissipation factor of ZrO_2 and TiO_2 based insulating oil showed the maximum increment in the concentration of 0.005%wt with more preference to TiO_2 [159]. Shen *et al.* [126] showed the abruptly high electrical conductivity of ZnO based insulated oil around 973 times than base oil and further temperature dependency have been measured [177]. Mergos *et al.* [69] illustrated the dielectric

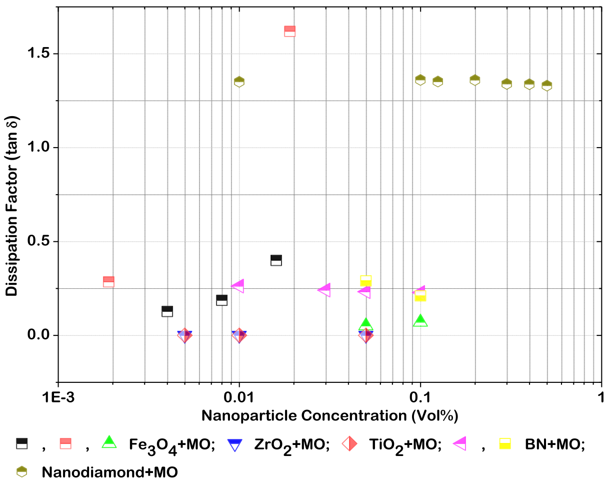

FIGURE 7. **The variation in dissipation factor of transformer oil with respect to mass fraction of nanoparticle: Fe_3O_4 [59], [62], [87], ZrO_2 [159], TiO_2 [78], [159] BN [87], [90], and nanodiamond [53].**

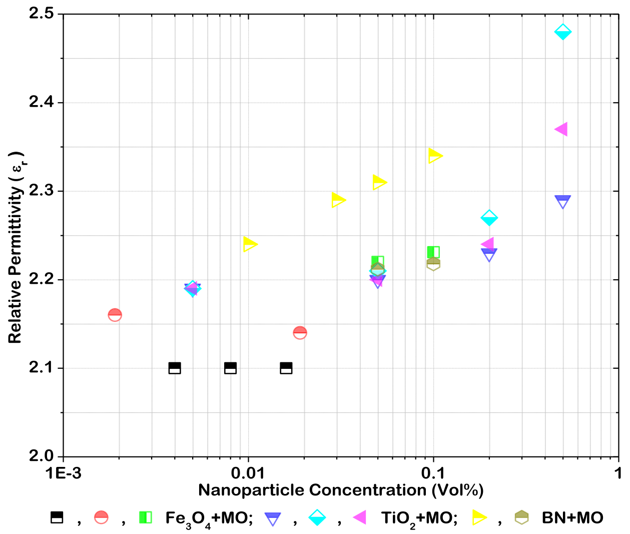

FIGURE 8. **The variation in relative permittivity of transformer oil with respect to mass fraction of nanoparticle: Fe_3O_4 [59], [62], [87], TiO_2 [78], and BN [87], [90].**

response and polarization phenomenon in paraffin oil with the dispersion of metal oxide and nanopowder through complex permittivity and dissipation factor as a function of frequency.

Vegetable oil based nanofluid gave very similar resistivity and dissipation factor and enhanced permittivity as the base oil for over a range of frequency greater than 1Hz [73]. ZnO based NF enhanced the relative permittivity with concentration changed from 2.135 to 2.180 at 0.2 vol% [142] and the result ZnO and TiO_2 based nano-oil are validated with randomly arranged model [78]. BN based NF showed increase in relative permittivity to 2.34 with increased filler to 0.1wt%, while the reduction in dissipation factor from 0.315 to 0.226 [90]. The effects of moisture on ferrofluid [153] and silica and fullerene-based oil [94], [97] observed is minimum as compared to the base oil. Du *et al.* [87] illustrated the dielectric behavior with varying temperature showing better property for Fe_2O_3 based oil as compared to BN based oil.

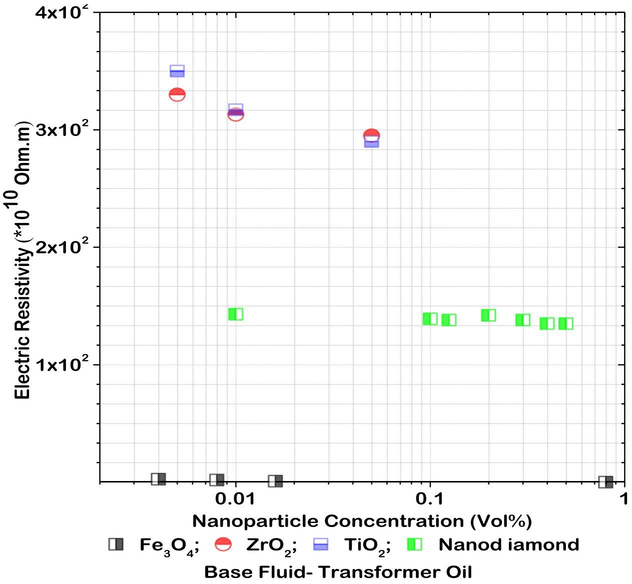

FIGURE 9. **The variation in electric resistivity of transformer oil with respect to mass fraction of nanoparticle: Fe_3O_4 [59], [62], [87], ZrO_2 [159], TiO_2 [78], [159], and Nanodiamond [53].**

C. DISCHARGE

Partial discharge is *a localized electrical discharge that only partially bridges the insulation between conductors and may or may not occur adjacent to a conductor* [150]. Magnetic-based nanofluid deterioration and loss analysis using partial discharge current impulses showed the optimized performance with concentration of $\Phi = 0.0024$ [62]. PDIV of Semiconductive-based NP is enhanced by 66.8% from 13.08 kV for OP to 21.82 kV for NP [173]. Zhong *et al.* [77] illustration on TiO_2 based ester oil effectively improved the partial discharge characteristics and lessened the aging impact [80]. The discharges magnitudes decreased with BN nanoparticle concentration and improved the dielectric strength of oil [90].

Irwanto *et al.* [153] showed the minimum impact on PDIV due to the dispersion of ferrofluid in presence of moisture. Jin [97] and Jin *et al.* [125], [178] discussed silica and fullerene-based oil showing inception voltage up to 20% and 10% respectively which is higher than pure oil and reduction in discharge magnitude have been observed as well, which is depicted in Table 3. PDIV of AlN-based oil enhanced by 20% than base oil [70].

D. PHYSICAL CHARACTERISTIC

The efficient and stable nano insulating oil (NIO) depends upon the size and construction of NP. NPs with size in the range of hundreds of nm can be stably dispersed in the solvent and doesn't fall or precipitate due to the high interaction of NP and liquid dielectric [15]. The smaller sized NP is well dispersed [179] but larger sized NP needs a surfactant

TABLE 3. Percentage variation in PDIV with nanoparticles in oil.

Nano-based Insulating oil	PDIV, (kV)		Enhancement %
	Base oil	NIOs	
Titanium oxide, TiO_2 [85]	30.6	33.1	8%
Ferrofluid, Fe_3O_4 [57]	15.1	19.5	29%
Graphene oxide, GO [66]	11	12	9%
Silicon oxide, SiO_2 [60],[116]	11	18	64%
Fullerene [125]	22	25	14%
Natural ester+TiO_2 [77]	21.60	23.20	7%
Aluminum nitride, AlN [70]	31.1	38.1	23%

to stabilize in insulating oil. The size of NP varies with fabrication, compound rheological structure, implemented by authors for dielectric improvement. Particle size goes on increasing as time passes due to the large affinity of agglomerate together [122]. Atiya *et al.* [84] illustrated that NPs with large zeta potential have less attraction between them and show more stability. The ultimate activeness of NP is due to the increase in surface energy from the increment of surface atoms [180]. DLVO theory [111] explained that the stability of NPs is the balancing of Van der Waals force of attraction (V_A) and electrical double layer repulsive force (V_R) as given in equation (3). The total potential force on the particle is V_T, while V_A and V_R are expressed in equation (4) and equation (5) respectively.

$$V_T = V_A + V_R \tag{3}$$

$$V_A = A/12\pi D^2 \tag{4}$$

$$V_R = 2\pi\varepsilon.a\xi.\exp^{-\kappa D} \tag{5}$$

where, A is the Hamaker constant, D is the particle separation, a is the particle radius, ε is the solvent solubility, ξ is the zeta potential, and κ is a function of the ionic composition. Higher zeta potential signifies the stability of NPs with the lower surface potential energy and lesser attraction [181].

E. THERMAL CONDUCTIVITY

Choi [6] developed nanofluids for application of heat exchange in the early 1990s, which latter showed ideal replacement of conventional transformer oil with extraordinary thermal conductivity characteristics. Cu-transformer oil based NF is utilized for theoretical thermodynamics model to observe the enhancement up to 40% than the base oil [182]. Choi *et al.* [124] characterized the diverse shaped Aluminum compounds (AlN, Al_2O_3) nanoparticle-based oil with enhanced thermal conductivity along with other thermal properties and its deterioration with a mass of surfactant. Chiesa and Das [120] explained the thermodynamics of different characteristics nanoparticles in transformer oil by analyzing thermal conductivity and medium effective theory. Hwang *et al.* [92] discovered thermal conductivity enhancements of oil-based MWCNT and fullerene nanofluids as a function of the particle volume fraction up to 8.7% at 0.5 vol% and 6.0% at 5 vol% respectively. Jin [97] illustrated the minimum impact of Silica and fullerene on thermal conductivity of transformer oil over the range of temperature and even poor thermal conductivity at the higher concentration of NP. Fontes *et al.* [160] showed the thermal conductivity of mineral with carbon nanotube and diamond nanoparticle concentration increased up to 20% as compared to mineral oil. Du *et al.* [87] and Du and Li [90] explained the significant increment in thermal characteristics of transformer oil with a dispersion of BN and Fe_3O_4 NP due to the ballistic phonon transport and minor influence of Brownian motion with BN being superior in thermal characteristics. The synthesis with improvement (14.5%) in the thermal conductivity of sustained nanodiamond implemented on the Newtonian nanofluids-based on naphthenic oil has been performed by Shukla and Aiyer [53]. The experimental results showed that the thermal conductivity has been increased by 3-7% because of the addition of AlN nanoparticles, which got saturated at specific NP concentration [70].

VI. ELECTRODYNAMICS PROCESS

Insulating oil based Nanofluid fabricated with a dispersion of nanoparticles have been categorized into conductive nanoparticles, semiconductive nanoparticle and dielectric nanoparticle pertaining to its characteristics which yielded positive results. The Electrodynamic process undergone in nanofluid is beyond convention breakdown theory, delivered realization for the improved dielectric characteristics.

O'Sullivan [169] proposed the model based on streamer propagation in nano-based oil. The streamer is the resultant of the ionization of oil molecules depending upon the electric field leading to the formation of electric field wave but nanoparticles act as the electron absorber and convert it into a slow moving negatively charged ion. The relaxation time (T) signifies the duration of polarization as expressed in equation (6) is very minute for conductive nanoparticle, when compared to the oil molecules.

$$\tau = \frac{2\varepsilon_1 + \varepsilon_2}{2\sigma_1 + \sigma_2} \tag{6}$$

where, ε_1 and ε_2 are the permittivities of transformer oil and NP, respectively; and σ_1 and σ_2 are the conductivities. Finitely charged nanoparticles change the potential distribution, and negatively effects the streamer flow in nano insulating oil (NIO) resultantly improving its breakdown strength. The streamer propagation illustrates the better breakdown strength for NPs with lower relaxation time and unable to illustrate the better performance of the NP with larger relaxation time [120]. Du *et al.* [123] proposed the mechanism the Dielectric enhancement with the dispersion of high relaxation time for semiconductive nanoparticles (SNP). Charge flow in the insulating liquid is delayed by the trapping of fast moving electron by high shallow trap density of SNP and rebounds in oil, which decelerates the Electric field wave flow or the streamer movement. A verification of model is performed with the measurement of trap distribution and charge transportation characteristics of SNP based transformer oil with $TiO_2(\tau = 77s)$ [67], [85]. The dielectric breakdown of insulating oil is due to the formation bubble and its elongation allows the movement of electrons in the field to generate a conducting channel within the liquid gap [87]. One of the causes of bubble formation is joules heat produced at electrodes. The dispersion of NP improves the thermal conductivity of base oil and leads to the reduction in bubble formation and improvement in breakdown strength of NP-based oil.

VII. IMMINENT OPPORTUNITIES AND CHALLENGES

Nanotechnology is in the hotlist for many industrial application originators as it shows the inaccurately explained profitable features [7]. Nanofluids as modern insulating oil are profitable and eco-friendly replacement for conventional petroleum-based insulating oil [73]. The Dielectric improvement of even, aged operated oil with a dispersion of nano-sized particles in milli-range amount is making impossible to reality [151]. The extraordinary thermal convention features with better breakdown strength of nano-based oil will be opening future opportunities.

The obstacles still remain in transforming practical investigation to real life applications. The long-term stable characteristics of dielectric liquid are the basic necessity, which is not possible in NFs due to the affinity of agglomeration shown by NPs [158]. The agglomeration is subsequently of diverse nature of oil-NPs, pH, moisture content, and Zeta potential [183]. The surfactant is mixed to enhance the stability but its volume influences the thermal [7] and electrical characteristics [122] of nano-based oil. The metal NPs in the presence of electric field gets electroplated on the electrode, which is unwanted, and reduces the optimized favorable concentration in transformer oil [71], [96]. The diverse value of electrical conductivity, permittivity and dissipation factor influence the existing electrical field distribution in transformer oil, may create stress point which is undesirable [62], [69].

VIII. CONCLUSION

Nanotechnology as a next generation tool allows us to provide smart solution to obtain advanced insulation system having extraordinary enhanced dielectric strength and minimum influence of environmental parameters with eco-friendly nature. This review includes preparation, experimental investigation, electrical and physio-thermal characterization, and mechanism of all kind of nanoparticles in the base dielectric, ranging from conventional paraffin-based mineral oil to synthetic environmental friendly MIDEL oil. The only significant challenge is the stability of nanoparticle in base oil, which agglomerates over the period and deterioration improves when size reaches in microns. The surfactant gives the capability of stable and uniform dispersion of NP but overcoating of NP is unwanted. The researchers and engineers need to topple the blockage to make it economic and efficient commercial insulating oil.

REFERENCES

[1] S. Mahmud, G. Chen, I. O. Golosnoy, G. Wilson, and P. Jarman, "Experimental studies of influence of different electrodes on bridging in contaminated transformer oil," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 22, no. 5, pp. 2433–2441, Oct. 2015.
[2] A. A. Pollitt, "Mineral oils for transformers and switchgear," *J. Inst. Elect. Eng.-II, Power Eng.*, vol. 90, no. 13, pp. 15–22, Feb. 1943.
[3] T. O. Rouse, "Mineral insulating oil in transformers," *IEEE Elect. Insul. Mag.*, vol. 14, no. 3, pp. 6–16, May 1998.
[4] Y. Z. Lv, Y. Zhou, C. R. Li, Q. Wang, and B. Qi, "Recent progress in nanofluids based on transformer oil: Preparation and electrical insulation properties," *IEEE Elect. Insul. Mag.*, vol. 30, no. 5, pp. 23–32, Sep./Oct. 2014.
[5] S. K. Das, *Nanofluids: Science and Technology*. Hoboken, NJ, USA: Wiley, 2008.
[6] S. U. S. Choi, "Nanofluids: From vision to reality through research," *J. Heat Transf.*, vol. 131, no. 3, p. 33106, 2009.
[7] R. Saidur, K. Y. Leong, and H. A. Mohammad, "A review on applications and challenges of nanofluids," *Renew. Sustain. Energy Rev.*, vol. 15, no. 3, pp. 1646–1668, 2011.
[8] S. U. S. Choi and J. A. Eastman, "Enhancing thermal conductivity of fluids with nanoparticles," *ASME Int. Mech. Eng. Congr. Expo.*, vol. 66, pp. 99–105, Nov. 1995.
[9] S. U. S. Choi, *Developments and Applications of Non-Newtonian Flows*, vol. 66. New York, NY, USA: ASME, 1995.
[10] R. N. Ramakoteswaa, L. Gahane, and S. V. Ranganayakulu, "Synthesis, applications and challenges of nanofluids—Review," *IOSR J. Appl. Phys.*, vol. 6, no. 1, pp. 21–28, 2014.
[11] Y. Li, J. Zhou, S. Tung, E. Schneider, and S. Xi, "A review on development of nanofluid preparation and characterization," *Powder Technol.*, vol. 196, no. 2, pp. 89–101, Dec. 2009.
[12] D. K. Devendiran and V. A. Amirtham, "A review on preparation, characterization, properties and applications of nanofluids," *Renew. Sustain. Energy Rev.*, vol. 60, pp. 21–40, Jul. 2016.
[13] X.-Q. Wang and A. S. Mujumdar, "A review on nanofluids—Part I: Theoretical and numerical investigations," *Brazilian J. Chem. Eng.*, vol. 25, no. 4, pp. 613–630, 2008.
[14] X.-Q. Wang and A. S. Mujumdar, "A review on nanofluids—Part II: Experiments and applications," *Brazilian J. Chem. Eng.*, vol. 25, no. 4, pp. 631–648, 2008.
[15] W. Yu and H. Xie, "A review on nanofluids: Preparation, stability mechanisms, and applications," *J. Nanomater.*, vol. 2012, Jul. 2012, Art. no. 435873, doi: 10.1155/2012/435873.
[16] V. Sridhara and L. N. Satapathy, "Al_2O_3-based nanofluids: A review," *Nanosc. Res. Lett.*, vol. 6, no. 1, pp. 456–472, 2011.
[17] M. J. Heathcote, *J & P Transformer Book*. Elsevier, 2007.
[18] I. Fofana, V. Wasserberg, H. Borsi, E. Gockenbach, and M. Farzaneh, "Specific investigations to quantify heavy damage causes on loading resistor modules," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 13, no. 3, pp. 593–600, Jun. 2006.
[19] B. N. Bowers and D. L. Johnston, "New oil-filled apparatus bushings," *Elect. Eng.*, vol. 67, no. 6, p. 580, Jun. 1948.
[20] R. E. Gerdt, J. M. Crowley, and J. C. Chato, "Electrohydrodynamic pumping of cable oil," *J. Electrostat.*, vol. 5, pp. 477–488, Sep. 1978.
[21] *IEEE Guide for Diagnostic Field Testing of Electric Power Apparatus—Part 1: Oil Filled Power Transformers, Regulators, and Reactors*, IEEE Standard 62-1995, 1995, pp. 1–59.
[22] J. Cosgrave *et al.*, "Intelligent optical fibre monitoring of oil-filled circuit breakers," *IEE Proc.-Gener. Transmiss. Distrib.*, vol. 146, no. 6, pp. 557–562, 1999.
[23] *IEEE Standard Requirements for Tap Changers*, IEEE Standard C57.131-2012, 1993.
[24] F. C. Beriger, J. Hengsberger, and G. W. Juette, "Cabora Bassa HVDC transmission: Oil cooled outdoor thyristor valves," *IEEE Trans. Power App. Syst.*, vol. 94, no. 3, pp. 1061–1071, May 1975.
[25] A. Sierota and J. Rungis, "Electrical insulating oils. I. Characterization and pre-treatment of new transformer oils," *IEEE Elect. Insul. Mag.*, vol. 11, no. 1, pp. 8–20, Jan. 1995.
[26] I. Fofana and J. Sabau, "Application of petroleum-based oil in power transformer," in *Natural Gas Research Progress—IB*, N. David and T. Michel, Eds. Hauppauge, NY, USA: Nova Science, 2008, p. 23.
[27] I. Fofana, "50 years in the development of insulating liquids," *IEEE Elect. Insul. Mag.*, vol. 29, no. 5, pp. 13–25, Sep./Oct. 2013.
[28] R. Bartnikas, *Electrical Insulating Liquids*. West Conshohocken, PA, USA: ASTM, 1994.

[29] C. McShane, "New safety dielectric coolants for distribution and power transformers," *IEEE Ind. Appl. Mag.*, vol. 6, no. 3, pp. 24–32, May 2000.

[30] D. K. Mahanta and S. Laskar, "Electrical insulating liquid: A review," *J. Adv. Dielectr.*, vol. 7, no. 4, pp. 1–9, 2017.

[31] J. Walker, A. Valot, Z. D. Wang, X. Yi, and Q. Liu, "M/DBT, new alternative dielectric liquids for transformers," in *Proc. CIGRE Paris Conf.*, 2012, pp. 1–10.

[32] M. A. Simmons, "Insulating liquids used in fluid filled cables," in *Proc. IEE Colloq. Eng. Rev. Liquid Insul.*, 1997, p. 7.

[33] *Insulating Liquids—Specifications for Unused Synthetic Organic Esters for Electrical Purposes*, document IEC 61099, 2010.

[34] *IEEE Guide for Loading Mineral-Oil-Immersed Transformers*, IEEE Standard C57.91-1995, 1996.

[35] E. D. Senkevitch, V. G. Arakelian, T. V. Glasunova, V. A. Lipshtein, T. I. Morozova, and N. M. Panova, "New synthetic liquids for transformers," in *Proc. CIGRE Symp.*, 1987, pp. 4–500.

[36] L. M. Goldenhar, A. M. Ruder, L. M. Ewers, S. Earnest, W. M. Haag, and M. R. Petersen, "Concerns of the dry-cleaning industry: A qualitative investigation of labor and management," *Amer. J. Ind. Med.*, vol. 35, no. 2, pp. 112–123, Feb. 1999.

[37] H. Borsi, "Dielectric behavior of silicone and ester fluids for use in distribution transformers," *IEEE Trans. Electr. Insul.*, vol. 26, no. 4, pp. 755–762, Aug. 1991.

[38] I. Fafana, V. Wasserberg, H. Borsil, and E. Gockenbach, "Retrofilling conditions of high voltage transformers," *IEEE Elect. Insul. Mag.*, vol. 17, no. 2, pp. 17–30, Mar. 2001.

[39] *Synthetic Organic Esters for Electrical Purposes—Guide for Maintenance of Transformer Esters in Equipment*, document IEC 61203, 1992.

[40] C. P. McShane, "Relative properties of the new combustion resistant vegetable oil based dielectric coolants," in *Proc. IEEE-IAS/PCA Cement Ind. Tech. Conf.*, Apr./May 2001, pp. 31–40.

[41] T. V. Oommen and C. C. Clairbone, "Biodegradable insulating fluid from high oleic vegetable oils," in *Proc. CIGRE Session*, 2008, p. 302.

[42] D. P. Stockton, J. R. Bland, T. McClanahan, J. Wilson, D. L. Harris, and P. McShane, "Seed-oil-based coolants for transformers," *IEEE Ind. Appl. Mag.*, vol. 15, no. 1, pp. 68–74, Jan. 2009.

[43] L. R. Lewand, "Laboratory testing of natural ester dielectric liquids," *Neta World*, pp. 1–4, 2004. [Online]. Available: http://citeseerx.ist.psu.edu/viewdoc/download;jsessionid=A461015AAEAB0C6329E39FF51CBA2C68?doi=10.1.1.492.5364&rep=rep1&type=pdf

[44] I. Fofana, V. Wasserberg, H. Borsi, and E. Gockenbach, "Challenge of mixed insulating liquids for use in high-voltage transformers. II. Investigations of mixed liquid impregnated paper insulation," *IEEE Elect. Insul. Mag.*, vol. 18, no. 4, pp. 5–16, Jul./Aug. 2002.

[45] C. Perrier and A. Beroual, "Experimental investigations on mineral and ester oils for power transformers," in *Proc. Conf. Rec. IEEE Int. Symp. Elect. Insul.*, Jun. 2008, pp. 178–181.

[46] I. V. Timoshkin, M. J. Given, M. P. Wilson, and S. J. MacGregor, "Review of dielectric behaviour of insulating liquids," in *Proc. 44th Int. Univ. Power Eng. Conf. (UPEC)*, 2009, pp. 1–4.

[47] R. Dua, N. Bhandari, and V. Kuma, "Multi-criteria optimization for obtaining efficiently blended transformer oils," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 15, no. 3, pp. 879–887, Jun. 2008.

[48] C. Perrier, A. Beroual, and J.-L. Bessede, "Improvement of power transformers by using mixtures of mineral oil with synthetic esters," in *Proc. IEEE Int. Conf. Dielectr. Liq. (ICDL)*, Jun./Jul. 2005, pp. 556–564.

[49] A. Beroual *et al.*, "Propagation and structure of streamers in liquid dielectrics," *IEEE Elect. Insul. Mag.*, vol. 14, no. 2, pp. 6–17, Mar. 1998.

[50] *Standard Specifications for Mineral Insulating Oil Used in Electrical Apparatus*, ASTM Standard D3487-09, West Conshohocken, PA, USA, 2009.

[51] *Fluids for Electrotechnical Applications-Unused Mineral Insulating Oils for Transformers and Switchgear*, document IEC 60296, 2012.

[52] D. Wen and Y. Ding, "Natural convective heat transfer of suspensions of titanium dioxide nanoparticles (nanofluids)," *IEEE Trans. Nanotechnol.*, vol. 5, no. 3, pp. 220–227, May 2006.

[53] G. Shukla and H. Aiyer, "Thermal conductivity enhancement of transformer oil using functionalized nanodiamonds," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 22, no. 4, pp. 2185–2190, Aug. 2015.

[54] W. Yu, D. France, S. Choi, and J. Routbort, "Review and assessment of nanofluid technology for transportation and other applications," *Argonne Lab.*, Apr. 2007, Art. no. ANL/ESD/07-9.

[55] W. Yu and S. U. S. Choi, "The role of interfacial layers in the enhanced thermal conductivity of nanofluids: A renovated Maxwell model," *J. Nanoparticle Res.*, vol. 5, nos. 1–2, pp. 167–171, Apr. 2003.

[56] H. Xie, J. Wang, T. Xi, Y. Liu, F. Ai, and Q. Wu, "Thermal conductivity enhancement of suspensions containing nanosized alumina particles," *J. Appl. Phys.*, vol. 91, no. 7, pp. 4568–4572, Apr. 2002.

[57] V. Segal, A. Hjortsberg, A. Rabinovich, D. Nattrass, and K. Raj, "AC (60 Hz) and impulse breakdown strength of a colloidal fluid based on transformer oil and magnetite nanoparticles," in *Proc. IEEE Int. Symp. Elect. Insul.*, Arlington, VA, USA, Jun. 1998, pp. 619–622.

[58] V. Segal, A. Rabinovich, D. Nattrass, K. Raj, and A. Nunes, "Experimental study of magnetic colloidal fluids behavior in power transformers," *J. Magn. Magn. Mater.*, vols. 215–216, pp. 513–515, Jun. 2000.

[59] P. P. C. Sartoratto, A. V. S. Neto, E. C. D. Lima, A. L. C. Rodrigues de Sá, and P. C. Morais, "Preparation and electrical properties of oil-based magnetic fluids," *J. Appl. Phys.*, vol. 97, no. 10, p. 10Q917, 2005.

[60] P. Kopčanský *et al.*, "Dielectric breakdown strength in magnetic fluids," *Phys. Status Solidi*, vol. 236, no. 2, pp. 454–457, Mar. 2003.

[61] J.-C. Lee, W.-H. Lee, S.-H. Lee, and S. Lee, "Positive and negative effects of dielectric breakdown in transformer oil based magnetic fluids," *Mater. Res. Bull.*, vol. 47, no. 10, pp. 2984–2987, Oct. 2012.

[62] F. Herchl *et al.*, "Breakdown and partial discharges in magnetic liquids," *J. Phys.-Condens. Matter*, vol. 20, no. 20, p. 204110, 2008.

[63] M. Nazari, M. H. Rasoulifard, and H. Hosseini, "Dielectric breakdown strength of magnetic nanofluid based on insulation oil after impulse test," *J. Magn. Magn. Mater.*, vol. 399, pp. 1–4, Feb. 2016.

[64] M. Nazari, M. H. H. Rasoulifard, and H. Hosseini, "Dielectric breakdown strength of magnetic nanofluid based on insulation oil after impulse test," *J. Magn. Magn. Mater.*, vol. 399, pp. 1–4, Feb. 2016.

[65] D. D. H. Fontes, G. Ribatski, and E. P. B. Filho, "Experimental evaluation of thermal conductivity, viscosity and breakdown voltage AC of nanofluids of carbon nanotubes and diamond in transformer oil," *Diamond Rel. Mater.*, vol. 58, pp. 115–121, Sep. 2015.

[66] A. Cavallini, R. Karthik, and F. Negri, "The effect of magnetite, graphene oxide and silicone oxide nanoparticles on dielectric withstand characteristics of mineral oil," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 22, no. 5, pp. 2592–2600, Oct. 2015.

[67] Y. Du *et al.*, "Effect of water adsorption at nanoparticle–oil interface on charge transport in high humidity transformer oil-based nanofluid," *Colloids Surfaces A, Physicochem. Eng. Aspects*, vol. 415, pp. 153–158, Dec. 2012.

[68] R. Madavan and S. Balaraman, "Investigation on effects of different types of nanoparticles on critical parameters of nano-liquid insulation systems," *J. Mol. Liq.*, vol. 230, pp. 437–444, Mar. 2017.

[69] J. A. Mergos, M. D. Athanassopoulou, T. G. Argyropoulos, and C. T. Dervos, "Dielectric properties of nanopowder dispersions in paraffin oil," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 19, no. 5, pp. 1502–1507, Oct. 2012.

[70] D. Liu, Y. Zhou, Y. Yang, L. Zhang, and F. Jin, "Characterization of high performance AIN nanoparticle-based transformer oil nanofluids," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 23, no. 5, pp. 2757–2767, Oct. 2016.

[71] M. E. Ibrahim, A. M. Abd-Elhady, and M. A. Izzularab, "Effect of nanoparticles on transformer oil breakdown strength: Experiment and theory," *IET Sci. Meas. Technol.*, vol. 10, no. 8, pp. 839–845, Nov. 2016.

[72] J. G. Hwang, M. Zahn, F. M. O'Sullivan, L. A. A. Pettersson, O. Hjortstam, and R. Liu, "Effects of nanoparticle charging on streamer development in transformer oil-based nanofluids," *J. Appl. Phys.*, vol. 107, no. 1, pp. 1–17, 2010.

[73] J. Li, Z. Zhang, P. Zou, S. Grzybowski, and M. Zahn, "Preparation of a vegetable oil-based nanofluid and investigation of its breakdown and dielectric properties," *IEEE Elect. Insul. Mag.*, vol. 28, no. 5, pp. 43–50, Sep. 2012.

[74] H. Bönnemann, S. Botha, B. J. Bladergroen, and V. Linkov, "Monodisperse copper- and silver-nanocolloids suitable for heat-conductive fluids," *Appl. Organometallic Chem.*, vol. 19, no. 6, pp. 768–773, 2005.

[75] A. Amiri, M. Shanbedi, G. Ahmadi, and S. Rozali, "Transformer oils-based graphene quantum dots nanofluid as a new generation of highly conductive and stable coolant," *Int. Commun. Heat Mass Transf.*, vol. 83, pp. 40–47, Apr. 2017.

[76] Y.-Z. Lv, X.-X. Li, Y.-F. Du, F.-C. Wang, and C.-R. Li, "Preparation and breakdown strength of TiO_2 fluids based on transformer oil," in *Proc. Annu. Rep. Conf. Elect. Insul. Dielectic Phenomena*, 2010, pp. 1–3.

[77] Y. Zhong *et al.*, "Insulating properties and charge characteristics of natural ester fluid modified by TiO_2 semiconductive nanoparticles," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 20, no. 1, pp. 135–140, Feb. 2013.

[78] M. Hanai, S. Hosomi, H. Kojima, N. Hayakawa, and H. Okubo, "Dependence of TiO_2 and ZnO nanoparticle concentration on electrical insulation characteristics of insulating oil," in *Proc. Annu. Rep.-Conf. Elect. Insul. Dielect., Phenomena*, 2013, pp. 780–783.

[79] Y. Du, Y. Lv, F. Wang, X. Li, and C. Li, "Effect of TiO_2 nanoparticles on the breakdown strength of transformer oil," in *Proc. IEEE Int. Symp. Elect. Insul.*, vol. 2, Jun. 2010, pp. 1–3.

[80] Z. Hu *et al.*, "Thermal aging properties of transformer oil-based TiO_2 nanofluids," in *Proc. IEEE 18th Int. Conf. Dielectr. Liq. (ICDL)*, Jun./Jul. 2014, pp. 1–4.

[81] Y. Lv, Y. Du, C. Li, B. Qi, Y. Zhong, and M. Chen, "TiO_2 nanoparticle induced space charge decay in thermal aged transformer oil," *Appl. Phys. Lett.*, vol. 102, no. 13, p. 132902, 2013.

[82] M. M. Emara, D. E. A. Mansour, and A. M. Azmy, "Dielectric properties of aged mineral oil filled with TiO_2 nanoparticles," in *Proc. 4th Int. Conf. Elect. Power Energy Convers. Syst. (EPECS)*, 2015, pp. 15–19, 2015.

[83] Y.-F. Du, Y.-Z. Lv, Z. Jian-Quan, X.-X. Li, and C.-R. Li, "Breakdown properties of transformer oil-based TiO_2 nanofluid," in *Proc. Annu. Rep. Conf. Elect. Insul. Dielectic Phenomena*, 2010, pp. 1–4.

[84] E. G. Atiya, D.-E. A. Mansour, R. M. Khattab, and A. M. Azmy, "Dispersion behavior and breakdown strength of transformer oil filled with TiO_2 nanoparticles," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 22, no. 5, pp. 2463–2472, Oct. 2015.

[85] Y. Du *et al.*, "Effect of semiconductive nanoparticles on insulating performances of transformer oil," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 19, no. 3, pp. 770–776, Jun. 2012.

[86] Q. Wang, M. Rafiq, Y. Lv, C. Li, and K. Yi, "Preparation of three types of transformer oil-based nanofluids and comparative study on the effect of nanoparticle concentrations on insulating property of transformer oil," *J. Nanotechnol.*, vol. 2016, Nov. 2016, Art. no. 5802753.

[87] B. X. Du, X. L. Li, and J. Li, "Thermal conductivity and dielectric characteristics of transformer oil filled with BN and Fe_3O_4 nanoparticles," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 22, no. 5, pp. 2530–2536, Oct. 2015.

[88] B. X. Du and M. Xiao, "Thermal accumulation and tracking failure process of BN-filler epoxy-matrix composite," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 20, no. 6, pp. 2270–2276, Dec. 2013.

[89] B. X. Du and X. L. Li, "Dielectric and thermal characteristics of vegetable oil filled with BN nanoparticles," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 24, no. 2, pp. 956–963, Apr. 2017.

[90] B. X. Du and X. L. Li, "High thermal conductivity transformer oil filled with BN nanoparticles," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 22, no. 2, pp. 851–858, Apr. 2015.

[91] B. Wang, J. Li, B. Du, and Z. Zhang, "Study on the stability and viscosity of Fe_3O_4 nano-particles vegetable insulating oils," in *Proc. Int. Conf. High Voltage Eng. Appl.*, vol. 33, no. 3, pp. 307–310, 2012.

[92] Y. Hwang *et al.*, "Stability and thermal conductivity characteristics of nanofluids," *Thermochim. Acta*, vol. 455, nos. 1–2, pp. 70–74, 2007.

[93] S. Chakraborty, I. Sarkar, D. K. Behera, S. K. Pal, and S. Chakraborty, "Experimental investigation on the effect of dispersant addition on thermal and rheological characteristics of TiO_2 nanofluid," *Powder Technol.*, vol. 307, pp. 10–24, Feb. 2017.

[94] H. Jin, T. Andritsch, I. A. Tsekmes, R. Kochetov, P. H. F. Morshuis, and J. J. Smit, "Properties of mineral oil based silica nanofluids," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 21, no. 3, pp. 1100–1108, Jun. 2014.

[95] H. Jin, T. Andritsch, P. H. F. Morshuis, and J. J. Smit, "AC breakdown voltage and viscosity of mineral oil based SiO_2 nanofluids," in *Proc. Annu. Rep. Conf. Elect. Insul. Dielectr. Phenomena*, 2012, pp. 902–905.

[96] A. Katiyar, P. Dhar, T. Nandi, and S. K. Das, "Effects of nanostructure permittivity and dimensions on the increased dielectric strength of nano insulating oils," *Colloids Surfaces A, Physicochem. Eng. Aspects*, vol. 509, pp. 235–243, Nov. 2016.

[97] H. Jin, "Dielectric strength and thermal conductivity of mineral oil based nanofluids," Faculty Elect. Eng., Math. Comput. Sci., Dept. Elect. Power Eng., Delft Univ. Technol., Delft, The Netherlands, 2015.

[98] R. T. A. R. Prasath, N. K. Roy, S. N. Mahato, and P. Thomas, "Mineral oil based high permittivity $CaCu_3Ti_4O_{12}$ (CCTO) nanofluids for power transformer application," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 24, no. 4, pp. 2344–2353, Apr. 2017.

[99] D.-E. A. Mansour, E. G. Atiya, R. M. Khattab, and A. M. Azmy, "Effect of titania nanoparticles on the dielectric properties of transformer oil-based nanofluids," in *Proc. Conf. Electr. Insul. Dielectr. Phenomena (CEIDP)*, 2012, pp. 295–298.

[100] G. Cao, *Nanostructures and Nanomaterials—Synthesis, Properties, and Applications*, vol. 2. London, U.K.: Imperial College Press, 2004.

[101] G. D. Parfitt, *Dispersion of Powders in Liquids, With Special Reference to Pigments*. Canberra ACT, Australia: National Library of Australia, Applied Science Publishers, 1981.

[102] L. Kong, J. Sun, and Y. Bao, "Preparation, characterization and tribological mechanism of nanofluids," *RSC Adv.*, vol. 7, no. 21, pp. 12599–12609, 2017.

[103] J.-C. Lee and W.-Y. Kim, "Experimental study on the dielectric breakdown voltage of the insulating oil mixed with magnetic nanoparticles," *Phys. Procedia*, vol. 32, pp. 327–334, Jan. 2012.

[104] H. A. Mohammed, A. A. Al-Aswadi, N. H. Shuaib, and R. Saidur, "Convective heat transfer and fluid flow study over a step using nanofluids: A review," *Renew. Sustain. Energy Rev.*, vol. 15, no. 6, pp. 2921–2939, Aug. 2011.

[105] E. V. Timofeeva, W. Yu, D. M. France, D. Singh, and J. L. Routbort, "Base fluid and temperature effects on the heat transfer characteristics of SiC in ethylene glycol/H_2O and H_2O nanofluids," *J. Appl. Phys.*, vol. 109, no. 1, p. 014914, 2011.

[106] E. V. Timofeeva *et al.*, "Thermal conductivity and particle agglomeration in alumina nanofluids: Experiment and theory," *Phys. Rev. E, Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top.*, vol. 76, no. 6, p. 061203, 2007.

[107] E. V. Timofeeva, M. R. Moravek, and D. Singh, "Improving the heat transfer efficiency of synthetic oil with silica nanoparticles," *J. Colloid Interface Sci.*, vol. 364, no. 1, pp. 71–79, 2011.

[108] Z. Haddad, C. Abid, H. F. Oztop, and A. Mataoui, "A review on how the researchers prepare their nanofluids," *Int. J. Therm. Sci.*, vol. 76, pp. 168–189, Feb. 2014.

[109] B. R. Munson, D. F. Young, and T. H. Okiishi, *Fundamentals of Fluid Mechanics*, 3rd ed. Hoboken, NJ, USA: Wiley, 1998.

[110] T. Cosgrove, *Colloid Science: Principles, Methods and Applications*. London, U.K.: Applied Science, 2010.

[111] N. Ise and I. Sogami, *Structure Formation in Solution: Ionic Polymers and Colloidal Particles*. Berlin, Germany: Springer-Verlag, 2005.

[112] M. Wang, A. J. Vandermaar, and K. D. Srivastava, "Review of condition assessment of power transformers in service," *IEEE Elect. Insul. Mag.*, vol. 18, no. 6, pp. 12–25, Nov./Dec. 2002.

[113] J. Kirtley *et al.*, "Monitoring the health of power transformers," *IEEE Comput. Appl. Power*, vol. 9, no. 1, pp. 18–23, Jan. 1996.

[114] J. Kudelcik, P. Bury, P. Kopcansky, and M. Timko, "Dielectric breakdown in mineral oil ITO 100 based magnetic fluid," *Phys. Procedia*, vol. 9, no. 2, pp. 78–81, 2010.

[115] M. J. Given *et al.*, "The influence of magnetite nano particles on the behaviour of insulating oils for pulse power applications," in *Proc. Annu. Rep. Conf. Electr. Insul. Dielectr. Phenomena (CEIDP)*, Oct. 2011, pp. 40–43.

[116] J.-C. Lee, H.-S. Seo, and Y.-J. Kim, "The increased dielectric breakdown voltage of transformer oil-based nanofluids by an external magnetic field," *Int. J. Therm. Sci.*, vol. 62, pp. 29–33, Dec. 2012.

[117] P. Kopčanský, L. Tomčo, K. Marton, M. Koneracká, M. Timko, and I. Potočová, "The DC dielectric breakdown strength of magnetic fluids based on transformer oil," *J. Magn. Magn. Mater.*, vol. 289, pp. 415–418, Mar. 2005.

[118] P. Kopčanský, L. Tomčo, K. Marton, M. Koneracká, I. Potočová, and M. Timko, "The experimental study of the DC dielectric breakdown strength in magnetic fluids," *J. Magn. Magn. Mater.*, vols. 272–276, pp. 2377–2378, May 2004.

[119] P. Zou, J. Li, C.-X. Sun, Z.-T. Zhang, and R.-J. Liao, "Dielectric properties and electrodynamic process of natural ester-based insulating nanofluid," *Mod. Phys. Lett. B*, vol. 25, no. 25, pp. 2021–2031, 2011.

[120] M. Chiesa and S. K. Das, "Experimental investigation of the dielectric and cooling performance of colloidal suspensions in insulating media," *Colloids Surf. A Physicochem. Eng. Aspects*, vol. 335, nos. 1–3, pp. 88–97, 2009.

[121] W. Sima, J. Shi, Q. Yang, S. Huang, and X. Cao, "Effects of conductivity and permittivity of nanoparticle on transformer oil insulation performance: Experiment and theory," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 22, no. 1, pp. 380–390, Feb. 2015.

[122] J. Li, B. Du, F. Wang, W. Yao, and S. Yao, "The effect of nanoparticle surfactant polarization on trapping depth of vegetable insulating oil-based nanofluids," *Phys. Lett. A*, vol. 380, no. 4, pp. 604–608, 2016.

[123] Y. Du *et al.*, "Effect of electron shallow trap on breakdown performance of transformer oil-based nanofluids," *J. Appl. Phys.*, vol. 110, no. 10, p. 104104, 2011.

[124] C. Choi, H. S. Yoo, and J. M. Oh, "Preparation and heat transfer properties of nanoparticle-in-transformer oil dispersions as advanced energy-efficient coolants," *Current Appl. Phys.*, vol. 8, no. 6, pp. 710–712, 2008.

[125] H. Jin, P. Morshuis, A. R. Mor, J. J. Smit, and T. Andritsch, "Partial discharge behavior of mineral oil based nanofluids," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 22, no. 5, pp. 2747–2753, Oct. 2015.

[126] L. P. Shen, H. B. Wang, M. Dong, Z. C. Ma, and H. B. Wang, "Solvothermal synthesis and electrical conductivity model for the zinc oxide-insulated oil nanofluid," *Phys. Lett. A*, vol. 376, no. 10, pp. 1053–1057, 2012.

[127] P. Dhar, A. Katiyar, L. S. Maganti, A. Pattamatta, and S. K. Das, "Superior dielectric breakdown strength of graphene and carbon nanotube infused nano-oils," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 23, no. 2, pp. 943–956, Apr. 2016.

[128] S. Li, M. Karlsson, R. Liu, A. Ahniyaz, A. Fornara, and E. J. Salazar-Sandoval, "The effect of ceria nanoparticles on the breakdown strength of transformer oil," in *Proc. IEEE 11th Int. Conf. Properties Appl. Dielectr. Mater. (ICPADM)*, Jul. 2015, pp. 289–292.

[129] C. Cooke and W. Hagman, "Non-destructive breakdown test for insulating oil," in *Proc. EPRI Substation Equip. Diagnostics Conf. III*, 1994, pp. 1–6.

[130] J. Mak, V. Sokolov, A. Bassetto, T. V. Oommen, T. Haupert, and D. Hanson, "Transformer fluid: A powerful tool for the life management of an ageing transformer population," in *Proc. TechCon*, 2001, p. 1.

[131] *Insulating Liquids—Determination of the Breakdown Voltage at Power Frequency—Test Method*, Standard IEC 60156, 1995.

[132] *Standard Test Method for Dielectric Breakdown Voltage of Insulating Liquids Using Disk Electrodes*, Standard ASTM D877/D877M-13, West Conshohocken, PA, USA, 2013.

[133] *Standard Test Method for Dielectric Breakdown Voltage of Insulating Liquids Using VDE Electrodes*, Standard ASTM D1816-12, West Conshohocken, PA, USA, 2012.

[134] *Method for Determination of Electric Strength of Insulating Oils [ETD 3: Fluids for Electrotechnical Applications]*, Standard IS 6792:1992, New Delhi, India, 1992.

[135] F. Ahmad, Q. Khan, and A. Alam, "Analysis of flashover voltages of disc type insulator under artificial pollution condition," *Int. J. Eng.*, vol. 29, no. 6, pp. 1–6, Jun. 2016.

[136] C. Sugumaran, M. Mohan, and K. Udayakumar, "Investigation of dielectric and thermal properties of nano-filler (ZrO_2) mixed enamel," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 17, no. 6, pp. 1682–1686, Dec. 2010.

[137] A. K. Gupta and A. K. Sen, "Aspects of dielectric breakdown in a model for disordered nonlinear composites," *Phys. A Stat. Mech. Appl.*, vol. 247, nos. 1–4, pp. 30–40, 1997.

[138] *Methods for the Determination of the Lightning Breakdown Voltage of Insulating Liquids*, Standard IEC 60897, 1987.

[139] *Standard Test Method For Dielectric Breakdown Voltage Of Insulating Oils Of Petroleum Origin Under Impulse Conditions*, Standard ASTM D3300-12, West Conshohocken, PA, USA, 2012.

[140] *Guide for Determination of Lightning Impulse Electric Strength of Insulating Liquids [ETD 3: Fluids for Electrotechnical Applications]*, Standard IS 11697:1986, New Delhi, India, 1986.

[141] K. Bourzac, "Advanced manufacturing and new materials," MIT Technol. Rev., Bus. Rep., Jul. 2011.

[142] J. Miao, M. Dong, M. Ren, X. Wu, L. Shen, and H. Wang, "Effect of nanoparticle polarization on relative permittivity of transformer oil-based nanofluids," *J. Appl. Phys.*, vol. 113, no. 20, p. 204103, 2013.

[143] Z. Zhang, J. Li, P. Zou, and S. Grzybowski, "Electrical properties of nano-modified insulating vegetable oil," in *Proc. Annu. Rep. Conf. Electr. Insul. Dielectr. Phenomena (CEIDP)*, 2010, pp. 3–6

[144] *Insulating Liquids—Measurement of Relative Permittivity, Dielectric Dissipation Factor (Tan D) and D.C. Resistivity*, Standard IEC 60247, 2004.

[145] *Test Methods for AC Loss Characteristics and Permittivity (Dielectric Constant) of Solid Electrical Insulation Materials*, Standard ASTM D150-98, West Conshohocken, PA, USA, 2004.

[146] *Standard Test Method for Dissipation Factor (or Power Factor) and Relative Permittivity (Dielectric Constant) of Electrical Insulating Liquids*, Standard ASTM D924-15, West Conshohocken, PA, USA, 2015.

[147] L. Chetty, I. W. Serukenya, and N. M. Ijumba, "Vegetable oil based liquid nanocomposite dielectric," *South Africa J. Sci.*, vol. 109, nos. 1–2, pp. 1–6, 2003.

[148] S. Ganguly, S. Sikdar, and S. Basu, "Experimental investigation of the effective electrical conductivity of aluminum oxide nanofluids," *Powder Technol.*, vol. 196, no. 3, pp. 326–330, 2009.

[149] Q. Khan, F. F. Ahmad, A. A. Khan, and F. F. Ahmad, "Assessment of solid insulating material using Partial Discharge characteristics," in *Proc. Int. Conf. Electr., Electron., Optim. Techn. (ICEEOT)*, Mar. 2016, pp. 1786–1789.

[150] *High-Voltage Test Techniques—Partial Discharge Measurements*, Standard 60270, 2000.

[151] G. L. W. Lv, Y. F. Du, J. Q. Zhou, X. X. Li, M. T. Chen, and C. R. Li, "Nanoparticle effect on electrical properties of aged mineral oil based nanofluids," *CIGRE*, pp. 1–7, 2012.

[152] R. Karthik, F. Negri, and A. Cavallini, "Influence of ageing on dielectric characteristics of silicone dioxide, tin oxide and ferro nanofluids based mineral oil," in *Proc. 2nd Int. Conf. Adv. Elect., Electron., Inf., Commun. Bio-Inform. (AEEICB)*, 2016, pp. 40–43.

[153] Irwanto, C. G. Azcarraga, Suwarno, A. Cavallini, and F. Negri, "Ferrofluid effect in mineral oil: PDIV, streamer, and breakdown voltage," in *Proc. Int. Conf. High Voltage Eng. Appl. (ICHVE)*, 2014, pp. 1–4.

[154] *Insulating Liquids—Determination of the Partial Discharge Inception Voltage (PDIV)—Test Procedure*, document IEC TR 61294, 1993.

[155] X. Wang and Z. D. Wang, "Particle effect on breakdown voltage of mineral and ester based transformer oils," in *Proc. Annu. Rep.-Conf. Elect. Insul. Dielectr. Phenomena (CEIDP)*, 2008, pp. 598–602.

[156] M. Rafiq, D. Khan, and M. Ali, "Insulating properties of transformer oil-based silica nanofluids," in *Proc. Power Gener. Syst. Renew. Energy Technol. (PGSRET)*, 2015, pp. 1–3.

[157] Y.-Z. Lv, L.-F. Wang, X.-X. Li, Y.-F. Du, J.-Q. Zhou, and C.-R. Li, "Experimental investigation of breakdown strength of mineral oil-based nanofluids," in *Proc. IEEE Int. Conf. Dielectr. Liq.*, Jun. 2011, vol. 22, no. 5, pp. 1–3.

[158] Y. Hwang *et al.*, "Production and dispersion stability of nanoparticles in nanofluids," *Powder Technol.*, vol. 186, no. 2, pp. 145–153, 2008.

[159] S. Pugazhendhi, "Experimental evaluation on dielectric and thermal characteristics of nano filler added transformer oil," in *Proc. Int. Conf. High Voltage Eng. Appl.*, vol. 9, 2012, pp. 207–210.

[160] D. H. Fontes, G. Ribatski, E. Pedone, and B. Filho, "Experimental evaluation of thermal conductivity, viscosity and breakdown voltage AC of nanofluids of carbon nanotubes and diamond in transformer oil," *Diamond Rel. Mater.*, vol. 58, pp. 115–121, Sep. 2015.

[161] D.-W. Oh, A. Jain, J. K. Eaton, K. E. Goodson, and J. S. Lee, "Thermal conductivity measurement and sedimentation detection of aluminum oxide nanofluids by using the 3ω method," *Int. J. Heat Fluid Flow*, vol. 29, no. 5, pp. 1456–1461, 2008.

[162] N. L. Cadena-de la Peña, C. I. Rivera-Solorio, L. A. Payán-Rodríguez, A. J. García-Cuéllar, and J. L. López-Salinas, "Experimental analysis of natural convection in vertical annuli filled with AlN and TiO_2/mineral oil-based nanofluids," *Int. J. Thermal Sci.*, vol. 111, pp. 138–145, Jan. 2017.

[163] P. C. Mishra, S. K. Nayak, and S. Mukherjee, "Thermal conductivity of nanofluids-an extensive literature review," *Int. J. Eng. Res. Technol.*, vol. 2, no. 9, pp. 734–745, 2013.

[164] D. Li, W. Xie, and W. Fang, "Preparation and properties of copper-oil-based nanofluids," *Nanosc. Res. Lett.*, vol. 6, no. 1, p. 373, 2011.

[165] K. Anoop, R. Sadr, M. Al-Jubouri, and M. Amani, "Rheology of mineral oil-SiO_2 nanofluids at high pressure and high temperatures," *Int. J. Therm. Sci.*, vol. 77, pp. 108–115, Mar. 2014.

[166] D. Jasper, M. Ravindran, and R. Madavan, "Enhancement of characteristic performance of silicone oil with semi conductive nano particles," in *Proc. Int. Conf. Innov. Inf., Embedded Commun. Syst. (ICIIECS)*, 2015, pp. 1–4.

[167] K. Miners, "Particles and moisture effect on dielectric strength of transformer oil using VDE electrodes," *IEEE Trans. Power App. Syst.*, vol. PAS-101, no. 3, pp. 751–756, Mar. 1982.

[168] V. Segal and K. Raj, "An investigation of power transformer cooling with magnetic fluids," *Indian J. Eng. Mater. Sci.*, vol. 5, no. 6, pp. 416–422, 1998.

[169] F. M. O'Sullivan, "A model for the initiation and propagation of electrical streamers in transformer oil and transformer oil based nanofluids," Ph.D. dissertation, Dept. Elect. Eng. Comput. Sci., Massachusetts Inst. Technol., Cambridge, MA, USA, 2007, p. 309.

[170] J. G. Hwang, F. O'Sullivan, M. Zahn, O. Hjortstam, L. A. A. Pettersson, and R. Liu, "Modeling of streamer propagation in transformer oil-based nanofluids," in *Proc. Annu. Rep. Conf. Elect. Insul. Dielectr. Phenomena*, 2008, pp. 361–366.

[171] J. G. Hwang *et al.*, "Electron scavenging by conductive nanoparticles in oil insulated power transformers," in *Proc. Joint Electrostat. Conf.*, Boston, MA, USA, 2009, pp. 1–12.

[172] Z. Jian-Quan, D. Yue-Fan, C. Mu-Tian, L. Cheng-Rong, L. Xiao-Xin, and L. Yu-Zhen, "AC and lightning breakdown strength of transformer oil modified by semiconducting nanoparticles," in *Proc. Annu. Rep. Conf. Elect. Insul. Dielectr. Phenomena*, 2011, pp. 652–654.

[173] Y. Zhou *et al.*, "Effect of nanoparticles on electrical characteristics of transformer oil-based nanofluids impregnated pressboard," in *Proc. Conf. Rec. IEEE Int. Symp. Elect. Insul.*, Jun. 2012, pp. 650–653.

[174] Y. Z. Lv *et al.*, "Nanoparticle effects on creeping flashover characteristics of oil/pressboard interface," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 21, no. 2, pp. 556–562, Apr. 2013.

[175] M. F. Dehkordi, "Dielectric behavior of transformer oil when contaminated and/or fortified with nanoparticles," M.S. thesis, Univ. Du Quebec, Quebec City, QC, Canada, 2014. [Online]. Available: https://constellation.uqac.ca/3036/1/FarzanehDehkordi_uqac_0862N_10090.pdf

[176] G. D. Peppas, V. P. Charalampakos, E. C. Pyrgioti, M. G. Danikas, A. Bakandritsos, and I. F. Gonos, "Statistical investigation of AC breakdown voltage of nanofluids compared with mineral and natural ester oil," *IET Sci. Meas. Technol.*, vol. 10, no. 6, pp. 644–652, Sep. 2016.

[177] J. Miao, M. Dong, and L.-P. Shen, "A modified electrical conductivity model for insulating oil-based nanofluids," in *Proc. IEEE Int. Conf. Condition Monitor. Diagnosis*, Sep. 2012, pp. 1126–1129.

[178] H. Jin, P. H. F. Morshuis, A. R. Mor, and T. Andritsch, "An investigation into the dynamics of partial discharge propagation in mineral oil based nanofluids," in *Proc. IEEE 18th Int. Conf. Dielectr. Liq. (ICDL)*, Jun./Jul. 2014, pp. 1–4.

[179] M. Z. H. Makmud, H. A. Illias, C. Y. Chee, and M. S. Sarjadi, "Influence of conductive and semi-conductive nanoparticles on the dielectric response of natural ester-based nanofluid insulation," *Energies*, vol. 11, no. 2, p. 333, 2018.

[180] T. Tanaka, M. Kozako, N. Fuse, and Y. Ohki, "Proposal of a multi-core model for polymer nanocomposite dielectrics," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 12, no. 4, pp. 669–681, Aug. 2005.

[181] C. T. Wamkam, M. K. Opoku, H. Hong, and P. Smith, "Effects of *p*H on heat transfer nanofluids containing ZrO_2 and TiO_2 nanoparticles," *J. Appl. Phys.*, vol. 109, no. 2, pp. 1–6, Jan. 2011.

[182] L. Xuan and Q. Li, "Heat transfer enhancement of nanofluids," *Int. J. Heat Fluid Flow*, vol. 21, no. 1, p. 58, 2000.

[183] H. Younes, G. Christensen, X. Luan, H. Hong, and P. Smith, "Effects of alignment, *p*H, surfactant, and solvent on heat transfer nanofluids containing Fe_2O_3 and CuO nanoparticles," *J. Appl. Phys.*, vol. 111, no. 6, p. 064308, 2012.

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