Enhancing transformer liquid insulation with nanodielectric fluids: State of the art and future trends

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Abstract — **In the last years several, works have proposed the use of nanodielectric fluids as an improved insulation for different elechtrotecnical applications. The behaviour of nano dielectric fluids has been evaluated from the point of view of the dielectric and thermal properties. Although the results of the different authors are in any cases not in complete agreement, most investigations report promising performances for these new liquids. In this paper, a literature survey on this field is presented.**

Keywords — **Insulating liquids; Nanoparticles; Nanodielectric fluids Nanofluid; Ferrofluid**

I. Introduction

Recently, nanodielectric fluids have been proposed to be used as transformer liquid insulation. These materials are obtained by dispersing nanoparticles in a matrix fluid. The addition of particles seeks to improve the dielectric and thermal properties of the base liquids, giving rise to a new generation of insulating fluids. Several authors claim that the performance of nanodielectric fluids as insulators and coolers is superior to that of the base liquids.

The interest on these type of fluids has risen exponentially over the last years, as can be derived from the number of scientific works published in international journals and conferences (Fig. 1).

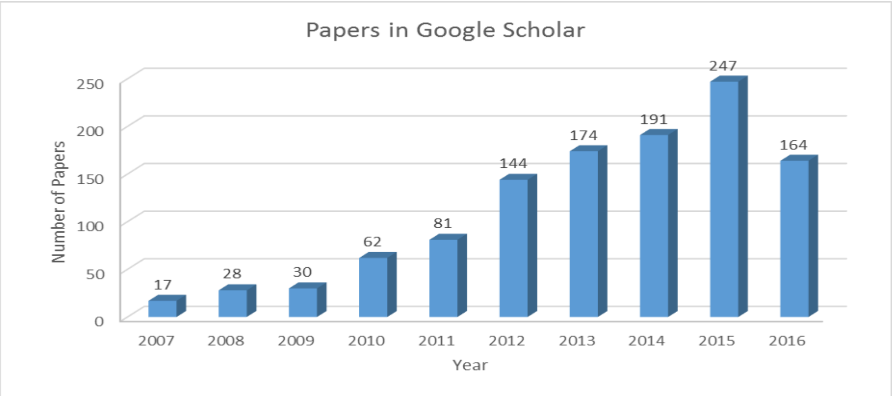

Figure 1. Papers dealing with the subject “nanofluids for application in transformers”, from 2007 to July 2016. Source, Google Scholar.

Nanodielectric fluids are not a feasible technical solution nowadays. Some issues related to their stability, the interaction with the magnetic fields present in the transformer, the effect of the nanoparticles on the transformer solid insulation performance, and the production costs should be studied and addressed before they could be applied in real transformers.

The aim of this paper is to present a state of the art on Nanodielectric fluids for electrotechnical use. The experimental results obtained by different authors are reviewed and compared. Additionally, practical issues, such as the manufacturing process of the liquids, and basic theoretical aspects are reviewed.

II. MANUFACTURING OF NANODIELECTRICS FLUIDS.

Although some companies, such as General Electric, have already registered patents related with the use of nanodielectric fluids in electric devices, those liquids are not commertially available nowadays. The investigations reported in literature are mostly based on fluids manufactured at laboratory scale. Dıfferent types of particles and base fluids have been proposed and tested to date. Nanofluids can be classified according to the type of nanoparticles disperssed in the base fluids, and by the base fluds used.

2.1 Nanoparticles

The selection of the nanoparticle is one of the most important issues when preparing a nanofluid. Nanoparticles can be categorized according to their conductivity into three groups [1]

- Conductive nanoparticles: Fe_3O_4, Fe_2O_3, ZnO,…
- Semiconductive nanoparticles: TiO_2, CuO, CuO_2,...
- Insulating nanoparticles: Al_2O_3, SiO_2, BN,…

Works have been published dealing with fluids manufactured using different conductive, semiconductive and insulating particles, reporting positive effects for most of them. Sima explains in [2] that the physical phenomena that takes place when an insulating fluid doped with particles is subjected to an electric field is the same, independently of the particle nature. This finding could seem to contradict the traditional theory of liquid dielectric breakdown, which assumes that the contamination of an insulating fluid with conductive particles or impurities would lead to a degradation of its performance.

Sima [2] states that, under the effect of an electric field, the electrons in the nanoparticles are orientated in a direction opposite to that of the electric field, generating a positive and negative charge distribution on the surface of the conductor (Fig. 2).

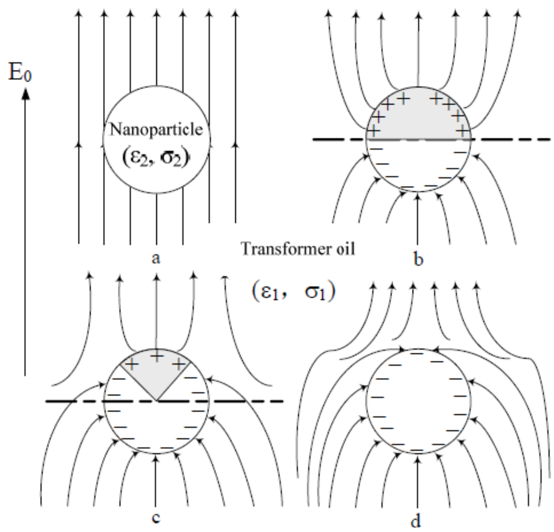

Figure 2. Electric field lines after a uniform z-directed electric field is activated at t = 0 around a Nanoparticle with radius R, permittivity ε_2, and conductivity σ_2. This nanoparticle is surrounded by transformer oil with permittivity ε1 and conductivity σ_1. Taken from [2]

2.2 Base Fluid

The base fluid is the liquid in which the nanoparticles are dispersed. Although most of the works in the field of Nano-dielectric fluids are focused in mineral-oil based liquids, some investigations have also been reported on the use of natural ester or synthetic ester based nanofluids [3], [4] or [5]. Dombek in [6] compares the enhancement in the thermal properties that can be achieved by adding nanoparticles to Mineral oil and Synthetic esters. Other authors as Wang [7] have also tested Natural-Ester based fluids.

The development of ester-based nanodielectric fluids could be an important area in the future, since the addition of nanoparticles can lead to an improvement of the cooling properties of the fluid, which are one of the weak points esters fluids.

2.3 Manufacturing procedure

In the vast majority of the cases, the nanoparticles to be dispersed in dielectric fluids are prepared outside the fluid or purchased to nanotechnology companies. This is known as a two-step manufacturing process. The particles are dispersed in the matrix fluid by sonication or magnetic stirring, being precise, in most cases, to add a surfactant to prevent particle agglomeration or sedimentation [6].

It must be also highlighted that appropriate health and safety measures must be implemented in the laboratories in order to manipulate the nanoparticles, being advisable to protect or isolate the workers from them to prevent their being breathed.

2.4 Stability

One of the main problems when working with nanofluids, is to guarantee the stability of the nanoparticles dispersed in the oil in the long term. Nanofluids stabilities have been reported to go from a few weeks to several months. As mentioned before, it is common to use surfactants and dispersants to prevent the agglomeration of the nanoparticles by coating its surface with a layer of specific products. One of the major surfactants employed to this end is oleic acid [8], [9].

III. THERMAL PROPERTIES

Thermal properties are important for transformer oils, since, as it is well known, the oil also acts as a coolant in transformers. The main thermal properties of dielectric oil are the viscosity and the thermal conductivity of the fluid.

3.1 Thermal Conductivity

Several researchers have reported experimental studies dealing with the thermal conductivity of nanofluids. In Yanijao Li's paper [10], three factors that influence the nanofluids’ thermal conductivity are highlighted. These factors are the properties of the nanoparticles, the liquid matrix and the liquid-solid interface.

The influence of nanoparticles in the thermal conductivity of the nanofluid mainly depends on the effect of the volume fraction of particles, the thermal conductivity of the particles, their morphology and the Brownian motion. Many investigations have revealed a large increase on thermal conductivity as the volume fraction of nanoparticles rises. This improvement in some cases is not linear. This may be due to an organized structure in the solid-liquid interface.

The influence of the base liquid has been less studied than the influence of the nanoparticles concentration and type. It can be summarized that thermal conductivity experiments show an increase with increasing temperature and this in turn depends on the type of matrix liquid used.

Finally, the influence of the solid-liquid interface is one of the important factors affecting the thermal conductivity. Several studies claim that the interfacial layer between the nanoparticle and the fluid has a very important role in improving the thermal properties of nanofluids. According to Choi [11] in particles smaller than 10 nm, the nano-layer is more important than the nanoparticles used to manufacture the nanofluid.

Donbek [6] published an experimental study in which the thermal properties of different nanofluids were determined. Fig. 3 shows the increase of thermal conductivity of a mineral oil modified by nanoparticles TiO_2 and surfactant about mineral oil as a function of temperature.

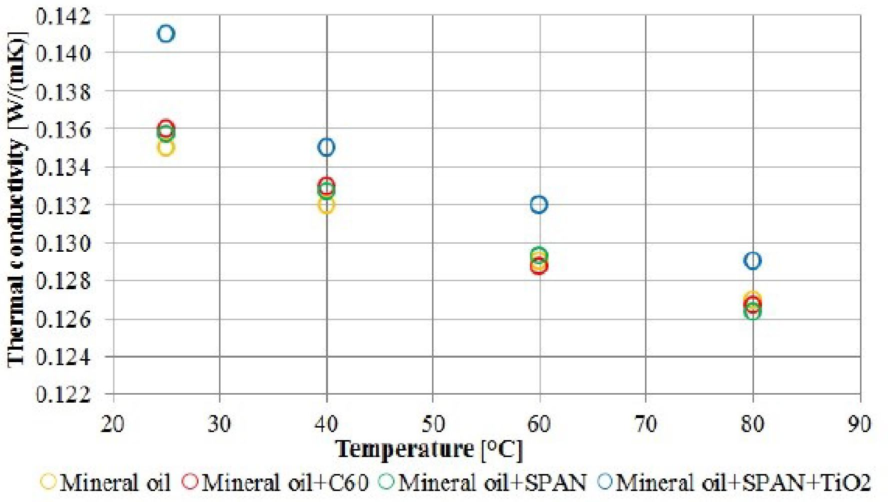

Figure 3. Thermal conductivity coefficient of mineral oil and nanoliquids formed on its basis, as a function of temperature. Take from [6]

3.2 Viscosity

The viscosity of nanofluids has been little studied, despite of being a thermal property as important as the thermal conductivity for the cooling performance of the fluids. The vast majority of studies are focused on the factors influencing the viscosity of those liquids, such as the concentration or size of nanoparticles and the temperature.

Li [12] showed that the viscosity of nanofluids decreases with increasing temperature and increases with the increase of the concentration of the nanoparticles, being much greater the effect of temperature.

Fig. 4, shows how viscosity of a mineral oil varies with the addition of several nanoparticles as a function of temperature. As can be seen the viscosity of all the included fluids decrease as temperature increase, but not a big variation is observed when the particles are added.

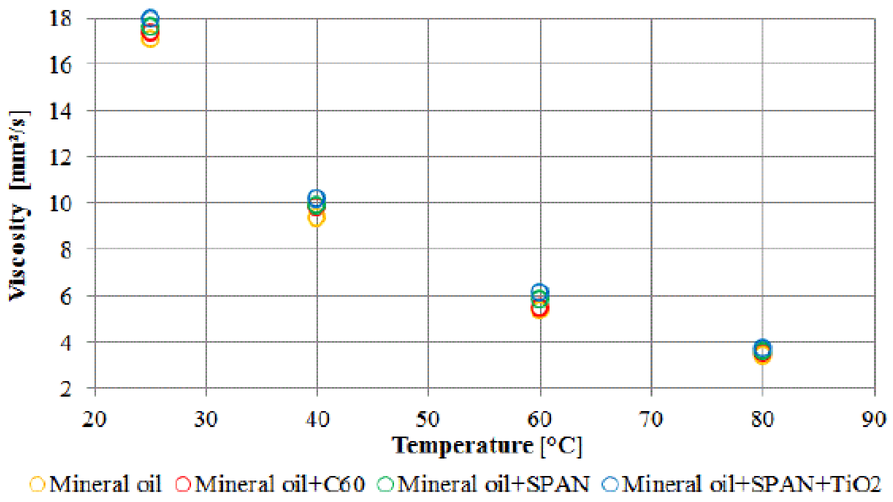

Figure 4. Viscosity of mineral oil and nanoliquids formed on its basis, as a function of temperature. Taken from [6]

IV. DIELECTRIC PROPERTIES

Several authors have tested the dielectric properties of nanofluids comparing them with those of base fluids. This section discusses the results obtained by the different authors:

4.1 AC Breakdown Voltage

AC Breakdown voltage has been measured on several nanodielectric fluids obtained by mixing mineral oil with insulating, semiconductive and conductive particles.

Table I compares the results reported by different authors, including details of the experiments such as the particles added to the oil, the particle size or the concentration of the nanoparticles in the base fluid. As can be seen, an improvement was observed in all cases. An author, [13] reports an increase of more than 40 % on the AC Breakdown voltage.

Table I. Increase in AC Breakdown Strength reported by several authors.

Nanoparticle/ Oil System	Nanoparticle Size (nm)	Nanoparticle loading	% Increase in AC Breakdown Strength	Ref
Fe_3O_4/MO	10	-	42,8%	[13]
Fe_3O_4/VO	30	-	19.8%	[14]
ZnO/MO	34	0.0005 % vol	8.3%	[15]
TiO_2/VO	20	0.00625 % vol	31%	[4]
SiO_2/MO	15	0.0074 % vol	17%	[16]
TiO_2/MO	<20	0.006g/L	15%	[17]
SiO_2/MO	15	0.01 % vol 0.02% vol	19% 26%	[18]

Y. Zhou [1], states that a clear increase in the AC Breakdown Strength of Mineral Oil based nanofluids containing Fe_3O_4 nanoparticles is observed. This improvement is especially noticeable when the moisture content of oil is high. The authors suggest that this effect might be due to the formation of water clusters that are attached by the surface of the nanoparticles. A similar improvement in dielectric properties was observed when the particles added were TiO_2, as Du et al [19] report.

Table II shows a study presented by Du Yue-fan et al [17] where the effect of adding TiO_2 nanoparticles in the AC (50Hz) Breakdown Voltage of mineral oil was determined. As can be seen, a certain improvement is reported for low concentrations of particles, although it must be noted that for concentrations greater than 0.03 g/L the performance of the nanofluid is similar or even worse than that of mineral oil. This same effect has been also reported in other works and it seems clear that depending on the nanoparticle concentration in oil, their effect can be even detrimental.

Table II: Comparison of AC Breakdown voltages between nanofluid and transformer oil reported by [17].

Samples	Mean Breakdown Voltage (KV)	% Increase in Breakdown Voltage
Transformer Oil	71,59	0%
TiO_2 (0.003g/L)	67,33	-5,9%
TiO_2 (0.006g/L)	82,48	15,2%
TiO_2 (0.01g/L)	77,82	8,7%
TiO_2 (0.03g/L)	71,76	0,2%
TiO_2 (0.05g/L)	53,25	-25,6%

One of the most widely used nanoparticle is magnetite (Fe_3O_4). In [20] Nytro Libra mineral oil is mixed with magnetite nanoparticles with a volume concentration of 0.1-0.6%. The breakdown voltage measured according to IEC 60156 standard [23] for mineral oil was 60.44 kV, while for volume concentrations of nanoparticles

0.2%, 0.3% and 0.6% was 63.76 kV, 70.16 kV and 53.84 kV, respectively. So, increasing the volume concentration may increase the voltage breakdown, but up to a limit in which the magnetic nanoparticle concentration could result in a decrease of the breakdown voltage due to the form of conducting chains close to the electrodes. In this case, the optimal nano oil volume concentration for having the higher breakdown voltage is around 0.2-0.3% [20], [21].

In [22], the statistical behaviour of the AC breakdown voltage is compared in mineral, synthetic and natural ester oils according to IEC 60156 standard [23]. The breakdown voltage of insulating oils, generally follows a Normal distribution and its average value is higher in natural esters than in mineral oils. Besides, this value is also higher for natural esters at the risk levels of 1%, 10% and 50% ($U_{1\%}$, $U_{10\%}$, and $U_{50\%}$). As an additional result, the dielectric strength of ester oils is generally greater than that of mineral oils under AC voltages.

Another effect that must be taken into account [24] is that the AC breakdown voltage rises with the size of the nanoparticles up to a certain limit that depends on the nanoparticles concentration in the fluid. As an example, for the ester fluid FR3, the breakdown voltage is 55.1 kV, while for the same fluid containing 40.7 nm Fe_3O_4 is 68.5 kV, an increase of 24.5%. Besides, in [25] it is found that the AC breakdown voltage also depends on the chemical composition of the nanoparticles.

Additionally, in [13] is found that the improvement on the AC breakdown voltage, in Fe_3O_4 mineral oil-based nanofluids, is greater as the water content of the oil increases, Fig. 5.

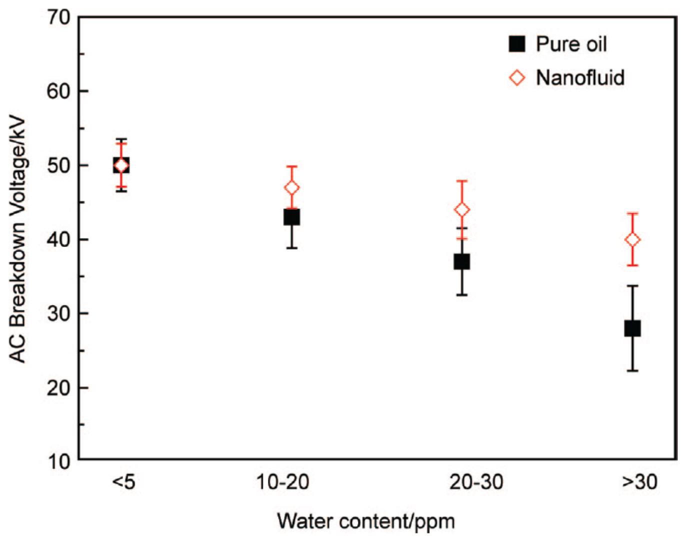

Figure 5. AC breakdown for mineral oils and Fe_3O_4 mineral oil-based nanofluids as function of water content. Taken from [1] that adapted it adapted from [13]

Finally, [24] shows that the polarization of the surfactants that coat the particles can significantly influence the electron trapping depth of natural ester based nanofluids. The results have shown that the breakdown strength increases for nanofluids with a smaller thickness ratio of surfactant. Besides, in [1] it is shown that the choice of a certain surface modifying agent can increase or decrease the AC breakdown strength of mineral oil-based ferrofluids. According to this, Fig. 6 shows the influence of two TiO_2 nanoparticle surface modification agents compared with the AC breakdown voltage of TiO_2 mineral-oil based nanofluids related to the TiO_2 concentration.

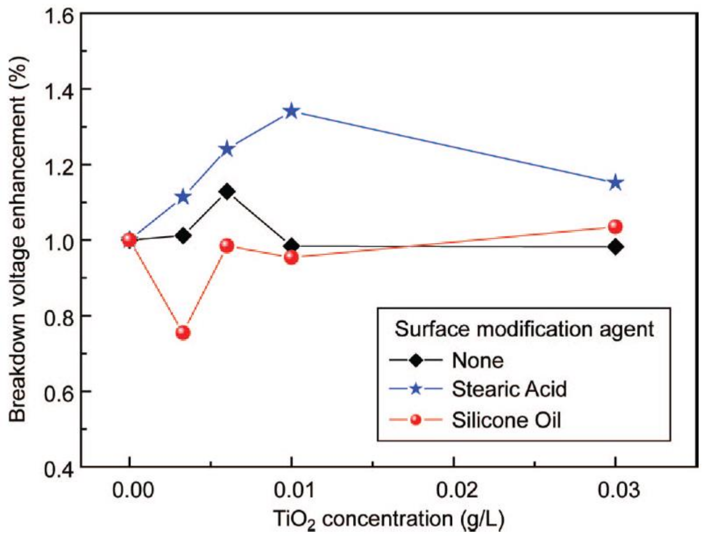

Figure 6. AC breakdown voltage dependency of surfactants for different mineral oil-based TiO_2 nanofluids compared with different TiO_2 concentrations [1] adapted from [26]

4.2 DC Breakdown Voltage

Several authors have reported an increase of the DC Breakdown Voltage of insulating fluids when nanoparticles are added [1]. As shown in Fig. 7, the DC breakdown voltage showed an increases as the concentration of Fe_3O_4 nanoparticles increased from 0.2-2 vol%. Besides, in some tests, the specimen was subjected to a 20 mT external magnetic field, and this effect reduced the DC breakdown voltage compared to the same concentration without external magnetic field applied [27]. The authors sustained that the reason for this observation is the formation of a micrometer-sized aglomerated Fe_3O_4 particles in the nanofluid as a result of magnetic dipole-dipole interaction between each nanoparticle under the external magnetic field [1].

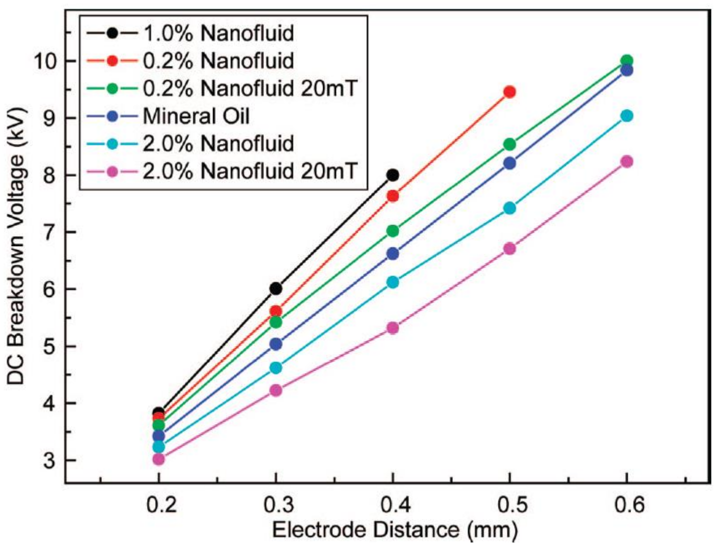

Figure 7. DC breakdown voltage compared with electrode distance for mineral oil and different concentrations of Fe3O4 oil-based nanofluids, some of them are subjected to a 20 mT external magnetic field [1] adapted from [27]

According to [28], it is found that the DC breakdown behaviour it is very different from positive to negative DC applied voltage, i.e. for mineral oil compared with TiO_2 nanoparticles (0.075 vol%), the positive DC breakdown is quite similar for mineral oil and for nanofluid, however, the negative DC breakdown showed a significant increase, according to Table III.

Table III DC breakdown voltage of mineral oil and nanofluid. Taken from [29].

Samples	DC(+) Breakdown Voltage(KV)	Standard Deviation (KV)	DC(-) Breakdown Voltage(KV)	Standard Deviation (KV)
Mineral oil	49.1	2.6	66.3	4.0
Nanofluid	45.1	1.8	84.6	6.4

4.3 Streamer propagation in nanofluids. Lightning impulse.

A streamer discharge is a transient electrical discharge that can appear when an insulating medium, e.g. insulating oil, is exposed to a large voltage drop, such as in the case of a lightning impulse.

Streamer propagation in transformer fluids depends on the field ionization and thus, as many of the mobile electrons produced by ionization are trapped before they can be swept away from the ionization region, the electrodynamics involved in the development of the streamer in the nanofluid will be significantly slower than that of pure oil. Besides, nanofluids have slower positive streamer velocities and higher positive voltage breakdown than that of pure conventional oil [30]. In [13] the effect of the nanoparticles on the propagation velocity of positive streamers was studied, observing that that parameter was reduced by as much as 46% by the addition of the particles. The effect of reducing the propagation velocity of streamer is higher as the nanoparticle conductivity increases [30]. A slower propagation velocity allows more time for the impulse voltage to be extinguished, so the positive voltage breakdown must be higher than that obtained in conventional transformer oil. Note that positive streamer implies a greater risk for the insulation of electrical equipment than negative streamers.

In [3], the average breakdown voltage for positive lightning impulse of a natural ester was found to be 73.9kV, while for the Fe_3O_4 based nanofluid it rose to 101.5kV, a 27.2% increase. In the case of the negative lightning impulse, the average values for the breakdown voltage were 83.8 kV for the base fluid vs. 93.7 kV for the nanofluid, a 10.6% increase. In addition, the breakdown time also increased for the nanofluid compared with the base liquid [14], i.e. 9.9 μs for vegetal oil and 12.0 μs in nanoparticle's oil-based, which represents a 17.5% increase of the breakdown time.

Finally, O'Sullivan [31], Sima [2] and [30] implemented several mathematical models in Finite Elements to study streamer phenomena in insulating fluids when different types of nano-particles are dispersed in them.

4.4 Partial discharges (PD) in nanofluids

Breakdown occurs after discharge initiation and propagation across the oil. Besides, the breakdown voltage measurement alone provides little information on the discharge process. Therefore, it is important to investigate the details of the discharge mechanisms in mineral oil and in nanofluids. In [32], the PD inception voltage (PDIV), PD duration, PD rise time, total discharge magnitude and PD voltage amplitude is compared for mineral oil, silica nanofluid and fullerene nanofluid (with an average particle size of 15 [nm] and 1 [nm], respectivelely) under DC voltage. The discharge mechanism in mineral oil depends strongly on the polarity of the applied DC voltage. Under negative DC polarity, inception voltage and discharge magnitude are quite similar between nanofluids and the reference mineral oil. However, under positive DC voltage, the nanofluids show an increased inception voltage and a reduction of the total discharge magnitude compared to the reference mineral oil, [33].

According to [29] the dielectric withstand of partial discharge of mineral oil can be improved by the addition of TiO2 nanoparticles. The PDIV is increased and the PD magnitudes and numbers of PD pulses are reduced, as it is shown in Table IV [1], [29].

Table IV. PDIV, PD magnitudes, and numbers of PD pulses acquired at 1.0 and 2.0 PDIV during 10 minute measurements intervals in mineral oil and TiO_2 nanofluids.

Sample	PDIV (kV)	Std. Deviation (kV)	Measured at 1.0 PDIV		Measured at 2.0 PDIV	
			Pulse number	Mean discharge magnitude (pC)	Pulse number	Mean discharge magnitude (pC)
Mineral oil	30.6	2.7	9	435	245	6062
TiO_2 Nanofluid	33.1	1.8	6	245	168	5180

Finally, in [33] three different nanofluids, silica ferrofluid 0.2, graphene oxide, and SiO_2, DC and AC withstand capability are compared with mineral oil. As a result, for all nanofluids, nanoparticle concentrations around 0.2 g/l enhance dielectric withstand properties under quasi uniform fields. Under divergent fields, partial discharge characteristics are improved under AC conditions. Under DC conditions silica nanofluid performs better than mineral oil, but the other two nanofluids do not perform well.

V. CONCLUSIONS

From the year 2010, interest in nanodielectric fluids applications has increased significantly. Several research groups are working with different materials (both fluid and particle type), focusing their studies on the thermal and dielectric properties of these liquids.

Authors have observed that the addition of nano-particles to the oil improves the dielectric behavior of the fluid increasing its breakdown voltage and the AC pulse and other thermal properties. The application of such liquids could achieve more compact designs of transformers and improve the reliability of the new high voltage transformers for AC (UHVAC-ultra-high voltage alternating current) or DC (Ultra-high voltage direct UHVDC- current).

Although the results reported in good number works are promising, more research is necessary to make nanofluids a feasible industrial solution. Investigations should be carried out to determine aspects such as influence of the applied materials and techniques, the long term stability of the fluids, the thermal and dielectric properties under different conditions or the interaction of the particles with other elements of the transformers.

VI. AKNOWLEDGEMENT

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