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Nanofluids in the Service of High Voltage Transformers: Breakdown Properties of Transformer Oils with Nanoparticles, a Review

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Abstract: The continuous development of electrical systems and high voltage transformers builds the need for looking for new insulating media or to improve the insulating properties of commercially available transformer oils (TO) by various modification techniques. One of these techniques is the modification of existing mineral oils by the addition of different types of nanoparticles in various concentrations. These types of materials, suspensions of nanoparticles called nanofluids, have found numerous applications in the energy industry, especially in heat exchanger systems and solar cells. Much research has been done on attempts to replace mineral oils (MO), which are harmful for the environment, with natural ester oils (NE), but to make this possible, it is necessary to improve the insulating properties of these oils, for example by adding nanoparticles. This paper presents an extensive overview of the insulating properties; including for AC, DC and the lightning impulse breakdown voltage; for both mineral and natural ester oils containing various type of nanoparticles (NP). It is presented that the use of nanofluids could improve the efficiency of existing high voltage infrastructures with a low financial cost.

Keywords: breakdown voltage; lightning breakdown voltage; nanofluids; insulating properties

1. Introduction

At the end of the 20th Century, Choi and Eastman showed that the thermal conductivity of conventional liquids could be enhanced by suspending nanoparticles (NP) in them; they called this type of dispersion a "nanofluid" [1]. Nanofluids are two-phase mixtures where the solid phase is comprised of nanoparticles with sizes less than 100 nm. After 1995, a large amount of research was done on nanofluids (NF). Figure 1 shows the significant increase in the number of papers on nanofluids, and citations to published articles, that has occurred since then. The studies on nanofluids can be classified into different groups, such as investigations into preparation and the measuring of properties, as well as research into different applications in engineering, sciences and medicine. Since instability has always been one of the main challenges in the implementation of nanofluids, scientists have attempted continuously to improve the preparation techniques to have more stable nanofluids [2–6]. Most of the industrial applications of nanofluids are correlated with their higher effective thermal conductivity compared to common liquids; therefore, heat transfer characteristics of nanofluids have been the subject of many experimental and theoretical studies [7–23].

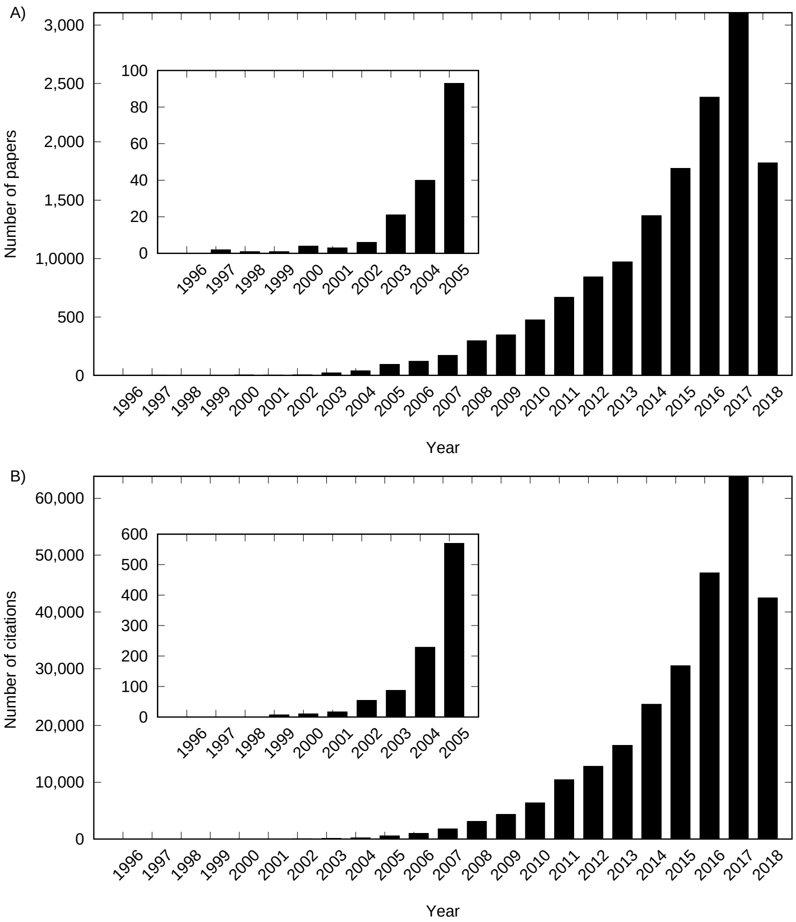

Figure 1. Number of (**A**) papers and (**B**) citation of papers with the word "nanofluid" or "nanofluids" in the title, abstract or keywords. Based on Web of Science as of 7 August 2018.

Moreover, the required pumping power in thermal systems depends on rheological properties; therefore, the rheological properties should also be evaluated to have a perfect design [24–30]. Researchers have also investigated the optical specifications [31–33], surface tension and wetting behavior [34] and electrical properties of nanofluids [35–39] due to their importance in the design of solar energy and electronic-based devices.

The other group of studies on nanofluids deals with the applications [40–43]. In recent years, scholars have focused on replacing fossil fuel-based systems by renewable energy based systems such as solar collectors and photovoltaic panels as a solution to air pollution and the global warming crisis, on the one hand, and the shortage of fossil fuel sources, on the other hand. Therefore, it would be worthy to increase the efficiency and performance of such systems. Adding nanoparticles to conventional working fluids might be used as a passive technique to ameliorate the performance of the target systems. Mahian et al. [44] evaluated the potential of nanofluids for efficiency enhancement of various solar energy systems, especially solar collectors. They concluded that nanofluids are mostly (not always) helpful to improve the performance of solar energy devices. Recently, many research studies have been done on the application of nanofluids in renewable energy systems; here, some of them are reviewed. Kim et al. [45] investigated experimentally the performance of a U-tube solar collector where the working fluid was alumina/water nanofluid. It was found that using nanofluid with a volume concentration of 1% provides a higher efficiency compared to the concentration of 1.5%. Moreover, they found that to achieve the maximum efficiency, alumina nanoparticles with the smallest size should be added to the base fluid (BF). The results indicated that efficiency decreases by 5.3% with the increase of nanoparticle size from 20 nm–100 nm. Loni et al. [46] theoretically studied the potential of oil-based nanofluids containing different nanoparticles, including Al_2O_3, Cu, SiO_2 and TiO_2 nanoparticles, on the performance of a dish concentrator having a cylindrical cavity receiver. They concluded that adding nanoparticles is advantageous from the second law of thermodynamics viewpoint, but it has a negative effect on the thermal efficiency of the system. Copper nanoparticles were introduced as the best option for adding to the base liquid. Hassani et al. [47] reported the usefulness of nanofluids in the performance enhancement of hybrid photovoltaic and thermal solar (PV/T) systems. Mahian et al. [48] showed that adding nanoparticles to the working fluid flowing in a heat exchanger coupled with a single slope solar still can enhance both the energy and exergy efficiencies of the solar still, although the amount of enhancement is negligible. Besides renewable energy systems, nanofluids have been employed efficiently to modify the performance of thermal systems. Various types of heat exchangers such as heat pipes, shell and tube, double pipe and plate are widely used in industries such as aerospace, food, automobile, air conditioning and electronic devices [49]. For instance, Hosseinian et al. [50] experimentally studied the effects of MWCNT-water nanofluid at three mass fractions (mas fr) including 0.04, 0.17 and 0.25% on the heat transfer rate from a double pipe heat exchanger that was under vibration. They found that vibration is effective in the decrease of sedimentation of nanoparticles on the tube surface. Moreover, the thermal analysis showed that using nanofluids with a mass fraction of 0.04% and applying the maximum value of vibration (9 ms^{-2}) can enhance the heat transfer coefficient by 100%. Xing et al. [51] investigated the performance of a vertical pulsating heat pipe using MWCNT-based nanofluids. They found that the thermal resistance of the water-based heat pipe was 34% higher than that of the nanofluid-based heat pipe (with a mass fraction of 0.1 wt%), so nanofluids can be suggested as a suitable option to enhance the heat pipe efficiency. Furthermore, Sarafraz et al. [52] experimentally investigated a plate heat exchanger using CuO/water nanofluid (concentrations of 0.1, 0.2, 0.3 and 0.4 wt%), where vibration was applied to reduce deposition of nanoparticles. They found that nanofluid at a mass fraction of 0.3% provided the maximum rate of heat transfer. Moreover, vibration intensifies the heat transfer. Shahrul et al. [53] evaluated the performance of a shell and tube heat exchanger using different water-based nanofluids. They reported that the values of highest heat transfer coefficient were enhanced by 50, 15 and 9% for ZnO, Al_2O_3 and SiO_2 nanoparticles, respectively, compared to the base fluid. These results reveal that the thermal conductivity of nanoparticles plays a crucial role in heat transfer enhancement of heat exchangers as ZnO nanoparticles have higher thermal conductivity than Al_2O_3 and SiO_2 nanoparticles.

In the above, a brief review of nanofluid applications in different energy systems was presented. The other possible application of nanofluids is in electrical equipment such as alternating current (AC) transformers, direct current (DC) transmission systems, converter transformers [54] or traction station/supply where DC is used. Insulation materials for all these systems are very similar or even the same, but with differences in their configuration [55]. Due to this, investigations in both AC and DC breakdown voltage (BDV) have been conducted by researchers. The DC BDV test also can be performed instead AC BDV, if we use DC voltage with a value equal to the AC voltage peak [56]. The advantage of using the DC to breakdown test is that the testing voltage is reached very fast and it is constant, opposite to the AC voltage, where the peak value is available only for a short period of time during one cycle. Additionally, DC is safer from the human health point of view [57].

Energy consumption is growing day by day because of population growth and the industrialization of human life. Accordingly, researchers are motivated to find novel solutions to minimize the energy usage. Indeed, electrical systems are one of the main targets for consumption optimization. Primom et al. [58] gave a literature overview related to the utilization of nanofluids in high voltage transformers. They considered such properties of nanofluids based on transformer oils such as breakdown voltage, streamer propagation, partial discharge, thermal properties and factors affecting it based on the chosen articles.

The primary goal of this review paper is to extend, order and systematize knowledge on the breakdown voltage in the context of the application of nanofluids in high voltage transformers.

This kind of application could improve the efficiency of existing high voltage infrastructure with low financial cost and without any significant changes in actual working systems.

2. Methods of Measurements

Breakdown voltage is one of the most important properties of insulating oils used in high voltage transformers. This parameter allows one to define the ability of transformer oil to be used as an insulating medium in electrical devices. The breakdown voltage test can also be used for the determination of impurities in transformer oils such as moisture, cellulose fibers, conducting particles or other contaminants. The presence of these impurities could decrease the breakdown voltage of transformer oils. On the other hand, the high values of BDV tests are not proof that the sample contains no impurities. It is possible that the concentration of contaminants is not enough to cause degradation of the insulating properties. Measurements of transformer oils breakdown voltage are mainly conducted according to two types of standards, The American Society for Testing and Materials (ASTM) and the International Electrotechnical Commission (IEC). ASTM introduced two standards for measuring BDV values: the first is ASTM D1816 [59], and the second is ASTM D877 [60]. For natural ester oils, the ASTM D6871 [61] standard was introduced, which refers to both previously mentioned standards. The main difference between them is in the shape of the electrodes used in the experiments. IEC presented one standard, which is IEC 6015 [62]. All standards, in detail, show test methods for measuring the breakdown voltage of insulating oils. The main differences in test procedures between each standard are presented in Table 1.

Table 1. Comparison of BDV measuring standards [59,60,62].

	Standards		
	ASTM D1816	**ASTM D 877**	**IEC 60156**
Electrodes' shape	sphere-capped plate	plate	spherical or spherically-capped
Electrodes' material	brass	brass	brass or steel
Gap (mm)	2 or 1	2.54	2.5
Test temperature	room temperature		
Rate of voltage rise	0.5 kV/s	3 kV/s	2 kV/s
Number of sequence	5	5	1–5 different samples
Time between BDV (s)	60–90	60	120
Time between filling and start of testing (min)	3–5	2–3	2

Another important examination for insulating transformer oils is lightning impulse breakdown voltage (LI BDV), which tests the ability of transformer oil to withstand impulse electric stress. In contrast to the BDV test, LI BDV is less dependent on contaminants that can be found in transformer oils. Measurements procedures for LI BDV are also described in detail by two standard organizations, ASTM and IEC, which introduced the following norms: ASTM D3300 [63] and IEC 60897 [64]. The main assumptions and comparison of both standards are summarized in Table 2.

The notation of concentration in the paper is the same as in the source papers, where authors, due to a lack of uniformity in concentration notation, use various units to describe concentrations of samples.

Table 2. Comparison of LI BDV measuring standards [63,64].

	Standards	
	ASTM D3300	**IEC 60897**
Electrodes' shape	point to sphere or sphere to sphere	point to sphere
Electrodes' material	steel or brass sphere and steel point	steel
Gap (mm)	25.4 or 3.8	10–25
Test temperature	room temperature	15–30 °C
Number of sequence	5	5
Time between filling and start of testing (min)	2	5

3. Breakdown Voltage of Nanofluids

Researchers and engineers are interested in improvement of the insulating properties of the breakdown voltage of transformer oils. Many attempts have been made to increase breakdown voltage in transformer oils by the addition of various types of nanoparticles with and without surfactants. Furthermore, natural oils have been tested as a more environmentally-friendly alternative to mineral oils. The most often used nanoparticles are oxides of metals, carbon and nitrides, as presented in the following sections.

3.1. Iron Oxide Nanoparticles

One of the most widely-used group of materials is iron oxide nanoparticles, which are added in various concentrations to increase the BDV of different insulating oils. Du et al. [65] conducted studies on the AC breakdown voltage properties of transformer oil containing Fe_3O_4 nanoparticles with concentrations in the range of 0.05 g/L–0.30 g/L and the addition of 0.15 ppm of hexadecyl trimethyl ammonium bromide (CTAB) (0.15 g) as a surfactant. The average size of nanoparticles was 10 nm. They observed initial improvement in AC BDV up to a 100-ppm load of nanoparticles, and it was about 10% (55 kV). Above this concentration, the value of AC BDV is decreasing, even below 50 kV, which is the AC BDV value of pure transformer oil. The nanofluids based on vegetable oils (VO) and iron oxide nanoparticles were investigated by Li et al. [66]. The stability of the nano-suspension was checked by the natural sedimentation method. The obtained results show that the mean breakdown voltage of vegetable oil with dispersed nanoparticles was 20% higher than pure oil.

Peppas et al. [67] studied nanofluids based on natural ester oil and Fe_3O_4 nanoparticles with an average diameter less than 50 nm with the surface modified by oleic acid (OA). Measurements were conducted according to the IEC standard, with a 2 kV/s rising rate in voltage. They compared the AC breakdown voltage of three samples, pure natural ester oil, natural ester oil with Fe_3O_4 nanoparticles and mineral oil. The results showed improvement in the values of BDV for natural ester oil with nanoparticles by 7%. With the addition of nanoparticles, the BDV of natural ester oil increased almost to the mineral oil level. Mohamad et al. [68] studied Fe_3O_4 nanoparticles with a size range 15–20 nm suspended in palm oil and modified by oleic acid as a surfactant. The sample of nanofluid with a concentration of 0.01 g/L was measured according to the ASTM D6871 standard. The moisture content was lower than 18.0 ppm and 24.9 ppm, respectively for pure oil and nanofluid. The two spherical electrodes of 36 mm in diameter and have a distance of 1 mm were used. As other researchers, Mohamad et al. also concluded that modification of pure oil by Fe_3O_4 nanoparticles can improve the insulating properties of oil. The combination of palm oil and 0.01 g/L of iron oxide nanoparticles improved AC BDV 42%. All results obtained by Mohammad et al. are presented in Figure 2. This also presents a graphical representation of the results obtained by other researchers discussed in the following parts of this review and expressing concentrations as g/L. Rafiq et al. [69] prepared five samples with the following w/v concentrations of Fe_3O_4 nanoparticles in oil: 0.05, 0.10, 0.20, 0.40, 0.60 and 0.80 g/L. The content of moisture for each sample was approximately 15 ppm. To achieve better stability of nanofluids, they used oleic acid as a surfactant. AC breakdown voltage for all samples was measured according to the IEC 60156 standard. Two spherical brass electrodes with a gap of 2 mm and a 2 kV/s voltage rise were employed. The results showed an increase in AC BDV with increasing of the concentration up to 40% *w*/*v*, but above this value, it clearly decreases in BDV, as presented in Figure 3. The highest value of BDV was 1.15 times greater than that of pure oil. Rafiq et al. [70] also investigated magnetic Fe_3O_4 nanoparticles dispersed in mineral oil with an unspecified concentration. They conducted measurements of BDV values according to the IEC standard and found that nanofluids exhibit 1.14 times higher values of BDV compared to pure mineral oil.

Zou et al. [71] investigated natural ester-based nanofluid with Fe_3O_4 nanoparticles and oleic acid as the surfactant. Measurements were performed according to the IEC 156 standard. The average value was calculated, and it was found that Fe_3O_4 natural ester nanofluids increase AC BDV by 20% compared to pure base fluid. Kudelicik et al. [72] investigated the DC breakdown voltage of Fe_3O_4 suspended in transformer oil (ITO100). They studied the dependence of breakdown voltage for nanofluids with three different volume concentrations (0.2, 1 and 2 vol%) and various distances between electrodes. They used two spherical electrodes (2.7 cm in radius) made with cooper, and the distance between them was set with an accuracy of 0.01 mm. The measurements were carried out for distances from 0.1–0.6 mm. The experimental uncertainty was determined as ±10%. For low volume concentrations (0.2 and 1%) of nanoparticles in transformer oil, they observed an increase in DC BDV; on the other hand, for 2 vol%, a decrease in DC BDV was observed, which was lower than pure transformer oil. Furthermore, the breakdown voltage was increasing with the increasing of distance between electrodes. The details of these investigations are presented in Table 3, which also contains a summary of the results obtained by other researchers, who investigated DC BDV of transformer oils. Segal et al. [73] prepared samples of mineral oil with magnetite nanoparticles (Fe_3O_4) and with four different levels of moisture content. Each sample aged for 34 weeks at 185 °C. AC BDV measurements were performed according to ASTM D877, and they observed a decrease in AC BDV for both pure oil and nanofluid with increasing moisture content. Additionally, Segal et al. observed also that inclusion of magnetite nanoparticles into oil caused an increase in AC BDV values.

Peppas et al. [74] studied the breakdown voltage of nanofluids containing commercially available Fe_2O_3 nanoparticles (<50 nm in diameter) modified by oleic acid and synthesized oleate-coated Fe_2O_3 nanoparticles (iron-oleated and oleic acid) and both dispersed in natural ester oil. They prepared six samples for each type of nanofluid with different concentrations from 0.004–0.014% *w*/*w* with a 0.002% *w*/*w* step. The stability of those nanofluids was also investigated, and it turned out that samples containing commercially available nanoparticles had much lower stability (one week to one month) than that synthesized samples (at least 16 months). The maximum value in BDV was very similar in both cases, and it was approximately 78 kV at 0.008% *w*/*w* and 0.012% *w*/*w* for commercially available nanoparticles and synthesized ones, respectively.

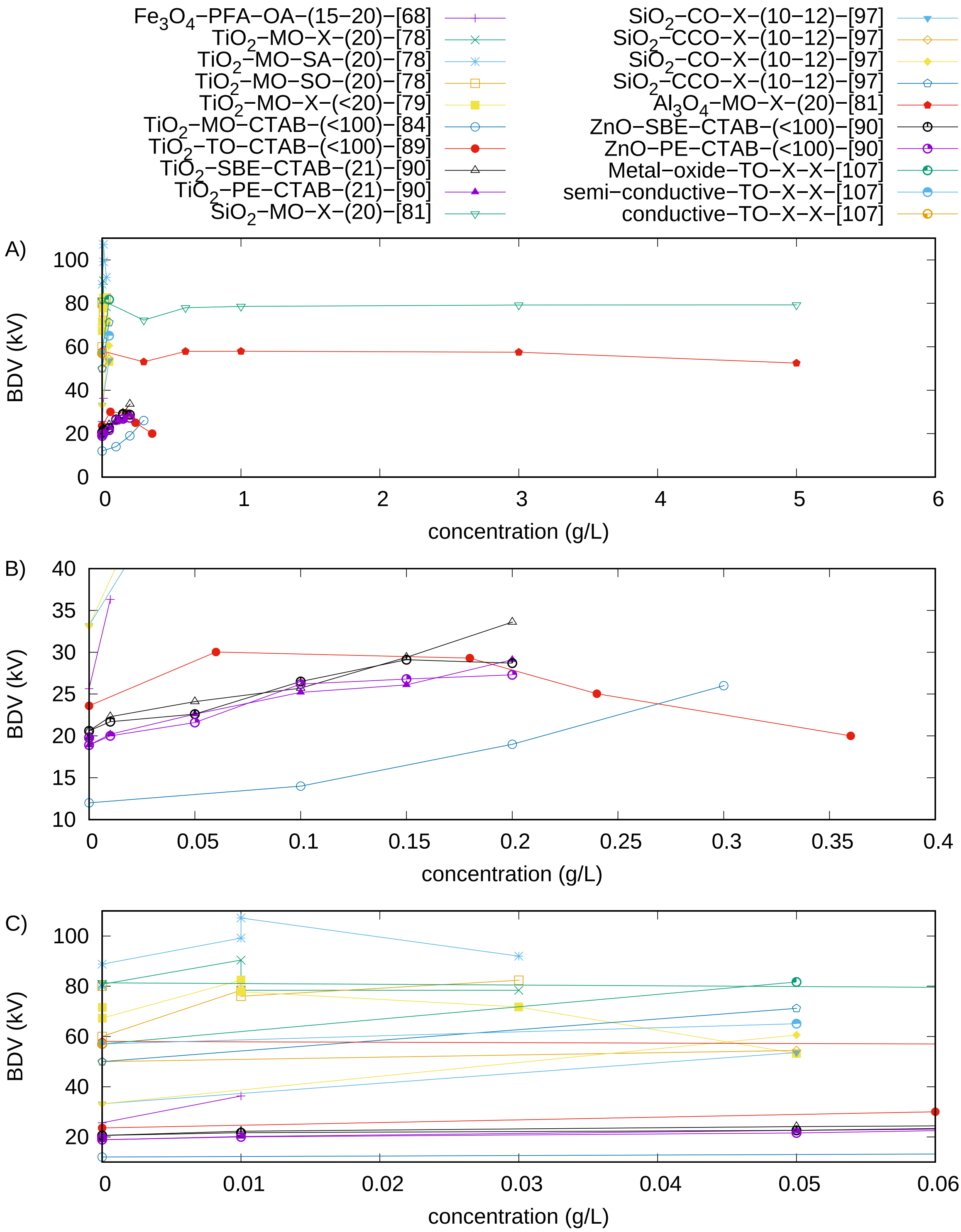

Figure 2. Graphical representation of the values of AC BDV for various types of oil-based nanoparticle nanofluids in concentrations expressed as g/L. (**A**) Full range of concentration, (**B**) magnification in concentration range 0–0.4 g/L and (**C**) magnification in concentration range 0–0.06 g/L. Structure of legend: nanoparticle-base fluid-surfactant-(nanoparticle size)-ref. X, no data available.

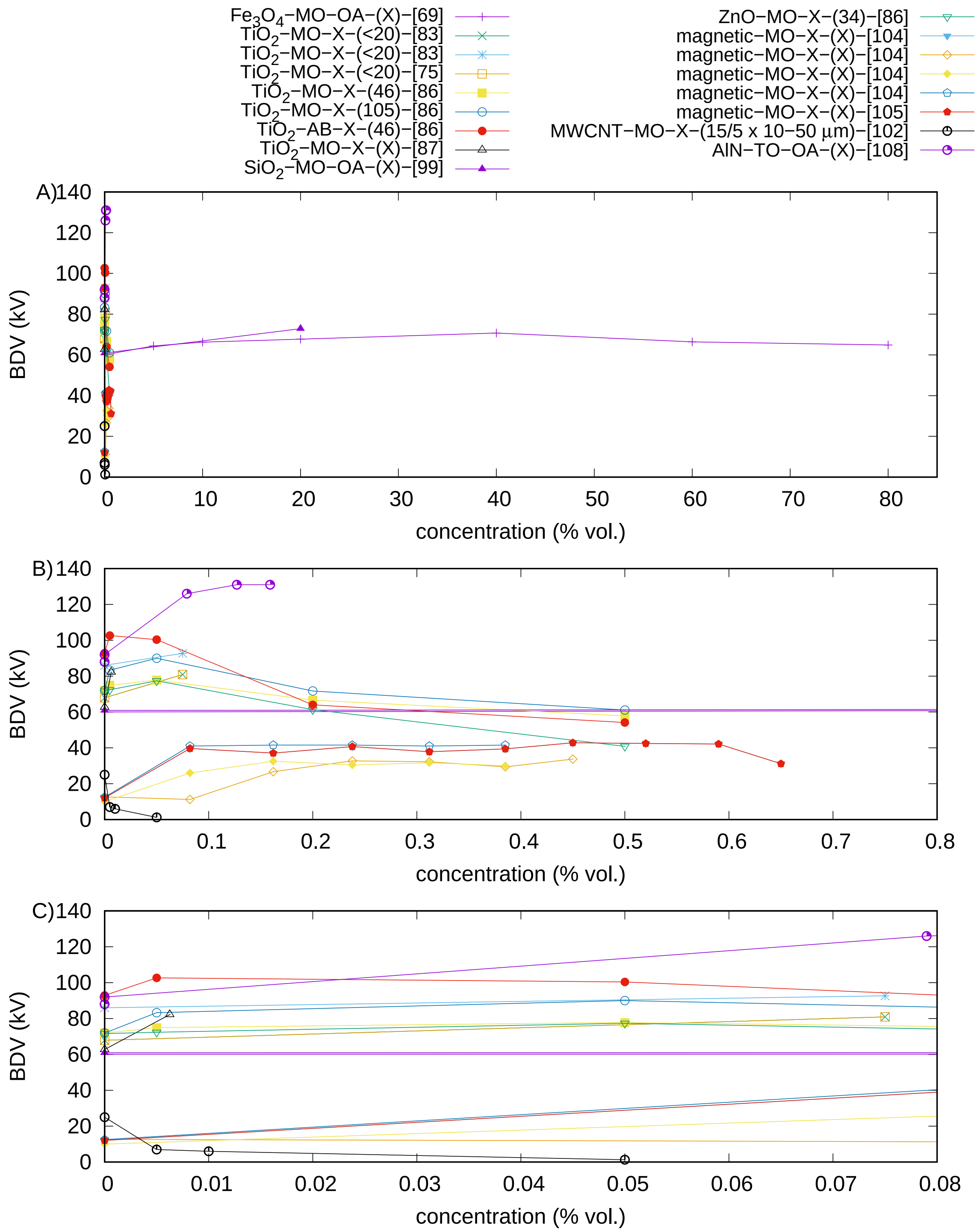

Figure 3. Graphical representation of values of AC BDV for various types of oil-based nanoparticle nanofluids in concentrations expressed by % of volume. (**A**) Full range of concentration, (**B**) magnification in concentration range 0–0.8 vol% and (**C**) magnification in concentration range 0–0.08 vol%. Structure of legend: nanoparticle-base fluid-surfactant-(nanoparticle size)-ref. X, no data available.

Table 3. Summary of DC breakdown voltage for various nanofluids.

NP	BF	Surfactant	Size (nm)	Concentration	BDV + (kV)	BDV + enh	BDV − (kV)	BDV − enh	Standard	Ref.
Fe_3O_4	MO	oleic acid	10.6	vol%	gap 0.2 mm				–	[72] *
				0.0	3.40	1.00	–	–		
				0.2	52.68	1.05	–	–		
				1.0	54.41	1.08	–	–		
				2.0	52.38	1.04	–	–		
					gap 0.3 mm					
				0.0	3.40	1.00	–	–		
				0.2	52.68	1.05	–	–		
				1.0	54.41	1.08	–	–		
				2.0	52.38	1.04	–	–		
					gap 0.4 mm					
				0.0	3.40	1.00	–	–		
				0.2	52.68	1.05	–	–		
				1.0	54.41	1.08	–	–		
				2.0	52.38	1.04	–	–		
					gap 0.5 mm					
				0.0	3.40	1.00	–	–		
				0.2	52.68	1.05	–	–		
				1.0	54.41	1.08	–	–		
				2.0	52.38	1.04	–	–		
					gap 0.6 mm					
				0.0	3.40	1.00	–	–		
				0.2	52.68	1.05	–	–		
				1.0	54.41	1.08	–	–		
				2.0	52.38	1.04	–	–		
TiO_2	MO	–	<20	vol%					ASTM D3300	[75]
				0.0	49.1	1.00	66.3	1.00		
				0.075	45.1	0.92	84.6	1.28		
TiO_2	MO	–	<20	0.0	–	1.00	–	–	–	[76]
				X	–	1.27	–	–		

* Data read from graph. X, no data available.

3.2. Titanium Oxide Nanoparticles

Another commonly studied material is titanium oxide (TiO_2) nanoparticles. Du et al. [77] investigated transformer mineral oil-based nanofluids with TiO_2 rutile nanoparticles, silicon oil (SO)-treated TiO_2 and octadecanoic acid (ODA)-treated TiO_2. The average size of the used nanoparticles was less than 20 nm. The concentration of nanoparticles was in the range 0.003–0.05 g/mL, and moisture content did not exceed 17.5 ppm. AC breakdown voltage was measured according to the IEC 60156 standard. They found that optimum concentrations for improvement of AC BDV depended on surface treatment of nanoparticles. Among studied samples, the highest improvement was observed for octadecanoic acid-treated TiO_2 suspensions with a concentration of 0.01 g/mL, and it was 52.9%. For nanofluid containing TiO_2 nanoparticles treated by silicon oil, the optimum concentration was also 0.01 g/mL, but the value of BDV was greater, only 29.6%, than for pure oil. The lowest improvement was reached for untreated TiO_2 nanoparticles, and it was 27.5% for a concentration of 0.006 g/mL. Lv et al. [78] used spherical TiO_2 nanoparticles with various concentration to modify the breakdown voltage properties of transformer oil. Three types of nanofluids with four concentrations (0.003, 0.006, 0.010, 0.030 g/L) were prepared. The first contained pure transformer oil with spherical TiO_2 nanoparticles. The second and third samples contained modified TiO_2 nanoparticles by stearic acid (SA) and silicon oil, respectively. BDV was measured in accordance with the IEC 60156 standard at room temperature. Based on the obtained results, the authors concluded that the best improvement in AC BDV was provided by the addition of stearic acid modified TiO_2 nanoparticles with a concentration of 0.010 g/L; above this content of nanoparticles, AC BDV decreased, but still remained higher than pure oil (up to 0.03 g/L). While silicon oil-modified TiO_2 transformer oil-based nanofluid initially showed decreases in AC BDV by 25%, only for a concentration of 0.03 g/L did AC BDV increase by 3%. Furthermore, samples with unmodified TiO_2 particles are not favorable to enhance the BDV of transformer oil; in turn, in low concentrations, below 0.006 g/L, a little improvement is visible, and above this concentration of nanoparticles, the BDV of this type of nanofluid decreases. Yue et al. [79] conducted studies of BDV of transformer oil-based nanofluids containing TiO_2 nanoparticles with a concentration ranging from 0.003 g/L–0.05 g/L. Moisture content in all samples was less than 10 ppm. Measurements were performed at room temperature and agreed with the IEC 60156 standard. Two brass spherical electrodes with a 2.5 mm distance between them were employed. Results presented by Yue et al. clearly indicated that using a low concentration of TiO_2 nanoparticles increases AC BDV, but above a 0.006 g/L concentration of nanoparticles, the BDV value decreases and even reaches a value lower than that of pure oil. Du et al. [80] measured the AC BDV of TiO_2 transformer oil-based nanofluids. The dimension of the used nanoparticles was less than 20 nm in diameter, and surface of the nanoparticles was also modified by surfactant. Measurements proceeded under the ASTM D1816 standard. Results showed that the BDV of transformer oil containing TiO_2 nanoparticles increased up to 19.1%. Lv et al. [81] prepared TiO_2 transformer oil nanofluids and studied their insulating properties. Nanoparticles with a 20 nm diameter without any surface modification were used to prepare nanofluids with concentrations in the range of 0–5.0 g/L. Measurements of BDV were conducted according to the IEC 60156 standard at room temperature. Results showed the dependence of BDV on TiO_2 nanoparticle concentrations. The maximum enhancement was achieved for 0.6%, and it was 13%. In excess of this concentration, the value of BDV decreased even lower than that of pure oil. Mutian et al. [82] used semiconductive TiO_2 nanoparticles to modify the breakdown properties of aged mineral oil. Nanoparticles with a size less than 20 nm in diameter and modified by surfactant were used. Measurements were performed according to ASTM standards (ASTM D1816) at room temperature, using two brass spherical electrodes with a 2 mm-gap and a 2 kV/s voltage rise. Results showed a 7.8% enhancement in AC BDV in the presence of TiO_2 nanoparticles. Yue-fan et al. [83] studied AC BDV of mineral oil modified by adding TiO_2 nanoparticles with a diameter less than 20 nm and a 0.075 vol% concentration. The content of moisture in all samples was between 9–10 ppm. They also measured the BDV of nanofluids after aging it at 130 °C for six days. All samples were dried after the aging process to control water content. Measurements were performed according to the IEC 60156 standard with brass spherically-capped electrodes and a 2 mm distance between them, as well as a 2 kV/s rise in voltage. Yue-fan et al. observed a 19% increase in AC BDV for mineral oil containing a 0.075% volume concentration of nanoparticles. They also noticed that the AC BDV for aged samples was higher compared to fresh samples, but it was caused by the lower content of water after drying. Samples after drying stand out due to the lower increase in AC BDV, which was only 8%. Mineral oil with the addition of 0.075% TiO_2 nanoparticles by volume concentration was investigated by Du et al. [75]. Measurements were conducted in line with the ASTM D1816 standard at room temperature. Results showed a 24% increase in AC BDV for mineral oil with the addition of nanoparticles. The DC BDV was also measured, and an increase was in negative DC BDV, being 27.6%, wherein for positive DC BDV, a decrease was observed, being 8%. Mansour et al. [84] examined the influence of TiO_2 nanoparticles with a diameter less than 100 nm and cetyltrimethylammonium bromide (CTAB) as the dispersant on the BDV properties of commercially available mineral oil. They prepared six samples with various contents of CTAB (0.1, 0.2, 0.3, 0.6, 1.0, 1.5 vol% fraction) to assess the minimum diameter of agglomeration and a good degree of dispersion. The 0.3 vol% fraction of CTAB as the dispersant had been chosen using an optical microscope. The three samples with concentrations of 0.1, 0.2, 0.3 g/L and a 0.3 vol% fraction of CTAB were prepared and investigated according to the ASTM D1816 standard at room temperature with a 2.7 mm gap and a voltage rise of 500 V/s. Results indicate an increase in BDV with increasing concentration of nanoparticles in the base fluid, and this increase was 217%. Bakrutheen et al. [85] studied the dielectric breakdown voltage of mineral oil containing two different volume fractions (vol fr) of TiO_2 nanoparticles (0.01% and 0.075%). All measurements were conducted in line with the IEC 60156 standard at room temperature with a 2 kV/s rise in voltage. Measurements conducted immediately after preparation showed a significant decrease in values of BDV for both concentrations. This fact was attributed to moisture absorption from the surrounding during samples preparation. To decrease the moisture content, samples were heated up to 100 °C. After heating the samples up to 100 °C and cooling them to ambient temperature, BDV measurements were repeated, and a 9% and 20% increase in BDV values for a 0.1% and 0.075 vol% fraction was observed, respectively. Hanai et al. [86] studied the insulating properties of mineral oil with two different types of TiO_2 nanoparticles (anatase and rutile) with various volume concentrations, as well as alkyl benzene (AB) with TiO_2-anatase nanoparticles. Samples were prepared with a concentration range from 0–0.5 vol% using a two-step method, and the water content was less than 15 ppm. They used two stainless steel spherical electrodes with a 2.0 mm gap. Measurements were conducted at room temperature with a 3 kV/s voltage rise. The maximum enhancement in BDV was achieved for TiO_2-rutile nanoparticles with a volume concentration of 0.05%. In turn, for alkyl benzene containing TiO_2-rutile nanoparticles, the maximum enhancement was achieved for a 0.005 vol% concentration, and it was only 10%. Similar improvement was observed in the case of mineral oil with TiO_2-anatase nanoparticles. Additionally, Hanai et al. found that for all cases, the maximum enhancement was observed for a surface area of nanoparticles around 10^2 cm^2/mL. Zhong et al. [87] studied the influence of TiO_2 nanoparticle inclusion with 0.00625 vol% concentration into natural ester oil FR3 (Cargill Inc., Wayzata, MN, USA). Measurements were conducted according to the ASTM D1816 standard at room temperature with a 2 kV/s rate of voltage rise. They observed an increase in BDV from 62.71 kV for pure natural ester oil to 82.23 kV for natural ester oil containing TiO_2 nanoparticles. Hu et al. [88] studied the time effect on the BDV properties of pure mineral oil and with the addition of TiO_2 nanoparticles. They placed samples at a temperature of 130 °C for 36 days. During this process, every six days, BDV was measured. Each sample before measurements was degassed at less than 1 kPa for two days, which allowed reaching a moisture content below 5 ppm. Measurements were conducted in line with the IEC 60156 standard, and the results indicated that BDV decreased with ageing. After 36 days of experiment, the breakdown voltage decreased 58% and 50% for pure oil and TiO_2-modified oil, respectively. Additionally, it was observed that BDV for TiO_2 nanofluid was always higher than that of pure mineral oil and at the end of the test was 40% higher than the pure oil sample. Rafiq et al. [76] also worked with TiO_2 nanoparticles suspended in insulating mineral oil. They performed measurements of BDV according to the standard of IEC 60156, using two brass spherically-capped electrodes and a 2 kV/s voltage rising rate for fresh samples and after the aging process (after heating at 130 °C for six days). Their results showed a 19% increase in AC BDV for the fresh sample and a 7% increase for the sample after ageing. Furthermore, DC BDV was measured, and it was found that the addition of TiO_2 nanoparticles to mineral oil caused a 27% increase in the value of DC BDV. Atiya et al. [89] studied the BDV of transformer oil with dispersed TiO_2 nanoparticles with various concentrations modified by CTAB. First, six samples with various contents of surfactant were prepared and examined by an optical microscope, TEM analysis and zeta potential, to choose the best amount of surfactant. Next, four samples with different concentrations of TiO_2 nanoparticles were prepared by dispersing TiO_2 nanoparticles in a base fluid. Measurements were conducted in line with the ASTM D1816 standard for a ramp voltage up to 500 V/s and 1.5 mm gap sizes. The obtained results showed that the maximum enhancement was achieved for the lowest concentrations of nanoparticles (0.06 g/L) in the base fluid, and it was 27%. Saenkhumwong et al. [90] studied the BDV properties of two types of nanofluids based on soybean ester (SBE) and palm ester (PE) in comparison with mineral oil. They prepared five samples with various concentrations (from 0–0.2 g/L) of TiO_2 nanoparticles and CTAB as the surfactant for each type of base fluid. Measurements were conducted according to the ASTM D1816 standard and revealed that both soybean and palm ester with dispersed TiO_2 nanoparticles showed an increase in the values of BDV with increasing concentration of nanoparticles in natural oils. The maximum enhancement was achieved for concentrations of 0.2 g/L for both types of natural oil, and it was 70% and 47% for soybean ester and palm ester, respectively. Pugazhendhi et al. [91] conducted studies on the AC BDV properties of mixtures of mineral oil and TiO_2 nanoparticles with three different concentrations. They found an increase in BDV for two of three prepared samples; one of them was below BDV values of pure transformer oil. The maximum enhancement was noted for a 0.005 wt% concentration, and it was 31%. The impact of TiO_2 nanoparticles on insulating properties was also investigated by Mansour et al. [92]. They prepared two types of nanofluids containing TiO_2 nanoparticles, both in the concentration range between 0.01 and 0.1 g/L. The first group of samples was prepared without any surfactant and the second with CTAB as the surfactant. Results showed improvement in BDV in both cases, but nanofluids containing surfactants exhibited greater improvement. In the tested concentration range, the maximum increase was observed for 0.07 g/L and 0.1 g/L, and it was 117% and 126%, respectively, for samples without surfactant and with CTAB.

3.3. Silicone Oxide Nanoparticles

Another type of nanoparticle used to modify BDV properties is silicon oxide. Lv et al. [81] studied AC BDV for mineral oil containing SiO_2 nanoparticles with various concentrations and without any surfactant. Their study showed that the addition of SiO_2 nanoparticles to mineral oil led to a decrease in BDV in the whole range of tested concentrations (0–5 g/L). SiO_2 transformer oil-based nanofluids with volume fractions of 0.01% and 0.075% were also investigated by Bakrutheen et al. [85]. They found that values of BDV for both nanofluids, measured immediately after preparation, were lower than that of pure oil, and they attributed this to moisture absorption from the air during sample preparation. To remove moisture from the samples, each of them was heated up to 100 °C and then cooled to ambient temperature. Repeated measurements revealed a 35% and a 39% increase in BDV for a 0.01% and a 0.075 vol% fraction, respectively. Jin et al. [93,94] studied the breakdown voltage properties of mineral oil with dispersed SiO_2 nanoparticles with two different mass fractions and two ranges of humidity. Samples with humidity between 20 and 30 ppm (average 24 ppm) and 10 and 20 ppm (average 15 ppm) were measured according to the IEC 60156 standard. Results indicated that the moisture level in samples had a significant impact on the values of BDV. Additionally, it was found that an increase in the concentration of nanoparticles increased BDV by 19% and 27% for 0.01% and 0.02% mass fractions, respectively, in the case of samples with higher humidity. For samples with a lower content of humidity, the BDV enhancement was also observed, but the nanoparticles' effect was less, being 12% and 17% for 0.01% and 0.02% mass fractions, respectively. Jin et al. [95] also studied the BDV properties of SiO_2 mineral oil-based nanofluids with particles modified by surfactant and two moisture levels. They prepared samples with two types of SiO_2 nanoparticles. The first was unmodified particles with a 15 nm average size, and the second was particles modified by Z6011 with an average size of 25 nm, both with a 0.01% mass fraction. Results indicated that surface modification of SiO_2 nanoparticles reduced the BDV values for both moisture levels. For the sample with a 25 ppm moisture content, it was 37%, but for the sample with a 15 ppm moisture content, it was just 1%. Samples with unmodified nanoparticles showed a 12% and 20% increase in BDV for the samples with lower and higher humidity, respectively. Rafiq et al. [96] studied the BDV properties of two oil-based nanofluids with SiO_2 nanoparticles synthesized at different temperatures, 80 °C and 100 °C, for nanoparticles called A and B, respectively. Both samples were prepared with 20% concentrations of nanoparticles, and measurements were conducted according to the IEC 60156 standard. They found that BDV was increased by the addition of SiO_2 nanoparticles with a 20% concentration for both types of nanoparticles, and it was 5.7% and 11.6% for the A and B nanoparticles, respectively. Karthik and Raymon [97] looked for a biodegradable alternative for insulating mineral oil and tested two types of natural oil with a 0.05 g/L concentration of SiO_2 nanoparticles. The BDV of corn oil (CO)- and coconut oil (CCO)-based nanofluids were examined according to the IEC 60156 standard. Measurements were conducted at 30 °C and 60 °C, and the results showed a 61.4% and an 8.8% increase in BDV for corn oil- and coconut oil-based nanofluids at 30 °C, respectively. The BDV for these samples at 60 °C was also increased, and it was 82.5% and 42.4% for corn oil- and coconut oil-based nanofluids, respectively. Prasad and Chandrasekar [98] conducted a study on the influence of additions of SiO_2 nanoparticles with various mass concentrations on the BDV properties of natural ester oil FR3. They performed measurements according to IEC 60156 with three different gaps between electrodes (1 mm, 2.5 mm, 4 mm). Similarly, Kudelcik et al. [72] observed increasing values of DC BDV with increasing distance between electrodes, and Prasad and Chandrasekar observed BDV enhancement for increasing gap between electrodes for all samples. They also found an increase in BDV with increasing mass concentration of SiO_2 nanoparticles in the base fluid, and the maximum enhancement was observed for the highest tested concentration (0.1 wt%), being 33.1%, 49.7% and 41.7% for 1 mm, 2.5 mm and 4 mm gaps, respectively. Rafiq and Lv [99] studied the impact of a 20 vol% concentration addition of SiO_2 nanoparticles on the BDV properties of mineral oil. Measurements conducted according to the IEC standard showed a 19.7% enhancement in AC BDV in comparison with the pure oil sample. Dong et al. [100] investigated the insulating properties of mineral oil with surface-modified SiO_2 nanoparticles with various volume fractions. They conducted measurements in line with the IEC 60156 standard and found a nonlinear increase in BDV with the increasing content of nanoparticles in the base fluid up to a 0.06 vol% fraction. Above this concentration, a decrease was observed, but it was still higher than the BDV for pure oil sample. The maximum enhancement observed for a 0.06 vol% fraction was 33%. Jianzhuo et al. [101] prepared five samples with various volume fractions of SiO_2 nanoparticles dispersed in transformer oil using oleic acid as the surfactant. The measurements were conducted at room temperature (25 °C), and the moisture content was 10 ppm. Their results indicated that the increase in nanoparticles content in transformer oil up to a 0.1 vol% fraction caused an increase in BDV, but above this concentration, a BDV decrease was observed, which was still higher than that in the case of pure base fluid. The most favorable value of BDV in this case was 1.4 higher than that of pure transformer oil.

3.4. Aluminum Oxide Nanoparticles

Al_2O_3 dispersed in mineral oil with five different concentrations and their BDV properties were studied by Lv et al. [81]. They used Al_2O_3 nanoparticles with a 20 nm diameter without any surfactant. They performed measurements of BDV according to IEC 60156. Results showed that in the case of SiO_2, transformer oil nanofluids decreased in their BDV values in the whole tested range of concentrations. The maximum decrease in BDV was observed for concentrations of 0.3 g/L and 5.0 g/L, and it was 20%. Aluminum oxide nanoparticles suspended in transformer oil were also studied by Mansour et al. [92]. They studied the difference between nanofluids containing Al_2O_3 nanoparticles suspended in base fluids without any surfactant and with surfactant (sodium dodecyl benzene sulfonate (SDBS)). Four samples for both types of nanofluids were prepared using Al_2O_3 nanoparticles with a 50 nm diameter with concentrations between 0.01 and 0.1 g/L. Their results clearly indicated that using surfactant improved the insulating properties of transformer nanofluids. In contrast to samples without surfactant, where adding nanoparticles negatively affected BDV in the whole range of tested concentrations, all samples with surfactant exhibited higher values of BDV than that of the pure base fluid. The maximum increase was noted for a concentration of 0.04 g/L, and it was higher by 28% than that pure transformer oil.

3.5. Zinc Oxide Nanoparticles

Bakrutheen et al. [85] investigated the AC BDV properties of mineral oil with dispersed ZnO nanoparticles with 0.01% and a 0.075 vol% fraction and two moisture content levels. Samples were measured immediately after preparation and indicated deterioration in the BDV values, which was attributed to the absorption of water from the surroundings during sample preparation. After removing the excess of moisture by heating samples up to 100 °C and repeating measurements of BDV, 32% and 41% increases were observed for 0.01% and 0.075 vol% concentrations, respectively. Hanai et al. [86] also conducted a study on the BDV properties of mineral oil with ZnO nanoparticles. They used nanoparticles of 34 nm in diameter dispersed in four various volume concentrations in the range from 0.005–0.05%. The results obtained by Hanai et al. revealed that the addition of ZnO nanoparticles in some concentrations could improve the insulating properties of mineral oil. For concentrations up to 0.05%, BDV values increased, but above this level of inclusion of nanoparticles, the insulating properties of ZnO mineral oil-based nanofluid decreased below the level of pure oil, achieving even a 43% decrease in BDV for a 0.5 vol% concentration. Saenkhumwong et al. [90] examined the possibilities of using natural ester oils (soybean and palm ester) instead of mineral oils in electrical systems. To improve the insulating properties, they proposed to use ZnO nanoparticles with a diameter less than 100 nm and CTAB as the surfactant. They prepared five samples with concentrations ranging from 0.01–0.20 g/L for both types of natural oils. Measurements conducted in line with the ASTM D1816 standard revealed that both types of nanofluids were characterized by increasing values of BDV with increasing concentration of nanoparticles. The maximum improvement was achieved for 0.15 g/L (soybean ester) and 0.20 g/L (palm ester), and it was 47% and 38%, respectively.

3.6. Carbon-Based Nanoparticles

Jin et al. [93] prepared nano-suspensions of mineral oil and fullerene nanoparticles with two different mass fractions in order to investigate their AC BDV properties in comparison with pure mineral oil. The size was specified by the dynamic light scattering (DLS) technique, and it was approximately 70 nm. Samples with 0.05% and 0.1% mass fractions and a humidity level of 24 ppm were studied according to the IEC 60156 standard. The study showed the favorable effect of nanoparticles addition on the BDV properties for both concentrations. The highest improvement was noticed for 0.1%, and it was 34%, while the enhancement for 0.05% was 20%. Fontes et al. [102] prepared nanofluids with multi-wall carbon nanotubes (MWCNT) and nanodiamonds dispersed in mineral oil. They used MWCNT with the following dimensions: 15, 5 nm and 10–50 µm for the outer diameter, inner diameter and length, respectively, to prepare samples with three volume concentrations: 0.005, 0.01 and 0.05%. The same concentrations were prepared using spherical diamond nanoparticles with a 6 nm diameter. The BDV of all samples were measured according to the ASTM D1816 standard. The results obtained by Fontes et al. clearly showed a huge decrease in values of the BDV properties for both types of nanofluids. The maximum degradation of BDV was observed for the MWCNT transformer oil nanofluid with the highest volume concentration (0.05%), and it was 95%, while for the nanodiamond transformer oil nanofluid, it was 76%.

3.7. Other Nanoparticles

Jian et al. [103] examined the AC BDV for mineral oil modified by three different concentrations of semiconductive nanoparticles. Nanoparticles with diameters less than 20 nm were used to prepare samples with low, medium and high concentrations. Moisture content in samples did not exceed 100 ppm. The properties of all samples were measured according to the IEC 60156 standard, and the results show that the best improvement in BDV values was obtained for a medium concentration of semiconductive nanoparticles, being 16%. Lee et al. [104,105] studied the BDV properties of magnetic mineral oil-based nanofluids with various concentrations, different gap sizes and under the influence of a magnetic field [104]. They prepared samples with a volume concentration in the range of 0.08–0.39%, and the BDV was measured according to the IEC 60156 standard. EFH-1 ferrofluid was used as a modifier of the insulating properties of the mineral oil. They found that an increase in the gap distance between electrodes decreased BDV, which was opposite the results presented by Prasad et al. [98]. Furthermore, the effect of the external magnetic field (250 mT) was observed. A summary of Lee et al.'s measurements is presented in Table 4. Lee et al. [106] also studied a mixture of EFH-1 ferrofluid and transformer oil with volume concentrations starting form 0.08–0.65% using the measuring stand presented in Figure 4. They conducted measurements according to the IEC 60156 standard with a 1.5 mm gap and a 1.0 kV/s voltage rise. Results showed approximately 3.3 times higher values of BDV in comparison to pure transformer oil for volume concentrations up to 0.6%.

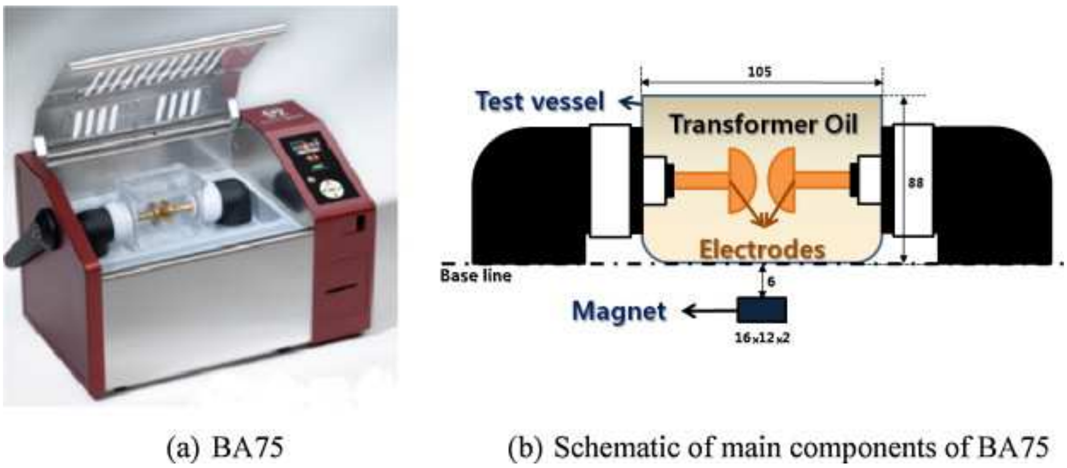

Figure 4. Device for BDV measurements. Reproduced with permission from [106].

For higher concentrations, a visible decrease in the value of BDV is noticed. ZrO_2 nanoparticles with a diameter less than 50 nm, dispersed with various mass concentrations in the transformer oil and their AC BDV values were studied by Pugazhendhi et al. [91]. Their results showed the maximum increase for a 0.01 wt% concentration of ZrO_2 nanoparticles, and it was 23%. Above a 0.01 wt% concentration was observed a decrease in the BDV value from 75.24 kV to 66.13 kV. Lv et al. [107] performed studies of the BDV properties of insulating, semiconducting and conducting nanoparticles dispersed in transformer oil with a 0.05-g/L concentration. They found improvement for all samples, and the highest was for insulating nanoparticles (43%). The enhancement for other samples was 14% and 23% for semiconducting and conducting nanoparticles, respectively. Liu et al. [108] conducted measurements of the AC BDV of AlN nanoparticles with a 40 nm diameter, dispersed in mineral oil with various concentrations. They found that AlN mineral oil nanofluids were stable at least six months. The maximum enhancement was observed for 0.127 vol% and 0.159 vol%, and it was 149%.

The results of all values of AC BDV measurements discussed in this review are summarized in Table 4 and plotted in Figure 5.

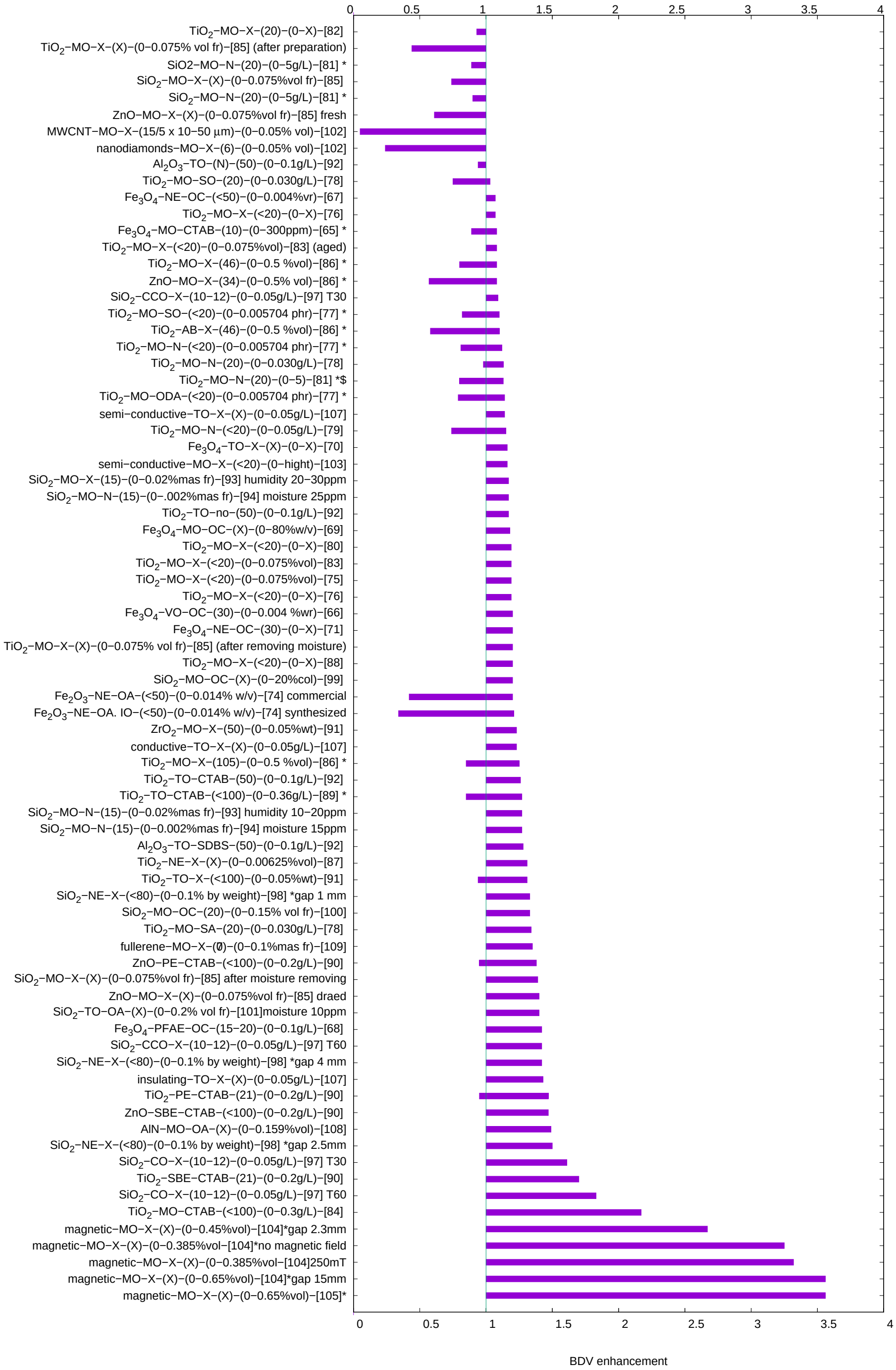

Figure 5. Range of enhancement in AC BDV values of nanoparticle oil-based nanofluids. Structure of legend: nanoparticle-base fluid-surfactant-(nanoparticle size)-(concentration range)-ref. X, no data available; N, no surfactant; Y, with surfactant, but unspecified; *, data read from graph.

Table 4. Summary of the AC breakdown voltage for various nanofluids.

NP	BF	Surfactant	Size (nm)	Concentrations	BDV	BDV enh	Comments	Standard	Ref.
Fe_3O_4	MO	CTAB (0.15 g)	10	0 ppm 50 ppm 100 ppm 150 ppm 200 ppm 250 ppm 300 ppm	50.24 52.68 54.41 52.38 53.11 49.09 44.88	1.00 1.05 1.08 1.04 1.06 0.98 0.89		IEC 60156	[65] *
Fe_3O_4	VO	OA	30	0.000% wr 0.004% wr	49.90 59.80	1.00 1.20		IEC 156	[66]
Fe_3O_4	NE	OA	<50	0.000% vr 0.004% vr MO	65.40 69.70 70.30	1.00 1.07 1.07		IEC 156	[67]
Fe_3O_4	PFA	OA	15–20	0.00 g/L 0.01 g/L	25.64 36.31	1.00 1.42		ASTM D6871	[68]
Fe_3O_4	MO	OA	-	0.00 g/L 0.05 g/L 0.10 g/L 0.15 g/L 0.20 g/L 0.40 g/L 0.60 g/L 0.80 g/L	60.05 64.37 66.26 67.71 70.75 66.42 64.87 60.05	1.00 1.07 1.09 1.13 1.18 1.11 1.08 1.00		IEC 60156	[69]
Fe_3O_4	TO	-	-	0.00 X	61.04 70.60	1.00 1.16		IEC 60156	[70]
Fe_3O_4	NE	OA (0.75 g)	30	0.00 X	49.90 59.80	1.00 1.20		IEC 60156	[71]

Table 4. *Cont.*

NP	BF	Surfactant	Size (nm)	Concentrations	BDV	BDV enh	Comments	Standard	Ref.
				0.00% *w*/*v*	64.50	1.00			
				0.004% *w*/*v*	70.00	1.09			
				0.006% *w*/*v*	73.00	1.13			
Fe_2O_3	NE	OA	<50	0.008% *w*/*v*	77.70	1.20	commercial		[74]
				0.010% *w*/*v*	59.00	0.91			
				0.012% *w*/*v*	51.00	0.79			
				0.014% *w*/*v*	27.00	0.42			
				0.00% *w*/*v*	64.50	1.00			
				0.004% *w*/*v*	54.00	0.84			
				0.006% *w*/*v*	55.00	0.85			
Fe_2O_3	NE	OA	<50	0.008% *w*/*v*	60.00	0.93	synthesized		[74]
				0.010% *w*/*v*	66.00	1.02			
				0.012% *w*/*v*	77.80	1.21			
				0.014% *w*/*v*	22.00	0.34			
				0.000000 phr	70.60	1.00	moisture 9.18–10.21 ppm; phr—parts per hundred resin		
				0.000393 phr	69.55	0.99			
		-		0.000701 phr	79.30	1.12			
				0.001095 phr	68.31	0.97			
				0.003401 phr	66.95	0.95			
				0.005704 phr	57.14	0.81			
				0.000000 phr	66.60	0.94			
				0.000393 phr	58.23	0.82			
				0.000701 phr	63.27	0.90	moisture 9.49–11.62 ppm		
TiO_2-r	MO	SO	<20	0.001095 phr	77.70	1.09		IEC 60156	[77] *
				0.003401 phr	74.99	1.06			
				0005704 phr	64.36	0.91			
				0.000000 phr	60.30	0.85			
				0.000393 phr	67.60	0.96			
				0.000701 phr	72.44	1.03	moisture 12.40–14.05 ppm		
		ODA		0.001095 phr	80.50	1.14			
				0.003401 phr	70.39	1.00			
				0.005704 phr	56.05	0.79			

Table 4. *Cont.*

NP	BF	Surfactant	Size (nm)	Concentrations	BDV	BDV enh	Comments	Standard	Ref.
TiO_2-r	MO	-	20	0.000 g/L	80.00	1.00		IEC 60156	[78]
				0.003 g/L	80.80	1.01			
				0.006 g/L	90.40	1.13			
				0.010 g/L	78.40	0.98			
				0.030 g/L	78.40	0.98			
		SA		0.000 g/L	80.00	1.00			
				0.003 g/L	88.80	1.11			
				0.006 g/L	99.20	1.24			
				0.010 g/L	107.20	1.34			
				0.030 g/L	92.00	1.15			
		SO		0.000 g/L	80.00	1.00			
				0.003 g/L	60.00	0.75			
				0.006 g/L	78.40	0.98			
				0.010 g/L	76.00	0.95			
				0.030 g/L	82.40	1.03			
TiO_2-r	MO	-	<20	0.000 g/L	71.59	1.00		-	[79]
				0.003 g/L	67.33	0.94			
				0.006 g/L	82.48	1.15			
				0.010 g/L	77.82	1.09			
				0.030 g/L	71.76	1.00			
				0.050 g/L	53.25	0.74			
TiO_2	TO	-	<20	0	67.90	1.00		ASTM D1816	[80]
				X	80.90	1.19			
TiO_2-r	MO	-	20	0.0	66.11	1.00	No data about type of concentration	IEC 60156	[81] *
				0.3	66.87	1.01			
				0.6	74.40	1.13			
				1.0	65.12	0.99			
				3.0	65.12	0.99			
				5.0	53.10	0.80			

Table 4. *Cont.*

NP	BF	Surfactant	Size (nm)	Concentrations	BDV	BDV enh	Comments	Standard	Ref.
TiO_2	MO	-	20	0 X	86.00 92.70	1.00 0.93			[82]
TiO_2	MO	-	<20	0.000 vol% 0.075 vol%	67.90 80.90	1.00 1.19	fresh	IEC 60156	[83]
				0.000 vol% 0.075 vol%	86.02 92.68	1.00 1.08	aged		
TiO_2	MO	-	<20	0.000 vol% 0.075 vol%	67.9 80.9	1.00 1.19		ASTM D1816	[75]
TiO_2	MO	CTAB	<100	0.0 g/L 0.1 g/L 0.2 g/L 0.3 g/L	12 14 19 26	1.00 1.17 1.58 2.17		ASTM D1816	[84]
TiO_2	MO	-	-	0.000 vol% fr 0.010 vol% fr 0.075 vol% fr	32 14 22	1.00 0.44 0.69	after preparation	IEC 60156	[85]
				0.010 vol% fr 0.075 vol% fr	35 38.4	1.09 1.20	after removing moisture		
TiO_2-a	MO	-	46	0.00 vol% 0.005 vol% 0.050 vol% 0.200 vol% 0.500 vol%	71.91 74.89 77.80 66.66 57.84	1.00 1.04 1.08 0.93 0.80			[86] *
TiO_2-r	MO	-	105	0.000 vol% 0.005 vol% 0.05 vol% 0.2 vol% 0.5 vol%	71.91 83.29 90.01 71.71 61.07	1.00 1.16 1.25 1.00 0.85			[86] *

Table 4. *Cont.*

NP	BF	Surfactant	Size (nm)	Concentrations	BDV	BDV enh	Comments	Standard	Ref.
TiO_2-a	AB	-	46	0.000 vol%	92.88	1.00			[86] *
				0.005 vol%	102.62	1.10			
				0.05 vol%	100.38	1.08			
				0.2 vol%	63.95	0.69			
				0.5 vol%	54.09	0.58			
TiO_2	NE	-	-	0.000 vol%	62.71	1.00		ASTM D1816	[87]
				0.00625 vol%	82.23	1.31			
TiO_2	MO	-	<20	Time (day)				IEC 60156	[88] *
				0	67.47	1.00	pure oil		
				6	60.39	0.90	pure oil		
				12	59.10	0.88	pure oil		
				18	55.93	0.83	pure oil		
				24	40.19	0.60	pure oil		
				30	39.20	0.58	pure oil		
				36	28.54	0.42	pure oil		
				0	80.68	1.00	nanofluid		
				6	71.08	0.88	nanofluid		
				12	66.52	0.82	nanofluid		
				18	64.64	0.80	nanofluid		
				24	59.40	0.74	nanofluid		
				30	60.59	0.75	nanofluid		
				36	40.08	0.50	nanofluid		
TiO_2	MO	-	<20	0	-	1.00	fresh	IEC 60156	[76]
				X	-	1.19	fresh		
				0	-	1.00	after 6 days		
				X	-	1.07	after 6 days		
TiO_2	oil	CTAB	<100	0.00 g/L	23.60	1.00		ASTM D1816	[89] *
				0.06 g/L	30.03	1.27			
				0.18 g/L	29.30	1.24			
				0.24 g/L	25.04	1.04			
				0.36 g/L	20.00	0.85			

Table 4. *Cont.*

NP	BF	Surfactant	Size (nm)	Concentrations	BDV	BDV enh	Comments	Standard	Ref.
TiO_2	MO	CTAB (3 g/L)	<100	0.00 g/L	19.80	1.00		ASTM D1816	[90]
	SBE			0.00 g/L	20.60	1.04			
				0.01 g/L	22.30	1.13			
				0.05 g/L	24.10	1.22			
				0.1 g/L	25.70	1.30			
				0.15 g/L	29.40	1.48			
				0.2 g/L	33.60	1.70			
	PE			0.00 g/L	18.90	0.95			
				0.01 g/L	20.20	1.02			
				0.05 g/L	22.60	1.14			
				0.10 g/L	25.20	1.27			
				0.15 g/L	26.10	1.32			
				0.20 g/L	29.10	1.47			
TiO_2	TO	-	<100	0.000 wt%	61.20	1.00		IS 6792:1972	[91]
				0.005 wt%	80.36	1.31			
				0.010 wt%	75.15	1.23			
				0.050 wt%	57.60	0.94			
TiO_2	TO	-	50	0.00 g/L	69.00	1.00	moisture 25.7 ppm		[92]
				0.01 g/L	71.00	1.03			
				0.04 g/L	77.00	1.12			
				0.07 g/L	81.00	1.17			
				0.10 g/L	78.00	1.13			
		CTAB		0.00 g/L	69.00	1.00			
				0.01 g/L	82.00	1.19			
				0.04 g/L	78.00	1.13			
				0.07 g/L	80.00	1.16			
				0.10 g/L	87.00	1.26			
SiO_2	MO	-	20	0.0 g/L	81.40	1.00			[81]
				0.3 g/L	72.27	0.89			
				0.6 g/L	77.97	0.96			
				1.0 g/L	78.58	0.97			
				3.0 g/L	79.19	0.97			
				5.0 g/L	79.27	0.97			

Table 4. *Cont.*

NP	BF	Surfactant	Size (nm)	Concentrations	BDV	BDV enh	Comments	Standard	Ref.
SiO_2	MO	-	-	0.00 vol% fr 0.01 vol% fr 0.075 vol% fr	32.00 23.80 28.80	1.00 0.74 0.90	after preparation	IEC 60156	[85]
				0.01 vol% fr 0.075 vol% fr	43.20 44.60	1.35 1.39	after removing moisture		
SiO_2	MO	-	15	0.00% mas fr 0.01% masfr 0.02% mas fr	51.3 61.2 65.1	1.00 1.19 1.27	humidity 10–20 ppm	IEC 60156	[93]
				0.00% mas fr 0.01% mas fr 0.02% mas fr	76.00 85.4 89.2	1.00 1.12 1.17	humidity 20–30 ppm		
SiO_2	MO	-	15	0.00% mas fr 001% mas fr 002% mas fr	51 61 65	100 120 127	moisture 15 ppm	IEC 60156	[94]
				0.00% mas fr 0.01% mas fr 0.02% mas fr	76 85 89	1.00 1.12 1.17	moisture 25 ppm		
SiO_2	MO	- - Z6011	- 15 25	0.00% mass fr 0.01% mass fr 0.01% mass fr	76 85 75	1.00 1.12 0.99	humidity 15 ppm	IEC 60156	[95]
		 - Z6011	 15 25	0.00% mass fr 0.01% mass fr 0.01% mass fr	51 61 32	1.00 1.20 0.63	humidity 25 ppm		
SiO_2	MO	-	 A B	0 20 20	50.9 53.8 56.8	1.00 1.04 1.12		IEC 60156	[96]

Table 4. *Cont.*

NP	BF	Surfactant	Size (nm)	Concentrations	BDV	BDV enh	Comments	Standard	Ref.
SiO_2	CO	-	10–12	0.00 g/L	33.2	1.00	T = 30 °C	IEC 60156	[97]
				0.05 g/L	53.6	1.61			
	CCO			0.00 g/L	50	1.00			
				0.05 g/L	54.4	1.09			
	CO			0.00 g/L	332	1.00	T = 60 °C		
				0.05 g/L	60.6	1.83			
	CCO			0.00 g/L	50	100			
				0.05 g/L	712	142			
SiO_2	NE	-	<80	0.00 wt%	30.03	1.00	gap 1 mm	IEC 60156	[98] *
				0.01 wt%	34.92	1.16			
				0.05 wt%	37.96	1.26			
				0.10 wt%	39.97	1.33			
				0.00 wt%	39.95	1.00	gap 2.5 mm		
				0.01 wt%	44.67	1.12			
				0.05 wt%	52.80	1.32			
				0.10 wt%	59.81	1.50			
				0.00 wt%	61.93	1.00	gap 4 mm		
				0.01 wt%	67.74	1.09			
				0.05 wt%	79.68	1.29			
				0.10 wt%	87.74	1.42			
SiO_2	MO	OA	-	0 vol%	60.9	1.00		IEC 60156	[99]
				20 vol%	72.9	1.20			
SiO_2	MO	OA	20	0.00 vol% fr	48.14	1.00		IEC 60156	[100]
				0.01 vol% fr	58.24	1.21			
				0.02 vol% fr	60.84	1.26			
				0.04 vol% fr	62.08	1.29			
				0.06 vol% fr	63.90	1.33			
				0.15 vol% fr	60.59	1.26			

Table 4. *Cont.*

NP	BF	Surfactant	Size (nm)	Concentrations	BDV	BDV enh	Comments	Standard	Ref.
SiO_2	TO	OA	X	0.00 vol% fr		1.00	moisture 10 ppm		[101]
				0.01 vol% fr	58.50	1.28			
				0.02 vol% fr	61.00	1.35			
				0.05 vol% fr	62.00	1.38			
				0.10 vol% fr	64.50	1.40			
				0.20 vol% fr	59.00	1.32			
Al_2O_3	MO	-	20	0.0 g/L	58.05	1.00		IEC 60156	[81]
				0.3 g/L	53.03	0.91			
				0.6 g/L	57.87	1.00			
				1.0 g/L	57.97	1.00			
				3.0 g/L	57.52	0.99			
				5.0 g/L	52.50	0.90			
Al_2O_3	TO	-	50	0.00 g/L	69.00	1.00	moisture 25.7 ppm		[92]
				0.01 g/L	65.00	0.94			
				0.04 g/L	65.00	0.94			
				0.07 g/L	68.00	0.99			
				0.10 g/L	66.00	0.96			
		SDBS		0.00 g/L	69.00	1.00			
				0.01 g/L	80.00	1.16			
				0.04 g/L	88.00	1.28			
				0.07 g/L	85.00	1.23			
				0.10 g/L	74.00	1.07			
ZnO	MO	-	-	0.00 vol% fr	32.00	1.00	fresh	IEC 60156	[85]
				0.01 vol% fr	17.00	0.53			
				0.075 vol% fr	19.60	0.61			
				0.01 vol% fr	42.20	1.32	after removing moisture		
				0.075 vol% fr	45.00	1.41			
ZnO	MO	-	34	0.000 vol%	71.62	1.00			[86]
				0.005 vol%	72.38	1.1			
				0.05 vol%	77.36	1.08			
				0.20 vol%	61.34	0.86			
				0.50 vol%	40.88	0.57			

Table 4. *Cont.*

NP	BF	Surfactant	Size (nm)	Concentrations	BDV	BDV enh	Comments	Standard	Ref.
ZnO	MO	CTAB (3 g/L)	<100	0.00 g/L	19.80	1.00		ASTM D1816	[90]
	SBE			0.00 g/L	20.60	1.04			
				0.01 g/L	21.70	4.10			
				0.05 g/L	22.60	4.14			
				0.10 g/L	26.50	4.34			
				0.15 g/L	29.10	4.47			
				0.20 g/L	28.70	4.45			
	palm ester			0.00 g/L	18.90	0.95			
				0.01 g/L	20.00	1.10			
				0.05 g/L	21.60	1.09			
				0.10 g/L	26.20	1.32			
				0.15 g/L	26.80	1.35			
				0.20 g/L	27.30	1.38			
semiconducting	MO	-	<20	0	71.59	1.00		IEC 60156	[103]
				low	78.68	1.10			
				medium	83.20	1.16			
				high	75.87	1.06			
Fe_3O_4	MO	-	-	0	50.00	1.00	moisture <5 ppm	ASTM D877	[73]
				X	50.00	1.00			
				0	43.00	0.86	moisture 10–20 ppm		
				X	47.00	0.94			
				0	37.00	0.74	moisture 20–30 ppm		
				X	44.00	0.88			
				0	28.00	0.56	moisture >30 ppm		
				X	40.00	0.80			

Table 4. *Cont.*

NP	BF	Surfactant	Size (nm)	Concentrations	BDV	BDV enh	Comments	Standard	Ref.
magnetic NP (ferrofluid EFH-1)	MO	-	-	0.000 vol%	12.03	1.00	gap 1.5 mm	IEC 156	[104] *
				0.082 vol%	39.62	3.29			
				0.162 vol%	37.03	3.08			
				0.238 vol%	40.72	3.38			
				0.312 vol%	37.79	3.14			
				0.385 vol%	39.45	3.28			
				0.45 vol%	42.79	3.56			
				0.52 vol%	42.41	3.52			
				0.59 vol%	42.17	3.50			
				0.65 vol%	31.17	2.59			
				0.000 vol%	12.62	1.00	gap 2.3 mm		
				0.082 vol%	11.24	0.89			
				0.162 vol%	26.69	2.11			
				0.238 vol%	32.72	2.59			
				0.312 vol%	32.21	2.55			
				0.385 vol%	29.45	2.33			
				0.45 vol%	33.76	2.67			
				0.000 vol%	10.00	1.00	without magnetic field		
				0.082 vol%	26.00	2.60			
				0.162 vol%	32.50	3.25			
				0.238 vol%	30.50	3.05			
				0.312 vol%	31.70	3.17			
				0.385 vol%	30.00	3.00			
				0.000 vol%	12.50	1.00	with magnetic field		
				0.082 vol%	41.00	3.28			
				0.162 vol%	41.50	3.32			
				0.238 vol%	41.50	3.32			
				0.312 vol%	41.00	3.28			
				0.385 vol%	41.50	3.32			

Table 4. *Cont.*

NP	BF	Surfactant	Size (nm)	Concentrations	BDV	BDV enh	Comments	Standard	Ref.
magnetic NP (ferrofluid EFH-1)	MO	-	-	0.000 vol% 0.082 vol% 0.162 vol% 0.238 vol% 0.312 vol% 0.385 vol% 0.450 vol% 0.520 vol% 0.590 vol% 0.650 vol%	12.03 39.62 37.03 40.72 37.79 39.45 42.79 42.41 42.17 31.17	1.00 3.29 3.080 3.38 3.14 3.28 3.56 3.52 3.50 2.59		IEC 156	[105] *
ZrO_2	-	-	50	0.000 wt% 0.005 wt% 0.010 wt% 0.050 wt%	61.20 67.34 75.24 66.13	1.00 1.10 1.23 1.08		IS 6792:1972	[91]
fullerene spherical	MO	-	70	0.00% mas fr 0.05% mas fr 0.10% mas fr	51.00 61.00 69.00	1.00 1.20 1.35		IEC 60156	[109]
insulating NP (metal oxide)	TO	-	-	0.00 g/L 0.05 g/L	57.00 81.70	1.00 1.43		IEC 60156	[107]
semiconducting	TO	-	-	0.00 g/L 0.05 g/L	57.00 65.10	1.00 1.14		IEC 60156	[107]
conductive	TO	-	-	0.00 g/L 0.05 g/L	57.00 70.30	1.00 1.23		IEC 60156	[107]
conductive	MO	-	15/5X 10–50 μm	0.000 vol% 0.005 vol% 0.010 vol% 0.050 vol%	25.00 7.00 6.00 1.25	1.00 0.28 0.24 0.05		ASTM D1816	[102]
nanodiamond	MO	-	6	0.000 vol% 0.005 vol% 0.010 vol% 0.050 vol%	25.00 14.70 9.80 6.00	1.00 0.59 0.39 0.24		ASTM D1816	[102]

Table 4. *Cont.*

NP	BF	Surfactant	Size (nm)	Concentrations	BDV	BDV enh	Comments	Standard	Ref.
AlN	MO	-	6	0.00 vol% oleic acid oil 0.079 vol% 0.127 vol% 0.159 vol%	88.00 92.00 126.00 131.00 131.00	1.00 1.05 1.43 1.49 1.49		ASTM D1816	[108]

* Data read from graph. X, no data available.

4. Lightning Impulse Breakdown Voltage of Nanofluids

Not only the BDV magnitude of transformer oils is an important parameter, but also the lightning impulse breakdown voltage is a key factor for practical applications of nanoparticle insulating oil-based nanofluids in high voltage transformers, and that is why the LI BDV value of insulating oils is also of interest to researchers and engineers.

4.1. Nitrides and Other Nanoparticles

Iron oxide suspensions were studied by Liu et al. [110]. They investigated the lightning impulse breakdown voltage of magnetite (Fe_3O_4) and maghemite (Fe_2O_3) with the average size of nanoparticles in the range from 5–20 nm. To get better stability of nanofluids, they used an unspecified surfactant. They conducted examination according to the IEC 60897 standard using electrodes with the configuration of a needle/sphere and a lightning impulse of 1.2/50 µs. After adding nanoparticles to the mineral oil, they observed an increase in positive impulse breakdown voltage by 13.93% and a decrease in negative impulse breakdown voltage by 18.31%. Streamer velocity for both positive and negative impulse breakdown voltage values was lower than that in pure mineral oil (1.77 km/s), and it was 0.97 km/s and 1.01 km/s, respectively.

Li et al. [111] studied nanoparticles of Fe_3O_4 with a modified surface by oleic acid suspended in vegetable oil (rapeseed oil). The average size of used nanoparticles was 30 nm in diameter. Measurements of lightning impulse breakdown voltage were conducted according to the standard of IEC 60897. The electrode system was a steel needle/sphere with a 13 mm diameter of the sphere and distance between the electrodes of 15 mm. The content of moisture in the vegetable oil and nanofluid was 288 mg/kg and 283 mg/kg, respectively. They observed a 37.4% and a 11.8% increase for the nanofluid containing Fe_3O_4 nanoparticles, respectively for positive and negative LI BDV. Li et al. also noticed that the time to lightning impulse breakdown voltage of nanofluids was greater than for pure oil, and it was 21.2% and 14.4%, respectively. Li et al. [66] also studied a suspension of Fe_3O_4 nanoparticles in vegetable oil. Measurements were conducted according to the IEC standard for positive and negative impulse breakdown voltage. The average from five measurements showed that positive LI BDV was 37% higher than the pure oil sample. On the other hand, negative LI BDV was only 12% higher than the pure oil sample. Furthermore, the average streamer velocity for both positive and negative LI BDV was increased by 21% and 14%, respectively. Ghasemi et al. [112] investigated the ability to improve lightning BDV in transformer oil of Fe_3O_4 nanoparticles with three different volume concentrations (0.20, 0.40, 0.60%). The surface of nanoparticles was modified using oleic acid, which allowed achieving the stability of nanofluids without a precipitation longer than four months. They used two spherical electrodes with a 2.5 mm distance between them and a 1.2/50 µs impulse. The measurement setup is presented in Figures 6 and 7.

The findings indicate that the addition of iron oxide nanoparticles to the transformer oil was favorable in some ranges of the volume concentration of nanoparticles. The optimum improvement in LI BDV was achieved for 0.3 vol%, and it was 16% more than pure oil. Yang et al. [113] measured the impulse breakdown in oil samples containing dispersed 10 nm nanoparticles of Fe_3O_4 with a concentration of 0.03 g/L. For this purpose, they used the improved traditional Kerr electrooptic field mapping technique [114]. The picture of the measurement setup is presented in Figure 8.

They used two parallel plate electrodes made of aluminum with a 3 mm distance between them and a photodetector array. A voltage waveform of 150/500 µs was used in this study. They found that the mean breakdown voltage for transformer oil with nanoparticles was higher by 11.2% than that of pure oil. On the other hand, the time to breakdown voltage was decreased by the addition of nanoparticles by 38.5%. The positive and negative impulse breakdown voltages for the the suspension of iron oxide in mineral oil were measured also by Rafiq et al. [69,115]. The scheme of the measuring cell for this type of test is presented in Figure 9.

Figure 6. View of the measuring cell during the BDV test. Reproduced with permission from [112].

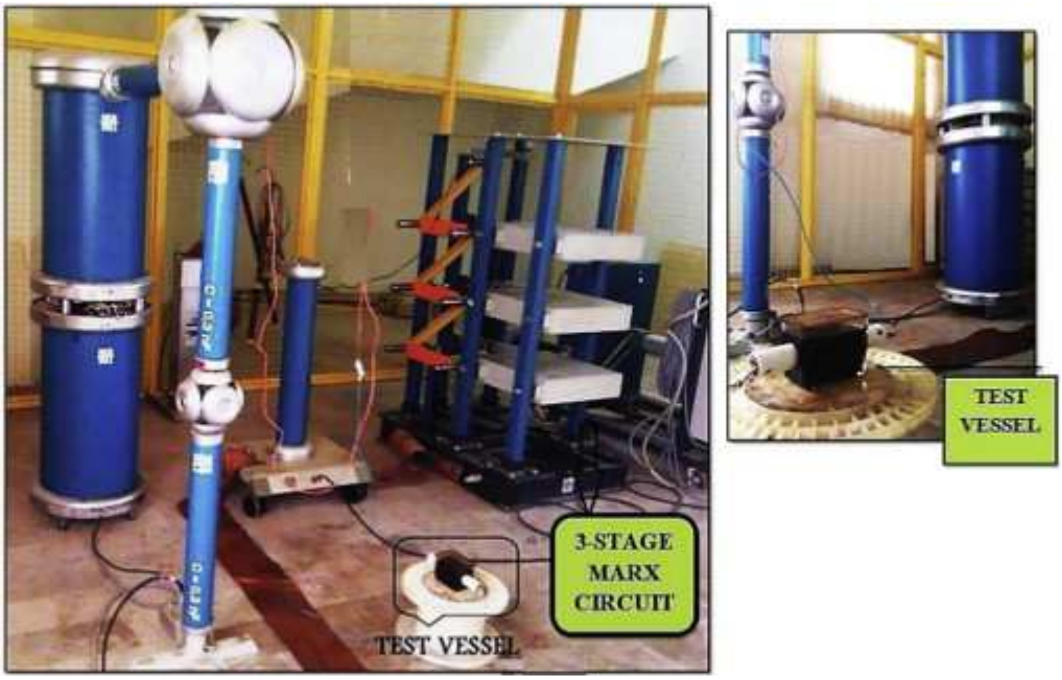

Figure 7. Impulse wave generator and measuring stand. Reproduced with permission from [112].

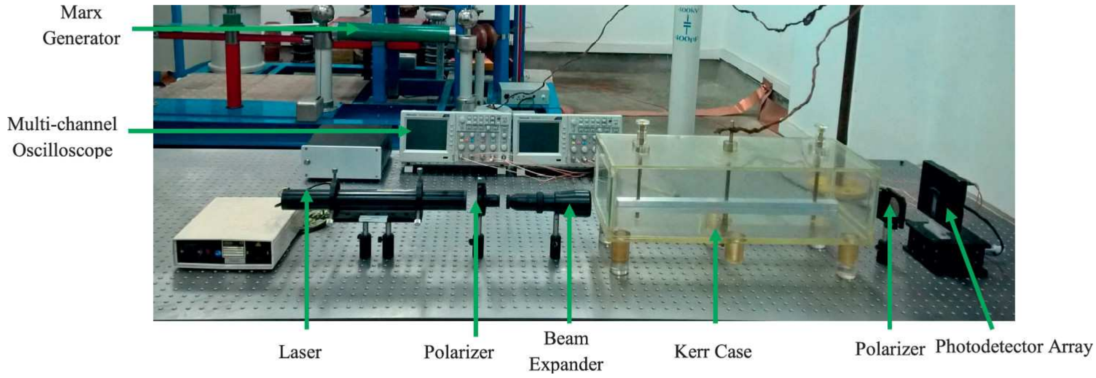

Figure 8. Photo of the measuring stand for Kerr electrooptic mapping measurements. Reproduced under the conditions of the Creative Commons Attribution license from [113].

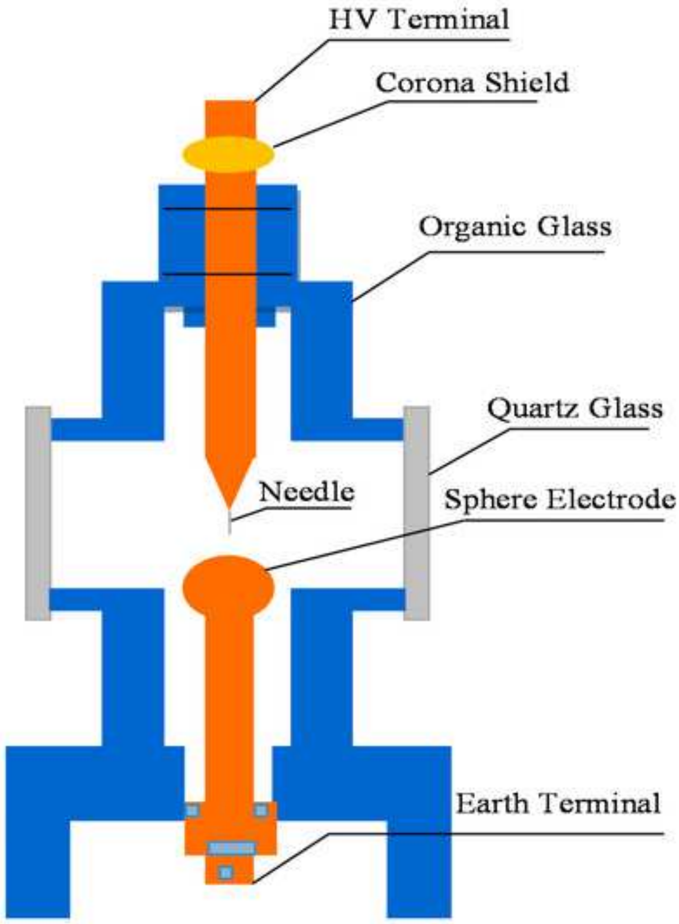

Figure 9. The scheme of the measuring cell for the LI BDV test. Reproduced under the conditions of the Creative Commons Attribution license from [115].

Similar to AC BDV, the maximum enhancement of positive LI BDV was achieved for a 0.4 g/L concentration of nanoparticles, and it was greater than 1.36 times in comparison to pure mineral oil; whereas, negative LI BDV constantly decreased with increasing concentration and dropped by 36% as compared to pure oil. In another paper, Rafiq et al. [70] examined the insulating properties of a suspension of magnetic Fe_3O_4 nanoparticles and mineral oil with one unknown concentration. Results showed that the addition of Fe_3O_4 nanoparticles increased in PLI BDV by 1.36 times. On the other hand, the values of NLI BDV decreased by the addition of magnetic nanoparticles by 0.85 times. Ramu et al. [116] studied transformer oil with Fe_3O_4 nanoparticles and tested their influence on both positive and negative lightning impulse (NLI) BDV. For this purpose, they employed a pair of needle/sphere electrodes according to the IEC standard and found an 81.4% increase in LI BDV for positive and a 9.4% decrease for negative LI BDV. Pure natural ester oil and their LI BDV properties were also studied by Li et al. [117]. The effect of Fe_3O_4 nanoparticles was also investigated. They found that inclusions of Fe_3O_4 could improve the LI BIDV properties of natural ester oil. Positive and negative lightning breakdown voltages were increased by 37% and 12%, respectively.

4.2. Titanium Oxide Nanoparticles

Lv et al. [78] studied the lightning impulse breakdown voltage of transformer oil containing stearic acid-modified TiO_2 nanoparticles with various concentrations. All measurements were conducted in accordance with the IEC 60897 standard with a 1.2/50 µs impulse. They observed improvements in LI BDV in a concentration ranging from 0.003–0.03 g/L, and the maximum enhancement was achieved for the highest examined concentration, being 17%. Yue et al. [79] measured LI BDV in TiO_2 transformer oil-based nanofluids. Five samples with concentrations in the range of 0.003–0.05 g/L were studied according to the IEC 60897 standard using a 1.2/50 µs voltage impulse and a 25 mm distance between electrodes. Results indicated that the addition of TiO_2 nanoparticles to transformer oil enhanced LI BDV. The maximum enhancement was achieved for 0.03 g/L, and it was 16.7% higher than that of pure oil. LI BDV for transformer oil with TiO_2 nanoparticles was also studied by Du et al. [80]. They conducted measurements based on the ASTM D3300 standard. Their results showed a 24% increase in LI BDV for this type of fluids in comparison to pure transformer oil, and the time to BDV increased 53.3% as well. Lv et al. [81] studied the LI BDV of TiO_2 transformer oil nanofluid with various concentrations and concluded that LI BDV increased in the concentration range from 0.3–0.6%, the maximum enhancement being 13%. Measurements were conducted in line with the IEC 60897 standard at room temperature. Mutian et al. [82] reported increases in the positive lightning (PLI) breakdown voltage for mineral oils enriched with TiO_2 nanoparticles. They observed 47% enhancement in PLI BDV for this type of nanofluid, and also, the time to breakdown was increased from 14.27 µs–25.11 µs. Du et al. [75] studied LI BDV for mineral oil with TiO_2 nanoparticles with a 0.075% by volume concentration. They observed that the presence of TiO_2 nanoparticles in the mineral oil increased LI BDV by 24%, and the time to breakdown also increased from 15.2 µs–23.3 µs. Hu et al. [88] studied the LI BDV of mineral oil with TiO_2 nanoparticles after heating at 130 °C for 36 days. They performed measurements of LI BDV every six days. For the first 18 days, they observed approximately 1.3 times higher values of LI BDV for nanofluid in comparison to pure oil. After, this time difference between pure oil and nanofluids was negligible. In both cases, LI BDV was decreasing with increasing aging time. Rafiq et al. [76] studied the LI BDV of mineral oil with dispersed TiO_2 nanoparticles for fresh samples and after six days in 130 °C. They found that LI BDV increased by 23% and 47% for fresh and aged samples, respectively. Pugazhendhi et al. [91] studied the LI BDV of TiO_2 nanoparticles suspended in transformer oil with three mass concentrations (0.005, 0.01, 0.05%). Their investigations revealed that the maximum improvement for this type of nanofluid was 19% for a 0.005 wt% concentration.

4.3. Silicon Oxide Nanoparticles

Liu et al. [110] prepared mineral oil-based nanofluid containing a 0.04 vol% concentration of SiO_2 nanoparticles modified by surfactant and compared its LI BDV to pure mineral oil according to the IEC 60897 standard. They found a 9% decrease in PLI BDV in comparison to the pure oil sample; on the other hand, the value of NLI BDV was almost unchanged. Furthermore, an impact on streamer velocity was observed for both positive and negative LI BDV, and it was a 4.5% increase and a 22% decrease for PLI BDV and NLI BDV, respectively. LI BDV of SiO_2 nanoparticles dispersed in mineral oil were also studied by Ramu et al. [116]. They measured LI BDV using a self-made measuring stand, prepared in line with the suggestions of the ASTM and IEC standards. The values of the positive and negative LI BDV showed a different behavior under the presence of SiO_2 nanoparticles. PLI BDV was increased by 81%, while NLI BDV was decreased by 4%. Similar situations were observed for the time to breakdown voltage, where its observed 41.7% increase and 4% decrease for positive and negative LI BDV, respectively, was reported. Streamer velocity was increased for both positive and negative LI BDV. The impact of SiO_2 nanoparticles with a 20 vol% concentration on insulating mineral oil was studied by Rafiq and Lv [99]. They found that PLI BDV increased 1.11 times, but, on the other hand, NLI BDV reduced 0.93 times. Similar behavior was observed in the time to BDV.

4.4. Aluminum Oxide Nanoparticles

Liu et al. [110] studied Al_2O_3 nanoparticles with a diameter ranging from 5–20 nm modified by surfactant and dispersed in transformer oil with a 0.1425 vol% concentration. They measured positive and negative LI BDV according to the IEC 60897 standard and found a decrease in both, 12% and 13% for positive and negative LI BDV, respectively.

4.5. Others Nanoparticles

Jian et al. [103] studied the LI BDV of mineral oil with semiconductive nanoparticles with three different concentrations. They conducted measurements using the ASTM D3300 standard and found that LI BDV increased with increasing concentration of nanoparticles. The maximum enhancement was observed for the highest semiconductive nanoparticles concentration. Segal et al. [73] measured the LI BDV of two mineral oils with magnetite nanoparticles according to the ASTM D3300 standard for a 25.4 mm and a 55 mm gap. They found that LI BDV increased with increasing the gap. Effect of nanoparticles concentration in base fluids was also observed. Positive lightning impulse breakdown voltage for both mineral oils was enhanced at least 80%. On the other hand, negative lightning impulse breakdown was decreased by at least 2%. Dispersion of ZrO_2 in transformer oil and their LI BDV was investigated by Pugazhendhi et al. [91]. They performed measurements and revealed that addition of ZrO_2 nanoparticles with a 0.005 wt% concentration to transformer oil caused the maximum increase in LI BDV, and it was 16%; also, other samples showed improvement in LI BDV. Lv et al. [107] studied the LI BDV properties of mineral oil with the inclusion of three types of nanoparticles (insulating, semi-conducting, conducting) with a 0.05 g/L concentration and found an increase in LI BDV for each of them, being 7%, 8% and 1% for insulating, semi-conducting and conducting nanoparticles, respectively. Liu et al. [110] used ZnO nanoparticles with a modified surface by surfactant to change the insulating properties of mineral oil. They prepared nanofluid using ZnO nanoparticles with a diameter in the range 5–20 nm with a 0.0475 vol% concentration. LI BDV was measured according to the IEC 60897 standard, and the obtained results exhibited a decrease in both positive and negative values of LI BDV. The addition of a 0.0475 vol% concentration to mineral oil caused a 3.4% and a 34.5% decrease in the positive and negative LI BDV, respectively.

The results of all AC LI BDV measurements discussed in this review are summarized in Table 5 and plotted in Figure 10.

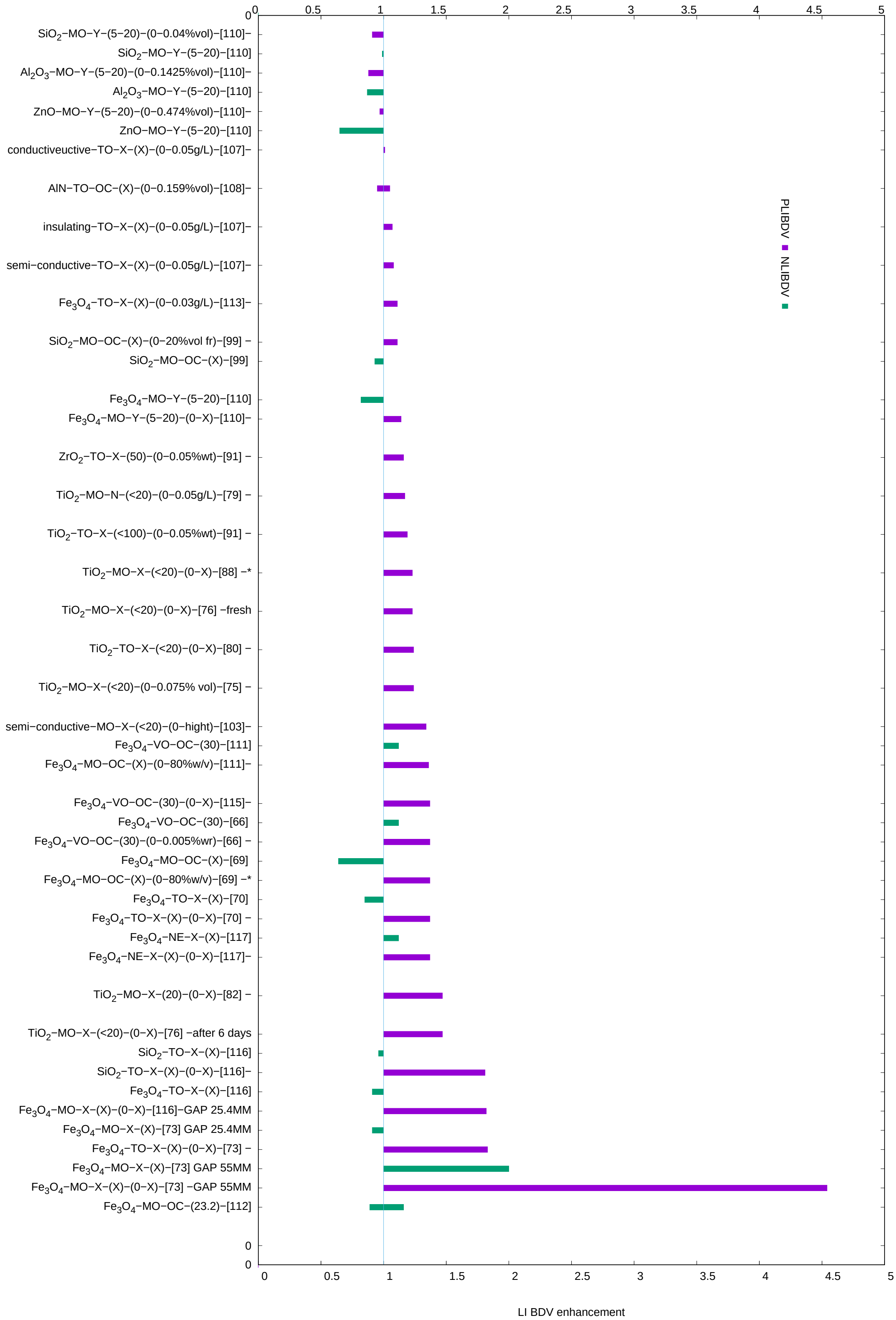

Figure 10. Range of enhancement in LI BDV values of nanoparticle oil-based nanofluids. Structure of legend: nanoparticle-based fluid-surfactant-(nanoparticle size)-(concentration range)-ref. X, no data available; N, no surfactant; Y, with surfactant, but unspecified; *, data read from graph.

Table 5. Summary of the lightning impulse breakdown voltage for various nanofluids.

NP	BF	Surfactant	Size (nm)	Concentrations	PL BDV	PL BDV_{nf}/PL BDV_{bf}	NL BDV	NL BDV_{nf}/NL BDV_{bf}	Time +	Time −	Stream +	Stream −	Comments	Standard	Ref.
Fe_3O_4	MO	Yes	5–20	0	98.77	1	−156.56	1			1.77	1.77		IEC 60897	[110]
				X	112.53	1.139	−127.9	0.82			0.97	1.01			
Fe_3O_4	VO	OA	30	0	73.9	1	83.8	1	9.9	11.1				IEC 60897	[111]
				X	101.5	1.373	93.7	1.12	12	12.7					
Fe_3O_4	VO	OA	30	0.000% wr	73.9	1	83.8	1	9.9	11.1				IEC 60897	[66]
				0.004% wr	101.5	1.373	93.7	1.12	12	12.7					
Fe_3O_4	TO	-	-	0	86	1	170	1	12	27	2.12	0.94			[116]
				X	157	1.826	154	0.91	26	15	0.98	1.69			
Fe_3O_4	MO	OA	23.2	0.0 vol%			151.1	1							[112]
				0.2 vol%			159.4	1.05							
				0.3 vol%			175.4	1.16							
				0.6 vol%			134.6	0.89							
Fe_3O_4	TO	-	-	0 g/L	99.1	1			306						[113]
				0.3 g/L	110.2	1.112			188						
Fe_3O_4	MO	OA	-	0% w/v	79.24	1	124.79	1	12.87		1.94			IEC 60897	[69] *
				5% w/v	83.56	1.05	122.7	0.98	14.82		1.68				
				10% w/v	84.08	1.06	119.71	0.96	18.32		1.36				
				20% w/v	93.47	1.18	115.57	0.93	21.19		1.17				
				40% w/v	107.47	1.37	106.19	0.85	25.33		0.98				
				60% w/v	102.36	1.3	92.14	0.74	25.08		0.99				
				80% w/v	88.07	1.11	80.3	0.64	21.98		1.13				
Fe_3O_4	TO	-	-	0	79.38	1	124.75	1.00	12.87	14.26	1.94	1.05		IEC 60897	[70]
				X	108.5	1.367	106.3	0.85	25.33	11.03	0.98	1.36			
				0% w/v		1			12.87		1.94				
				5% w/v		1.054			14.82		1.68				
				10% w/v		1.062			18.32		1.36				
				20% w/v		1.184			21.19		1.17				
				40% w/v		1.366			25.33		0.98				
				60% w/v		1.3			25.08		0.99				
			0	0% w/v	79.36		124.78								
			10	40% w/v	88.03		97.89								
			20	40% w/v	108.09		83.56								
			40	40% w/v	87.8		114.47								
			20	gap (mm)											
Fe_3O_4	MO	OA	-	5	67.82		85.24							IEC 60897	[115]
				10	99.5		102.54								
				15	127.27		106.55						Concentration 40%		
				20	157.45		132.07								
				30	175.59		151.61								
				40	218.61		172.67								
			0	gap (mm)											
				5	62.22		89.22								
				10	93.16		80.62								
				15	114.93		90.44						Concentration 0%		
				20	117.78		111.91								
				30	132.84		131.66								
				40	162.96		156.62								

Table 5. *Cont.*

NP	BF	Surfactant	Size (nm)	Concentrations	PL BDV	PL BDV$_{nf}$/PL BDV$_{bf}$	NL BDV	NL BDV$_{nf}$/NL BDV$_{bf}$	Time +	Time −	Stream +	Stream −	Comments	Standard	Ref.
Fe_3O_4	NE	-	-	0	73.9	1	83.8	1							[117]
				X	101.5	1.373	93.7	1.12							
TiO_2-r	MO	no	<20	0.003 g/L	79.7	1			14						[79]
				0.006 g/L	86.4	1.084			15.5						
				0.01 g/L	85.8	1.077			16						
				0.03 g/L	89.4	1.122			15.5						
				0.05 g/L	93	1.167			16						
TiO_2	TO	-	<20	0	77.6	1			15.2					ASTM D3300	[80]
				X	95.9	1.236			23.3						
TiO_2	MO	-	20	0	70.25	1			14.27						[82]
				X	103.33	1.471			25.11						
TiO_2	MO	-	<20	0 vol%	77.6	1			15.2					ASTM D3300	[75]
				0.075 vol%	95.9	1.24			23.3						
TiO_2	MO	-	<20	time (day)										IEC 60897	[88]
				0	77.64	1							pure oil		
				6	76.41	0.98									
				12	69.75	0.90									
				18	72.57	0.93									
				24	69.52	0.90									
				30	69.56	0.90									
				36	69.33	0.89									
				0	96.2	1.00							nanofluid		
				6	102.78	1.07									
				12	96.3	1.00									
				18	73.29	0.76									
				24	70.89	0.74									
				30	70.75	0.74									
				36	70.82	0.74									
TiO_2	MO	-	<20	0		1							fresh	IEC 60897	[76]
				X		1.23									
				0		1							after 6 days		
				X		1.47									
TiO_2	TO	-	<100	0.000 wt%	34.13	1.000								IS 11697:1986	[91]
				0.005 wt%	40.70	1.192									
				0.010 wt%	38.90	1.140									
				0.050 wt%	37.30	1.093									
SiO_2	MO	yes	5–20	0.00 vol%	98.77	1	−156.56	1			1.77	1.77		IEC 60897	[110]
				0.04 vol%	90.11	0.91	−156.42	0.99			1.85	1.38			
SiO_2	TO	-	-	0	86	1	170	1	12	27	2.12	0.94			[116]
				X	156	1.814	163	0.96	17	26	1.44	2.87			
SiO_2	MO	OA	20	0 vol%	81.01	1	135.4	1	12.95	16.3	1.93	1.53		IEC 60897	[99]
				20 vol%	90.21	1.11	126.2	0.93	18.01	12.79	1.38	1.95			

Table 5. *Cont.*

NP	BF	Surfactant	Size (nm)	Concentrations	PL BDV	PL BDV_{nf}/PL BDV_{bf}	NL BDV	NL BDV_{nf}/NL BDV_{bf}	Time +	Time −	Stream +	Stream −	Comments	Standard	Ref.
Al_2O_3	MO	yes	5–20	0 vol% 0.1425 vol%	98.77 87.3	1 0.88	−156.56 136.16	1 −0.87			1.77 2.01	1.77 1.45		IEC 60897	[110]
ZnO	MO	yes	5–20	0 vol% 0.0475 vol%	98.77 95.46	1 0.97	−156.56 −102.67	1 0.65			1.77 1.05	1.77 1.31		IEC 60897	[110]
semiconductive	MO	-	<20	0 Low Medium High	70 86 87 94	1 1.229 1.243 1.343							ASTM D3300	[103]	
Fe_3O_4	MO U60 MO N10x MO U60 MO N10x	-	-	0 0 X X	86 88 157 156	1 1.023 1.826 1.814	170 177 154 173	1 1 0.91 0.98	12 16 26 25	27 23 15 17			gap 2.5 mm	ASTM D3300	[73]
	MO U60 MO U60			0 X	225 390	2.616 4.535	340 321	2 1.89	25 46	28 32			gap 55 mm		
ZrO_2	-	-	50	0 wt% 0.005 wt% 0.010 wt% 0.050 wt%	34.13 39.60 38.59 36.61	1.000 1.160 1.131 1.073							Indian Standard (IS)	IS11697:1986	[91]
Insulation (metal oxide)	MO	-	70	0% mass fr 0.05% mass fr	72.5 77.5	1 1.07								IEC 60897	[107]
Semiconductive	TO	-	-	0 g/L 0.05 g/L	72.5 78.3	1 1.08								IEC 60897	[107]
Conductive	TO	-	-	0 g/L 0.05 g/L	72.5 73.3	1 1.01								IEC 60897	[107]
AlN	TO	OA	-	0 vol% OA 0.079 vol% 0.127 vol% 0.159 vol%	162 154 155 170 166	1 0.95 0.96 1.05 1.03									[108]

*, data read from graph, X, no data available.

5. Possible Mechanism

The mechanism behind improvement of the breakdown voltage in nanofluids based on both mineral and ester oils is not well understood yet. Some researchers assigned this enhancement to creating an electrical double layer (EDL) around the nanoparticles suspended in base fluid, as shown in Figure 11 [83,92,101]. Free ions existing in base fluid are attracted to the surface of nanoparticles and due to electrostatic forces are immobilized. This part of EDL is called the compact layer, and the density of net charge in this region drops down with the increasing radius of the layer, reaching zero. Electrostatic interaction in this area is lower, and ions can be mobile, creating a diffuse layer. The charge carrier in nanofluids under an external electrical field are moving through the sample using the channel created in EDL, where carriers can be trapped and de-trapped by opposite charges, leading to slowing down of the carriers. In effect, higher external power is needed to create the conducting path between electrodes [101].

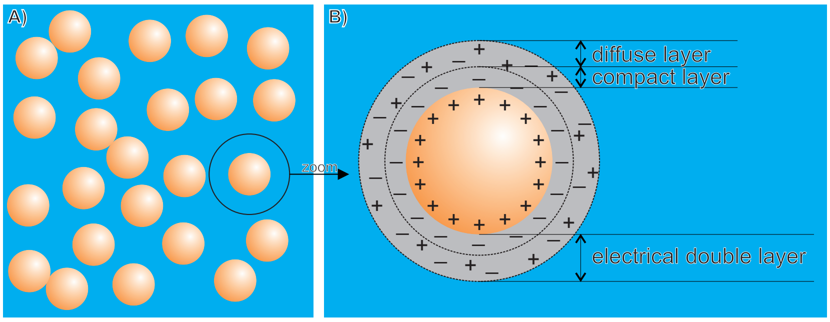

Figure 11. (**A**) Schematic view of nanoparticles dispersed in base fluid and (**B**) schematic view of the formation of an electrical double layer around a nanoparticle.

6. Conclusions

The present work provides an extensive review on the insulating properties of both mineral and natural ester insulating oils containing different types of nanoparticles with various concentrations. The most often studied nanoparticles are titanium oxides and iron oxide. The maximum enhancement in BDV was observed by Lee et al. [104,106] for magnetic nanofluids prepared using EFH-1 ferrofluid and transformer oil. On the other hand, the biggest deterioration in values of BDV was observed by Fontes [102] for MWCNT dispersed in mineral oil. Values of both positive and negative LI BDV are also strongly dependent on the inclusion of nanoparticles into transformer oils. The maximum enhancement in positive lightning impulse breakdown voltage was noticed by Segal et al. [73] for iron oxide dispersed in mineral oil, and it was 4.5 times. Furthermore, the maximum increase in negative impulse breakdown voltage was observed for the same material, and it was 2.0 times.

This overview of papers leads to a few conclusions about the factors affecting the values of breakdown voltage (BDV) and the lightning impulse breakdown voltage (LI BDV). First, it is obvious that the concentration of nanoparticles in transformer oils has a strong effect on BDV values, and this effect is not unequivocal. As many researchers have revealed [97,104,105], the increase in the load of nanoparticles in the base fluid causes an increase in BDV. On the other hand, there are nanofluids that exhibit an increase in BDV only up to some concentration, above which a decrease in BDV is observed [77,86,90,95]. In some cases, the addition of nanoparticles causes the completely opposite effect: decreasing BDV below a pure base fluid [73,85,102]. Furthermore, the content of moisture is important for the good insulating properties of transformer oil-based nanofluids as Bakrutheen et al. [85] and Jin et al. [93–95] reported. The lifetime of nanofluids is not without significance, and it was investigated by Yue-fan et al. [83] and Rafiq et al. [76]. To improve the stability of nanofluids, researchers often use surfactants. One of the most used surfactants is oleic acid, but from the point of view of the AC BDV values of transformer oil-based nanofluids, the most effective surfactant is CTAB. As was presented in this review paper, nanoparticles might be used to improve the insulating properties of transformers. Unfortunately, at the moment, the mechanisms occurring in transformer oils containing nanoparticles during breakdown voltage tests are not fully understood; additionally, a lack of a unified method of preparation and testing of the BDV of nanofluids and concentration representation cause problems with the comparison of the results obtained by different researcher, so further work in both the experimental and the theoretical field of this issue should be considered, taking into account standardized rules of sample preparation, measurement methods and data representation.

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Abbreviations

The following abbreviations are used in this manuscript:

AB	alkyl benzene
AC	alternating current
ASTM	The American Society for Testing and Materials
BDV	breakdown voltage (kV)
BF	base fluid
CCO	coconut oil
CO	corn oil
CTAB	hexadecyl trimethyl ammonium Bromide
DC	direct current
IEC	International Electrotechnical Commission
LI	lightning impulse
MO	mineral oil
NE	natural ester oil
NF	nanofluid
NLI	negative lightning impulse
NP	nanoparticle
OA	oleic acid
ODA	octadecanoic acid
PE	palm ester
PFAE	palm fatty acid ester
PLI	positive lightning impulse
PV/T	hybrig photovoltaic and thermal solar system
SA	stearic acid
SBE	soybean ester
SDBS	sodium dodecyl benzene sulfonate
SO	silicon oil
TO	transformer oil
VO	vegetable oil

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