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Study of Dielectric Breakdown Performance of Transformer Oil Based Magnetic Nanofluids

Yuzhen Lv, Muhammad Rafiq *, Chengrong Li and Bingliang Shan

Beijing Key Laboratory of High Voltage & EMC, North China Electric Power University, Beijing 102206, China; yuzhenlv@163.com (Y.L.); lcr@ncepu.edu.cn (C.L.); shanbingliang521@163.com (B.S.)
* Correspondence: Jutt96@gmail.com; Tel.: +86-10-61772352

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Abstract: Research on the transformer oil-based nanofluids (NFs) has been raised expeditiously over the past decade. Although, there is discrepancy in the stated results and inadequate understanding of the mechanisms of improvement of dielectric nanofluids, these nanofluids have emerged as a potential substitute of mineral oils as insulating and heat removal fluids for high voltage equipment. The transformer oil (TO) based magnetic fluids (ferrofluids) may be regarded as the posterity insulation fluids as they propose inspiring unique prospectus to improve dielectric breakdown strength, as well as heat transfer efficiency, as compared to pure transformer oils. In this work, transformer oil-based magnetic nanofluids (MNFs) are prepared by dispersal of Fe_3O_4 nanoparticles (MNPs) into mineral oil as base oil, with various NPs loading from 5 to 80% w/v. The lightning impulse breakdown voltages (BDV) measurement was conducted in accordance with IEC 60897 by using needle to sphere electrodes geometry. The test results showed that dispersion of magnetic NPs may improve the insulation strength of MO. With the increment of NPs concentrations, the positive lightning impulse (LI) breakdown strength of TO is first raised, up to the highest value at 40% loading, and then tends to decrease at higher concentrations. The outcomes of negative LI breakdown showed that BDV of MNFs, with numerous loadings, were inferior to the breakdown strength of pure MO. The 40% concentration of nanoparticles (optimum concentration) was selected, and positive and negative LI breakdown strength was also further studied at different sizes (10 nm, 20 nm, 30 nm and 40 nm) of NPs and different electrode gap distances. Augmentation in the BDV of the ferrofluids (FFs) is primarily because of dielectric and magnetic features of Fe_3O_4 nanoaprticles, which act as electron scavengers and decrease the rate of free electrons produced in the ionization process. Research challenges and technical difficulties associated with ferrofluids for practical applications are mentioned. The advantages and disadvantages linked with magnetic fluids are also presented.

Keywords: breakdown strength; nanoparticles; nanofluids; dielectric improvement; transformers

1. Introduction

The evolution of prospective high voltage systems and smart grids has placed significant demands on the reliability and conduct of insulating materials applied in electric power networks to cope with vital and volatile operating conditions [1]. An essential component of electrical networks which alters voltage levels and transforms energy is called a transformer [2]. The majority of transformer units in operation across the world are near or beyond their design life; thus, it has been a major aim to enhance the operational reliability of the existent entities [3]. The high voltage (HV) machinery collapse statistics illustrated that usual service life of transformers, which collapse due to insulation complications, is 17.8 years, which is half of their anticipated life of 35 to 40 years [4] and 75% of transformer failures are mainly caused by insulation issues [5]. The status and properties of insulation materials are very important for the functional reliability and lifetime of transformers [5–8].

Mineral oil and cellulose insulation systems have been successfully applied in the transformer industry over the last century. The rise in system voltage levels with recent developments has put a continuous pressure on these insulation systems to meet the demands of high reliability, high tolerance to field strength and smaller size. Nevertheless, in oil/cellulose insulation, the disparity between liquid permittivity (~2.2) and a solid one (ranging, 3.6~4.5) has been a serious concern that might confine the compact design of high voltage machinery, since the liquid undergoes a higher stress than the solid at alternating current (AC) and/or impulse voltages. Whereas, the BD strength of the liquid is basically less than that of the solid.

The insulation liquid basically executes two primary actions in high voltage equipment: insulation and cooling. Insulating and thermal features of mineral oil typically restrain the minimal size and maximal transfer of power [9,10]. Nonetheless, the greatly refined mineral oils (MOs) commonly employed as insulation liquids in high voltage apparatus, possess low thermal conductivity and thus, achieve low cooling efficiency [11].

Transformer oil is one the most significant elements of the transformer, which executes the aforementioned two major functions: as a cooling fluid, it is helpful in transferring the heat produced in the active parts (windings and magnetic core) to the tank walls of the transformer, where it may be exhausted; as an insulating material, the oil hinders the flow of electric current outside of the electric elements [10]. The low thermal conductivity of transformer oil (TO) causes restraints in the conduct of transformers, because of conditions such as over loading and extreme rise in temperatures causing enormous local increase in temperature in the oil (hotspot), so that the efficiency of the TO is restricted.

Refining the inquiry of materials down to the nanometer scale frequently shows new characteristics of matter that have no equivalent on a large scale. This phenomenon is encouraging in many current investigations of nanomaterials, which can disclose some new interesting phenomena. Fluids with suspended nanoparticles (NPs) (of a few tens of nanometers) well distributed in liquids are noted as nanofluids (NFs), a word suggested by Choi et al. [12], denoting the suspension of fine particles in a host liquid with no significant sedimentation of particles over time [13]. In addition to MOs, other inorganic and organic liquids have been applied as the matrix for nanofluids development. The nanoparticles with a larger surface area, as compared with ordinary particles, do not only considerably enhance transfer capacity, but also boost the stability of the suspensions [14]. Liquid or solid insulators, integrating within their volumes suspended NPs, manifest appealing permittivity traits, with supplementary polarization mechanisms evolving across the interface of the matrix material and distributed particles. Nanofluids can be considered as two-phase systems, the one phase being the matrix and the other being the scattered NPs. Materials applied to nanofluids formation include metals, metal oxides and nitrides. Accordingly, the resulting fluid may display different conductivities and/or permittivities. NFs have been found to have upgraded thermo-physical features e.g., thermal conductivity, viscosity, thermal diffusivity and convective heat transfer coefficients, as compared to those of carrier liquids. It has displayed significant potential applications in various fields. The biggest issues being faced by this two-phase system is the stability of NFs; there is as of yet, no clear way to stabilize NFs to the required levels. Nanofluids are being discussed as the future-era heat transfer liquids, because they show overwhelming potential to enhance heat transfer conduction, as compared to base liquids [12].

Different nanoparticles Fe_3O_4, TiO_2 and Al_2O_3 can upgrade the breakdown voltage (BDV) of TO. Nevertheless, magnetic NPs (Fe_3O_4), that is, a type of well-known nanoparticles in multiple research areas such as chemistry, biology and applied physics [15–18]. They can also improve the heat transfer by thermo-magnetic convection, due to magnetic characteristics of Fe_3O_4, which has significant advantages for the cooling of the transformer [19]. They are ferromagnetic materials and have strongest magnetism between iron oxides. Colloids consisting of magnetic nanoparticles (magnetite) coated surfactants and suspended in liquid carrier are called ferrofluids or magnetic fluids [13]. A ferrofluid typically has three primary components: ferromagnetic particulates, such as magnetite, and composite ferrite; a surfactant, such as oleic acid or citric acid, and/or tetramethylammonium hydroxide, to avoid the NPs from clustering, and a host liquid, such as mineral oil or vegetable oil (as shown in Figure 1). The surfactant is used to coat the particles. This helps in impeding clotting and maintains the distribution of particles uniformly throughout the host fluid. Its dispersibility remains additionally stable when the magnetic field is applied appropriately [12,20]. One of the elementary necessities for a ferrofluid is the stability of magnetic particles against aggregations. For ferrofluids based on dielectric liquids, the magnetic field includes particle cluster formation that exerts significant influence on the permittivity of the ferrofluid. This phenomenon is called the magnetodielectric effect [9,21,22]. The first magnetic colloid with the aim of liquid insulation was produced to improve the heat transfer from the transformer windings by imposing the magnetic interplay between the field formed by the windings and fluid [23].

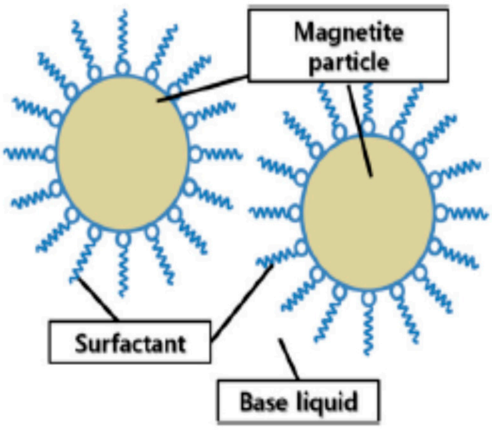

Figure 1. Depiction of magnetic nanoparticles (MNPs) in a nanofluid (NF) [20].

The extensive application of MOs for HV insulation and cooling of electrical appliances have lead significant research works to focus on improvement of both its thermal and dielectric features. An appropriate creative instance of such a research task is the preparation of dielectric NFs. This may be achieved by addition of the MNPs into TO with the intention of improving the insulating and thermal traits [24–26]. Magnetic nanofluids have been the subject of significant research due to their particular supermagnetic, tribological, mechanical and thermal features [27–29]. The results have showed that magnetic nanofluids may improve the AC, DC and lightning impulse (LI) breakdown strength of TO, with certain loadings of Fe_3O_4 nanoparticles [10,30]. Nevertheless, it was noted that magnetic nanoparticles have a tendency to agglomerate into larger particles, particularly at higher concentrations, leading to an abrupt decease in the breakdown performance of nanofluids [31]. Currently, many efforts have been made to raise the dispersion stability of NPs in the host liquid, e.g., by applying certain dispersants or surfactants [32–36]. It has been noted that surface modified iron oxide NPs show better dispersion stability in the mineral oil by using various synthesizing and modifying procedures at room temperature [32]. The dispersion of other NPs in base oil may also be enhanced by tailoring the quantity of modifying agents for surface modification of nanoparticles [33]. To avail these inherent advantages associated with nanofluids, a number of investigation studies have been conducted to formulate the nano-insulation oil.

1.1. Breakdown Phenomenon in Insulating Fluids

One of the most significant parameters of liquid insulation is BDV. The BDV of oils is the value of voltage at which the oil is unable to oppose the flow of electricity and that the electricity will go through it [37]. Molecular ionization of insulating channel, which is dependent on the electric field, is the major phenomenon for electrical breakdown (BD) in TO [38]. After ionization, oil molecules transform into high mobility electrons and low mobility positive ions, the high speed electrons are expelled away to the positive electrode from the ionization channel, because an area of net positive space charge instantly originates. The electric field distribution in the oils is altered during ionization, such that, the electric field ahead of the positive charge in the oil rises, although when it reaches the positive electrode, it tends to decline. The electrodynamics processes motivate an evolving ionizing electric field wave that vaporizes the TO and initiates the gas phase due to the temperature rise. The outcome of oil vaporization is the development of the low density streamer media in the oil [39]. Streamers are edifices having little density that are originated in parts of the oil where the electric field gradient is extreme.

1.2. Ferrofluids in Transformers

Mineral oil is mostly applied as a liquid insulating medium in high voltage equipment around the world [6]. Under the electrical stress, the space charge will originate and accumulate within the insulating materials, which may distort the internal electric field distribution and therefore, influence the dielectric breakdown performance [40,41]. A lot of efforts have been made to find the effective ways to decay/suppress the space charge in the insulating materials with an attempt to enhance the dielectric strength and lifetime of insulating materials [42,43]. Recently, nanoparticles with specific electrical and physical characteristics have been applied to boost the insulating properties of TO [24,44]. In recent years, some research investigations on the influence of NPs on the thermal and electrical traits of TO have been conducted. Segal et al. [9] studied that the suspension of MNPs into MO. They concluded that the AC BDV of the MNFs was improved in comparison to the carrier oil. The positive impulse BDV of ferrofluids showed significant increase, as compared to the base oil, of needle-sphere electrode geometry. The positive and negative LI BDV results of NFs prepared by MNPs conferred by different researchers are compiled in Table 1.

Table 1. Results for positive and negative lightning impulse (LI) breakdown voltage (BDV) and time-to-breakdown (BD) for mineral oil (MO) and developed nanofluids.

Samples	Gap Distance (mm) (+/−)	BDV (kV)		Time to BD (μs)		Streamer Velocity (km/s)		Remarks
		Positive	Negative	Positive	Negative	Positive	Negative	
U-60 [a]	25.4/25.4	86	170	12	27	2.12	0.94	Ref. [9]
U-60-Fe_3O_4 nanofluid	25.4/25.4	157	154	26	15	0.98	1.70	
Nytro [b]	25.4/25.4	88	177	16	23	1.58	1.10	
Nytro-Fe_3O_4 nanofluid	25.4/25.4	156	173	25	17	1.016	1.49	
U-60 [a]	55/55	225	340	25	28	2.2	1.96	
U-60-Fe_3O_4 nanofluid	55/55	390	321	46	32	1.19	1.71	
Mineral oil	5	51.84	83.10	4.44	4.02	1.126	1.244	Ref. [30]
Fe_3O_4 nanofluid	5	62.86	78.54	5.24	3.54	0.954	1.412	
Vegetable oil	15/15	73.9	83.8	9.9	11.1	1.51	1.35	Ref. [45]
Fe_3O_4 nanofluid	15/15	101.5	93.7	12.0	12.7	1.25	1.18	
Mineral oil	3	99.1	-	306	-	0.0098	-	Ref. [46]
Fe_3O_4 nanofluid	3	110.2	-	188	-	0.0159	-	

[a] Univolt 60 oil, [b] Nytro 10X oil.

In this paper, we intended to enhance the scattering ability of magnetic NPS in the MO at different concentrations. Monodisperse Fe_3O_4 NPs modified by oleic acid were produced through solvothermal method. The LI BD strength of the carrier MO and developed magnetic nanofluids with various concentrations of nanoparticles, sizes of nanoparticles and with various electrode gap distance was investigated. Moreover, the probable modification mechanisms of magnetic NPs on dielectric traits of TOs were also reviewed.

2. Materials and Methods

2.1. Formation of Transformer Oil-Based Ferrofluids

(a) Material Selection for Experiment

The MNPs (magnetite) are developed in our laboratory. The mineral oil (25#Kelamayi) was processed to remove the impurities and to meet the requisites of pure oil set by CIGRE board 12.17 [47]. As conductive nanoparticles have high surface energy and a tendency to agglomerate, suitable surface modifiers must be chosen to enhance the dispersion characteristics and stability of NPs [48]. Surfactant techniques have been applied to develop a glazed shell on the nanoparticles. The rear ends of surfactant molecules rebuff each other to ensure a distance between the particles to hinder them from agglomeration. Surface modification of NPs is an efficient method to avert NPs agglomeration in insulating liquids [49–52]. Nevertheless, the surface modifiers used for mineral oils cannot be used with other carrier oils, such as vegetable oils, because of different molecular forms/structures. Moreover, some significant features of conductive nanoparticles are also summarized in Table 2.

(b) Nanoparticles Synthesis

The magnetic nanoparticles Fe_3O_4 are developed by applying ferric chloride hexahydrate and iron powder as reactants by a solvo-thermal method. The oleic acid was applied as surface modifiers to ensure uniform distribution of nanoparticles in the mineral oil. In a conventional process, reactants are initially inducted into a combined solution of hexane and dodecylamine under stirring. Post stirring for 5 min, oleic acid was introduced into the aforementioned solution at room temperature with effective agitation. The emerging combination was later heated to the temperature of 180 °C. After heating for 3 h, the derived compound was naturally cooled down, washed with distilled water and absolute ethanol multiple times to eliminate the probable remaining ions in the product, and eventually dried in the vacuum at a temperature of 70 °C [53].

Table 2. Properties of the selected nanoparticles.

Properties	Transformer Oil	Magnetic Nanoparticles (Fe_3O_4)
Conductivity (S/m) [37,54]	10^{-12}	10^4–10^5
Relaxation time (s) [37,54]	-	7.47×10^{-14}
Relative permittivity [37,54]	2.2	80
Density (g/cm^3)	0.89	5.18
Surface modification	-	Oleic Acid
Material type	Dielectric	Conductive

(c) Development of Nanofluids

The typical process was employed to develop transformer oil-based nanofluids with desirable features as follows:

(1) The prepared nanoparticles (Fe_3O_4), after surface modification, are added into MO to the required concentrations, and then ultrasonic processes were applied [55].
(2) The developed nanofluids are acquired and put into vacuum drying for approximately 48 h to exclude the influence of gas bubbles and moisture generated while forming NFs.
(3) The moisture content of produced NFs is measured by Rishang coulmetric methods moisture meter JF-5. The flowchart for preparation of nanofluids is shown in Figure 2.
(4) The morphology of the prepared NPs is given in Figure 3. The TEM image demonstrates the nano-crystals are uniform and well-distributed without any significant agglomeration. The prepared samples with multiple concentrations are shown in Figure 4.

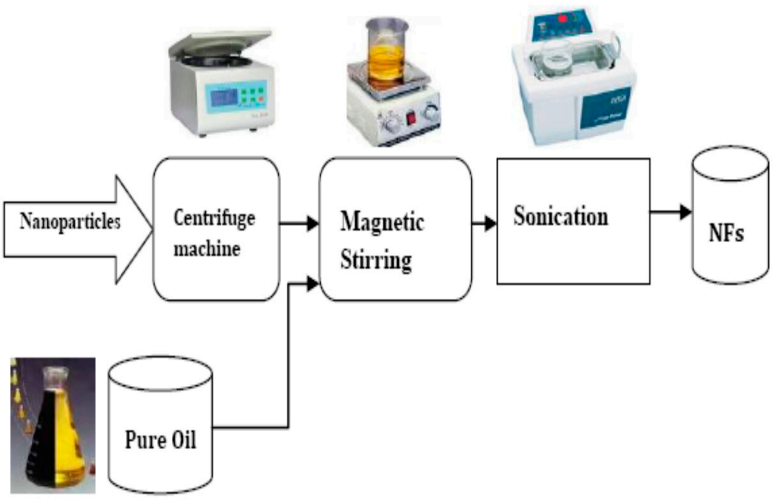

Figure 2. Flow chart for nanofluids preparation.

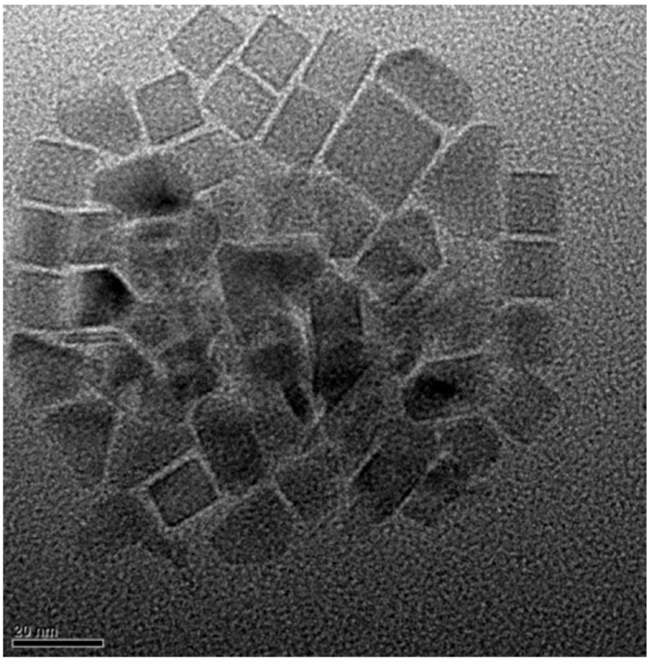

Figure 3. TEM image of prepared Fe_3O_4 nanoparticles (NPs).

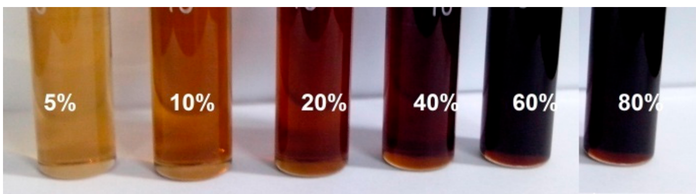

Figure 4. Nanofluids with different nanoparticle concentrations (5% = 0.05 g/L, 10% = 0.1 g/L, 20% = 0.2 g/L, 40% = 0.4 g/L, 60% = 0.6 g/L, 80% = 0.8 g/L).

2.2. Electrical Properties of Insulation Fluids

All the transformer oils are necessary to fulfill the lightning impulse standards. Many investigations have been conducted by different investigators to measure the breakdown voltage and dielectric properties of various transformer oils from multiple suppliers [56].

The LI breakdown voltages simulate lightning strikes and normally use 1.2 microseconds rise for the wave to reach a magnitude of 90% and then after 50 s, drops to 50% amplitude. The LI breakdown voltages are generally measured in accordance with IEC 601897 standard and all the experimentations are executed at room temperature [57]. A standard lightning impulse wave is generated by a ten stage generator. An oil vessel with needle to sphere arrangement was employed to measure the breakdown voltages for formulated NFs (as exhibited in Figure 5). A 25 mm gap distance was used for positive and 15 mm for negative LI BDV measurement. The samples were exposed to initial selected voltage value and then were enhanced step by step (2.5 kV in each step) until breakdown takes place. The needle electrode is changed post BD to ensure the identical experimental conditions. A set of six BD voltage readings were achieved for each sample to enact repeatability. The mean value was considered as LI BDV [57]. Whereas, for the legitimacy of the experiments outcomes, three impulse waves must be used at each voltage level and each oil sample must endure at least three voltage levels prior the occurrence of BD.

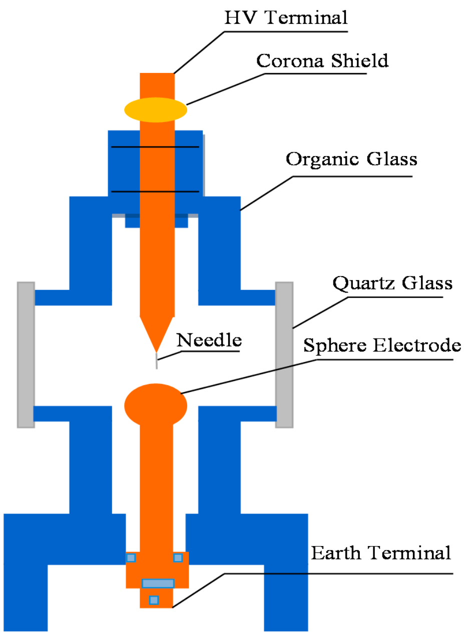

Figure 5. Oil tank and electrode geometry.

3. Results and Discussion

3.1. Breakdown Strength with Different Concentrations of Nanoparticles

(a) Positive LI BD Strength of Magnetic Nanofluids

The positive LI BDV test was conducted for both oil and developed NFs with multiple loadings of NPs. The outcomes are presented in Figure 6. NFs manifested an increase in the LI BDV as compared to MO. The mean LI BDV strength of NFs was enhanced 36% as compared to carrier TO at optimal loading of NPs. It is noted that 40% loading of NPs is the optimum concentration for positive LI BDV. With the rise in NPs concentration, the dielectric BDV increases until 40% concentration of NPs. However, the BDV tends to decline when the loading of NPs is raised beyond 40% concentration of NPs. The average BD outcomes of NFs under positive LI BDV with standard deviation are given in

Table 3. In the MNPs loadings range between 0 and 40%, the BDV indicated an improvement. Beyond the 40% concentration of the nanoparticles, the NPs may start to agglomerate and form chains in close proximity of electrodes that give rise to the internal local electric field development and a breakdown initiation at lower voltages [26].

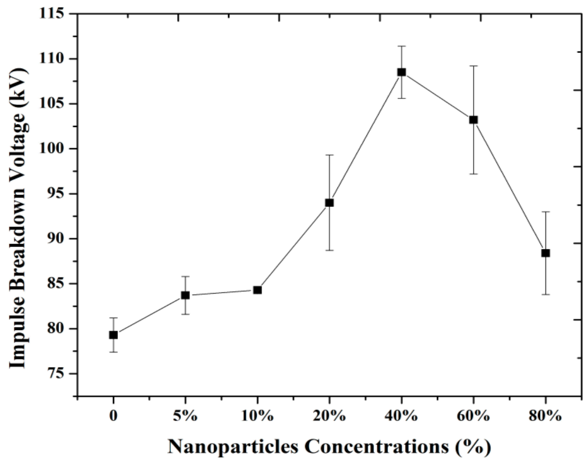

Figure 6. Positive LI BDV with multiple concentrations (25 mm gap distance).

(b) Negative LI BDV Strength of Magnetic Nanofluids

The negative LI BDV measurement was conducted for oil and NFs with various loadings of NPs. The outcomes in Figure 7 indicate that the conductive NPs reduce the negative BD performance of MO, which is incompatible with the conclusions of others [26].

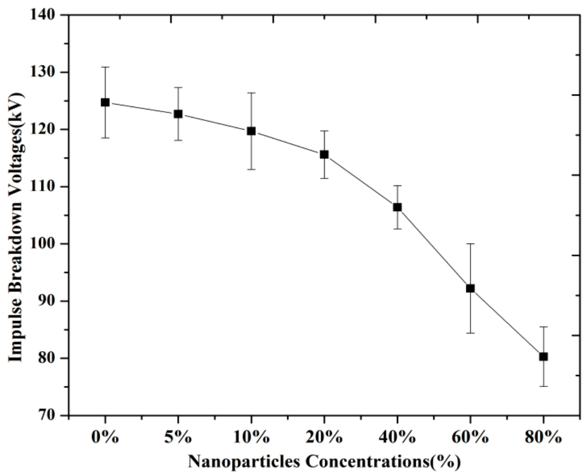

Figure 7. Negative LI BDV with multiple concentrations (15 mm gap distance).

Table 3. Breakdown outcomes of oil and prepared magnetic nanofluids under LI voltages.

NPs Loadings (% *w*/*v*)	Time to BD(μs)	Mean Streamer Velocity (km/s)	Improvement in BDV (%)
0	12.87	1.94	0
5	14.82	1.68	5.40
10	18.32	1.36	6.21
20	21.19	1.17	18.38
40	25.33	0.98	36.64
60	25.08	0.99	29.95
80	21.98	1.13	11.40

3.2. Breakdown Strength with Different Size of Nanoparticles

(a) Positive LI BDV Strength

The Positive LI BDV test was tested for oil and developed NFs (with 40% concentrations) with various sizes of NPs. The outcomes are indicated in Figure 8.

Nanofluids manifested an increase of LI BDV as compared to MO. The mean LI BDV of NFs was enhanced, as compared to base TO, at optimal size. There is significant enhancement in the BDV, when the size rises from 10 to 20 nm, but a significant reduction is noticed in the BDV, when there is a further enhancement in the size of NPs, i.e., 40 nm. As a result, it is clear from Figure 3, that 20 nm is the optimal size of NPs for positive LI BDV. These results are consistent with the previous report [10,31,44]. It is concluded that the increase of nanoparticle size will weaken the modification effect on breakdown strength of nanofluids.

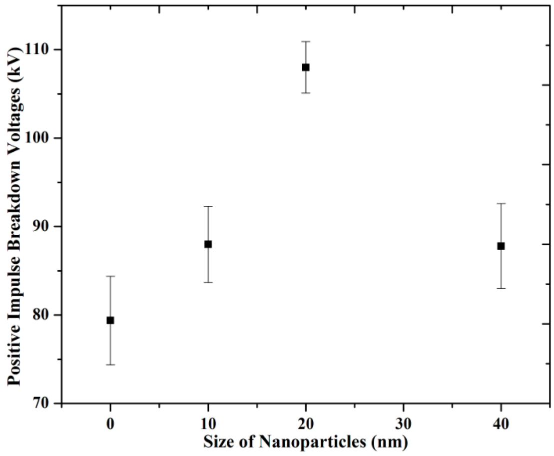

Figure 8. The effect of size on positive LI BDV (gap distance 25 mm).

(b) Negative LI Breakdown Strength

Negative LI BDV measurement was conducted for both MO and NFs. The outcomes are shown in Figure 9. The negative LI BDV decreases with the rise of size of NPs. The negative LI BDVs of the prepared NFs with various sizes of NPs are lower than that of pure oil, which is incompatible with the results of others [26].

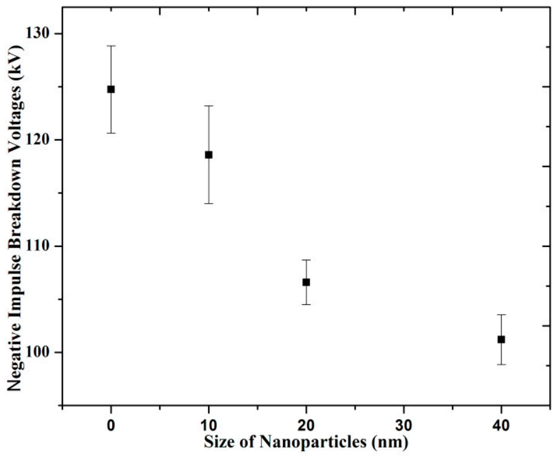

Figure 9. The influence of size on negative LI BDV (gap distance 15 mm).

3.3. Breakdown Strength with Different Gap Distance

(a) Positive LI BDV Strength

Positive LI BDV test was conducted for both MO and developed NFs (with 40% loadings and 20 nm size) with different gap distances. The outcomes are given in Figure 10. Nanofluids pointed out an enhancement of LI BDV than MO for all gap distances. The BDVs for all NFs samples improves with the increase of the gap distance. The result attained from this study is agreeable with the results of other researchers [58,59]. BDVs of NFs are always higher than MO for all gap distances.

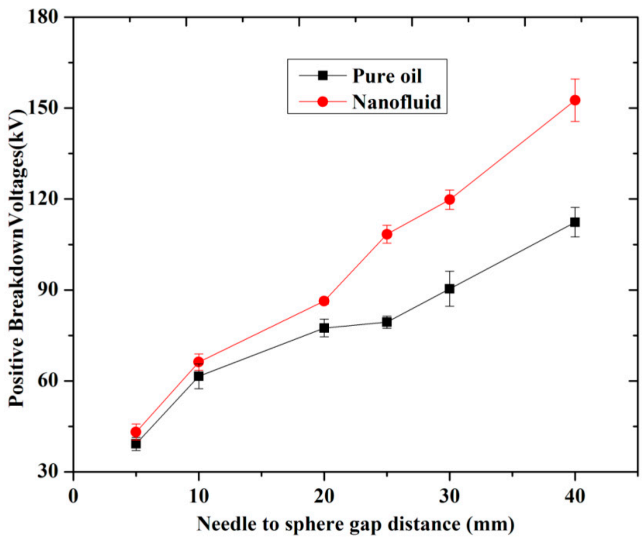

Figure 10. Positive impulse breakdown strength with different needle to sphere gap distances.

(b) Negative LI BDV Strength

Negative LI BDV measurement was done for both MO and nanofluids at different needle to sphere gap distances. The results are indicated in Figure 11. The results are inconsistent with the conclusions of others [26]. The negative LI BDVs for NFs are always lower than that of MO for all investigated electrode gap distances.

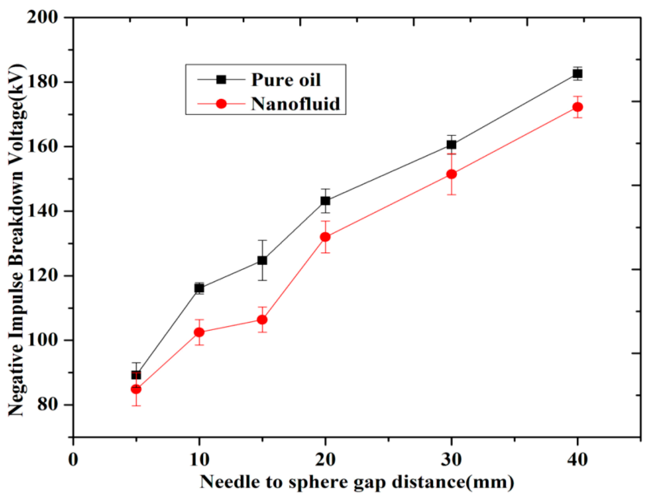

Figure 11. Negative impulse breakdown strength with different needle to sphere gap distances.

3.4. Breakdown Mechanism

The investigations further elaborated on the concept that the space charges effect in TO is a significant determinant that affects the inception and origination of streamer discharge [60]. The insulation BD strength of TOs is closely linked to the electric field and its internal space charge [55,61–63]. Many researchers suppose that the distinctive interface features between oil and nanoparticles perform an imperative role in the space charge transport during the BD mechanism in NFs [64–66]. The interface area comprise of enormous sum of electronic traps that can abduct and deliver electrons frequently. The process of trapping and de-trapping decreases the velocity and energy transfer of electrons and obstructs the further evolution of the streamer. Other researchers [67] believe that suspended nanoparticles introduce additional traps, which can capture the electrons and reduce the average energy of electrons travelling through the oil, and so the possibility of further electron production through impact ionization is also decreased. Therefore, the distortion of electric field in the oil by the electronic charge in transit would be decreased, and then hence, the dielectric strength is improved.

The BD process of TO stressed by applied voltages is largely associated with the electric field and space charge distribution in TO. The decrease of space charge density and uniform electric field in transformer oil can upgrade the breakdown voltage of the TO. It is believed that the introduction of Fe_3O_4 NPs into TO behaves as electron scavengers and captures electrons, transforming them into slow charged nanoparticles in the nanofluids. This conduct reduces the space charge density and result in a more uniform electric field distribution. Streamer development in the nanofluids is inhibited, and the BD performance of nanofluids is improved.

(a) Mechanism of Action of Magnetic Nanoparticles

From the conventional point of view, the existence of conductive particles into MO may act as impurity and must reduce its dielectric performance, but the experiments have manifested that distribution of conductive NPs into MO have demonstrated an improvement in its breakdown performance. Therefore, it is useful and essential to comprehend what makes the NFs have distinct BD features, as compared to carrier oil for new oil-paper insulation systems with favorable dielectric characteristics. The charge relaxation time constant of NP materials is deliberated to perform a dominant role in the electrodynamics processes in transformer oil. If the charge relaxation time constant of nanoparticles is shorter relative to time scales of interest for streamer development; their existence in the oil will effectively alter the electrodynamics. If, on the other hand, the nanoparticles' charge relaxation time constant is relative to the time scales of interest for streamer expansion, their existence will have minor effect on the electrodynamics [54]. The charge relaxation constant (τ_r) for mineral oil/nanoparticle is:

$$\tau_r = \frac{2\varepsilon_1 + \varepsilon_2}{2\sigma_1 + \sigma_2}$$

where ε_1, σ_1, ε_2, and σ_2 are permittivity and electrical conductivity of mineral oil and nanoparticle, respectively. A smaller value of relaxation time constant means faster electron absorption of nanoparticles. According to the authors of [26], the relaxation time constant of conductive MNPs (7.47×10^{-14} s) is less than the nanosecond to microsecond of propagation time of the streamer. The surface of the magnetic nanoparticles (Fe_3O_4) may consume the free electrons and hence, alter the potential distribution around the particle [54]. Therefore, the suspension of MNPs into transformer oil may effectively influence the electrodynamics process during the streamer development, and ultimately, enhance the BD performance of magnetite NFs.

(b) Analysis of Mechanism Improved Breakdown Properties

It is considered that the modifications in space charge distributions are motivated by the suspension of nanoparticles into MO and therefore, the breakdown features of nanofluids and pure oil are different. This work explicates the foregoing conditions by applying the needle–sphere model.

The rising positive LI voltages between electrodes originate a corona discharge to happen in close proximity to the positive needle electrode with high local electric field strength. This high local electric field strength causes ionization of molecules in the transformer oil, close to the needle electrode. A significant space charge is developed due to this field ionization. The electrons are produced at a high electric field and are neutralized at the needle electrode in pure oil. After electron neutralization at the needle electrode, there are a significant number of positive ions left accumulated close to the needle electrode due to relatively low mobility of these particles. This newly developed spatial electric field undermines the external field close to the needle electrode and invigorates the external field between positive ions and sphere electrode. This developed spatial electric field causes the strong distortion effect responsible for an early electric breakdown in pure oil (as in Figure 12).

In case of NFs, some portion of high mobility electrons generated after molecular ionization due to high local electric field stress is neutralized after approaching the needle electrode, whereas the remaining segment of electrons is abducted by suspended nanoparticles (as in Figure 13). The nanoparticles are transformed into negative ions after abduction of electrons. As the mobility of these negative ions developed is low, a large number of these negatively charged NPs are left in the ionization zone close to the needle electrode. This mal-position of positive and negative ions close to the needle electrode results in a superposition spatial electric field, which distorts the former electric field. The existence of these negatively charged NPs close to the needle electrode abate the distortion effect responsible for an early breakdown in pure oil.

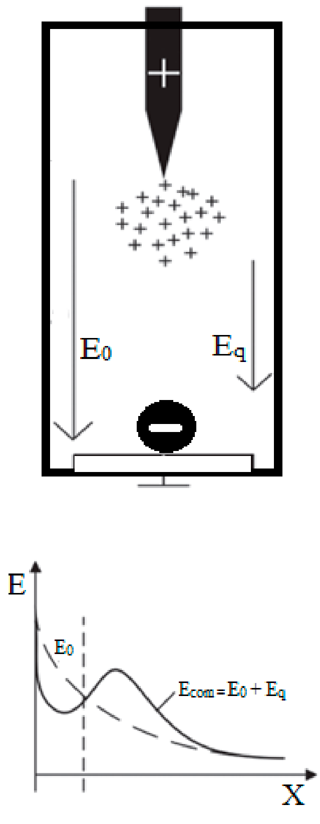

Figure 12. Space charge build-up under positive impulse voltage in transformer oil.

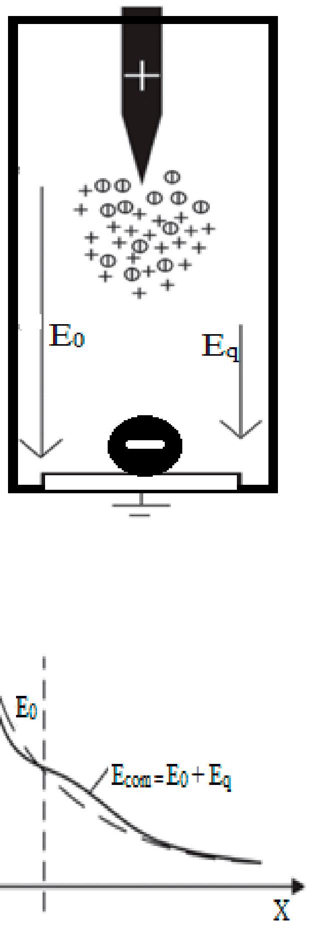

Figure 13. Space charge build-up under positive impulse voltage in nanofluids.

The corona discharge developed in nanofluids is harder to expand outwards than the corona discharge in pure oil when the voltages are enhanced continuously. The positive charges move toward sphere electrode and negatively charged nanoparticles moves towards the needle electrode. In this way, the distortion effect of the space charge field on the prior field is less than in the pure oil. Thus, the positive LI breakdown voltages are improved after the distribution of nanoparticles.

On the contrary, the condition under negative LI voltage is quite contrasting. In pure oil, after the application of negative impulse voltages to the needle electrode, the molecular ionization occurs close to the needle electrode after corona generation and the space charges are developed. The ionization of molecules will produce high mobility electrons, which will tend to move towards the sphere electrode and leave behind the positive ions close to the needle electrode. A portion of these positive ions is neutralized after approaching the needle electrode and the remaining part will retain near the needle electrode due to the low mobility of the positive ions. In case of nanofluids, the nanoparticles will capture the electrons generated after molecular ionization and transformed into negatively charged particles. A large number of negatively charged NPs will remain close to the needle electrode due to their low mobility. This phenomenon undermines the electric filed strength near the needle and bolsters the electric field near the sphere electrode. Thus, the breakdown happens at lower negative voltages for nanofluid as compared to the pure oil (Figure 14).

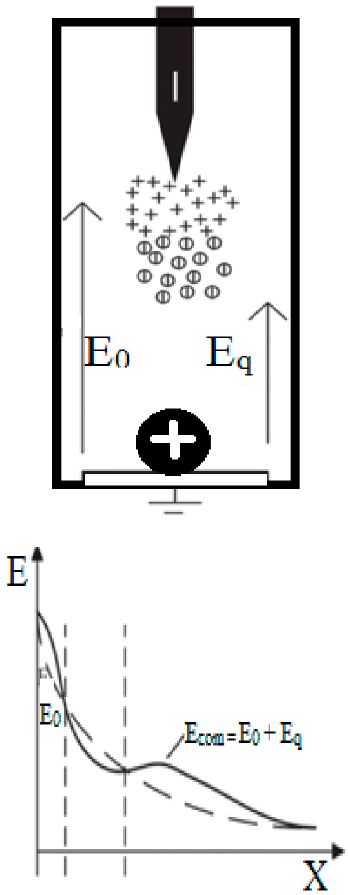

Figure 14. Space charge build-up under negative lightning impulse voltage.

4. Research Challenges, Technical Difficulties, and Research Gaps

Although the transformer oil-based ferrofluids have manifested excellent dielectric and thermal properties and are considered as potential substitute of mineral oils to be applied in high voltage equipment in the years to come, but the challenges which restrain their applications still persists. Also, there are numerous issues and other challenges that need to be further examined. There are challenges and problems associated with ferrofluids research that, we think, are closely linked to each other.

4.1. Research Challenges

The features of ferrofluids depend on the variety of factors including, method of preparation, type of base oil, and combinational characteristics of nanoparticles and oil.

(a) Synthesis of Ferrofluids

The successful use of nanoparticles mainly depends upon the synthesis method/process of NFs. Particular requirements, such as stable suspension, controlled size and concentration of nanoparticles are necessary. Normally, there are two methods of development of nanofuids: single-step and two-step method. Each method has its advantages and disadvantages. The one-step method is favorable for developing nanofluids which consists of high conductive metals to hinder oxidation. The disadvantage of the single step technique is its limited control over significant factors such as size of nanoparticle. Preparing nanofluids by using two-step technique is also very challenging, because of potential agglomeration of nanoparticles. The issue of agglomeration becomes very serious at higher volume concentrations.

(b) Stability of Ferrofluids

The tendency of nanoparticles to merge into larger particulates under attractive forces and external stresses can adhere together and produce aggregates of larger size, which may settle out of suspension because of gravity [68,69]. Agglomeration means that the particles begin to aggregate at a meaningful rate. The agglomeration is one of the most important issues for a (liquid-solid) two-phase system. The agglomeration of nanoparticles may act as a weak link, from which a disastrous process usually initiates, leading to deterioration of not only dielectric properties, but also thermal characteristics of liquid insulation. For instance, the electrical breakdown performance of transformer oil suspended with conductive nanoparticles was found to be adversely influenced by the presence of significant agglomerates of nanoparticles [70]. Thermal conductivity of liquid insulation is also affected by nanoparticles agglomeration [71]. Therefore, the suitable addition of nanoparticles into transformer oil needs to be accomplished to ensure the optimized properties of the resulting ferrofluids. The agglomeration of magnetic nanoparticles may be reduced by the use of certain surfactants, surface modification techniques and ultrasonic agitation [72–75].

(c) Application of Surfactants and Surface Modification

Although the use of surfactants and surface modification of NPs has illustrated a potential to enhance the dispersion stability of magnetic nanoparticles at low concentrations, but the stability of magnetic nanofluids with higher concentrations is still a significant challenge. The inclusion of surfactants decreases the surface tension of base fluids and enhances the immersion of NPs. Dispersants or surfactants are chemical compounds applied to NPs in order to reduce the surface tension of fluids and enhance the immersion of nanoparticles. The excess of surfactant may also cause instability. The excess of surfactant will dissociate from the surface of nanoparticles and may dissolve into the mineral oil as an impurity, thus adversely affecting the breakdown strength on NFs. The addition of surfactants in the two-phase systems is an easy and economic technique to improve the stability of NFs. The selection of suitable dispersants is also a major challenge. The surface modification technique is a surfactant-free approach and it uses functionalized nanoparticles to attain a long-term stability of nanofluids. This technique is applied to enhance the dispersion of NPs and to improve the compatibility between NPs and liquid materials.

(d) Dielectric Improvement Mechanism

The mechanism of dielectric enhancement of breakdown properties of transformer oil is not fully elaborated. Hwang et al. [76] presented the electron scavenging model which is dependent on the relaxation time constant. It may describe the enhancement of insulating strength of oil with conductive (Fe_3O_4) NPs distribution, but it is incapable of explaining the insulating strength improvement of other conductive, semiconductive and insulative nanoparticles suspensions. For instance, Chiesa et al. [5] manifested that other type of conductive nanoparticles ($\sigma = 1 \times 10^2$ S/m) with a short relaxation time constant ($\tau = 1.1 \times 10^{-12}$ s) is unable to enhance BD strength of TO. The electron scavenging by conductive nanoparticles deduced by the relaxation time constant, which was not able to describe this phenomenon. Thus, it is also a significant challenge in nanofluids research to explore the modification mechanism of NPs on dielectric characteristics of TO.

(e) Other Related Issues and Challenges

The investigations have manifested that the electrical conductivity, relative permittivity and loss factor of prepared magnetic fluids is very different from the host oil [76]. The practical application of magnetic fluids in transformers with these unique properties may have different electrical stress distribution and thus have severe complications on the transformer structure. The standard maintenance and testing procedures also need to be revised. The long term oxidation stability of magnetic fluids also needs to be improved, and other related issues also still need to be investigated, such as sedimentation problems, oxidation stability, as well as moisture absorption.

4.2. Technical Problems and Difficulties

The major technical difficulties regarding the use of magnetic fluids as insulation and cooling liquid in high voltage equipment, which require further investigations, are summarized as below [44,77]:

(1) It is complicated to apply magnetic fluids in the existent transformers because of disparity of the electrical specifications, so it is necessary to conduct more research work regarding the application of magnetic fluids in these existing transformers.
(2) More investigative studies are needed to explore more efficient synthesis processes, to decrease the production cost of FFs and to recognize the potential industrial applications of ferrofluids.
(3) A significant research is necessary to curtail the severe human body and environmental impacts of transformer oil-based ferrofluids.
(4) The coating chemistry of nanoparticles have a significant influence on the dielectric features of a ferrofluid, therefore more research work is required to discover a better coating chemistry for magnetic nanoparticles.

4.3. Other Problems and Research Gap

Although transformer oil-based ferrofluids have demonstrated exceptionally interesting dielectric properties, but still there are some imperative issues and challenges which require attention. The following crucial problems must be given thorough focus in subsequent research work. Firstly, more experimental and theoretical investigations are required to explain the mechanism of enhancement of dielectric BD strength of ferrofluids. Secondly, up to now, there is an inadequacy of agreement between the experimental results obtained by various researchers, so it is important to conduct more research about the precise and definite development of ferrofluids and it may be significant to elaborate the discrepancy between experimental results. Thirdly, the agglomeration of nanoparticles is a very critical problem, from both a research perspective and a view of practical applications. This issue can be reduced to a certain extent by the application of surface modifiers on nanoparticles, but still more research work is necessary for the long term stability of ferrofluids. Lastly, the size and shape of magnetic nanoparticles are crucial for characterization of ferrofluids; thus, a modern synthesis approach will also make for interesting research inquiry in the near future.

5. Advantages and Disadvantages of Transformer Oil-Based Ferrofluids

5.1. Advantages of Transformer Oil-Based Ferrofluids

The transformer oil-based ferrofluids possess many performance advantages as compared to transformer oils and are summarized as follows [9–13,21–24,30–33,40–44]:

(i) The transformer oil-based ferrofluids have better AC and impulse breakdown performance as compared to mineral oils, so it is favorable to be used in high voltage alternating current (HVAC) and high voltage direct current (HVDC) applications.
(ii) The AC BD strength of transformer oil-based ferrofluids is less influenced by moisture as compared to mineral oils, so it is helpful in improving insulation life of transformers.
(iii) The transformer oil-based ferrofluids have better partial discharge characteristics, as compared to mineral oil.
(iv) The transformer oil-based ferrofluids have a better anti-aging characteristic, as compared to MO, so it can improve the operational reliability and lifetime of high voltage transformers.
(v) The transformer oil-based ferrofluids have a higher thermal conductivity than the transformer oil and they are more helpful in cooling the transformers.

5.2. Disadvantages of Transformer Oil-Based Ferrofluids

The use of ferrofluids provides a better breakdown performance, partial discharge characteristics, and anti-aging properties than transformer oil [25], but there still are some parameters which limit their use on a large scale in industrial and commercial applications. The application of ferrofluids in industrial application requires long-term stability, low cost availability, and understanding of the brunt of nanomaterials on human health and environment. In this section, an overview of stability of ferrofluids and their impact on human health and the environment is presented [9–13,21–24,30–33,40–44].

(a) Agglomeration of Particles

A ferrofluids is known as theoretically stable if the particle size is smaller than 100 nm [14]. However, it is a big challenge to keep this size due to existence of attractive forces between nanoparticles, which can lead to the agglomeration of nanoparticles. The sedimentation arises in most of the ferrofluids, due to gravity, and the fact that the density of nanoparticles is higher than that of mineral oil, which could lead to a reduction in breakdown voltages.

(b) Human Health Problems

Nanoparticles have been considered as one of the major health and safety hazards for human body. Nanoparticles have been recognized as more dangerous than the micron-sized or bulk materials, due to the high reactivity of their surface area [78]. One way of infiltration of nanoparticles into the human body may be through the nasal cavity [79,80]. The exposure of smaller quantity of nanoparticles is even more vulnerable to the health. For instance, iron oxide is recognized more detrimental for human lungs [81,82]. The nanoparticles, if they invade through the digestive system, may invade the blood stream and accumulate in the liver [83]. The required safety measures should be taken while preparing ferrofluids to abstain from the above mentioned risks.

(c) Higher Cost of Ferrofluids

The higher development cost of ferrofluids is one the reasons hindering their application on commercial and industrial levels. The preparation of magnetite nanoparticles methods and development processes of ferrofluids make them expensive substitutes of transformer oils.

6. Conclusions

In this work, the dielectric strength of transformer oil with and without the suspension of MNPs with different concentrations and sizes of nanoparticles was measured. Moreover, the positive LI BD strength was also measured with different electrode gap distances of needle to sphere geometry. The results manifested the improvement in the breakdown strength of transformer oil after the addition of MNPs into it. Results of positive impulse BDV at various concentrations revealed that at 40% concentration of NPs, the mean LI BDV was 1.36 times as compared to carrier oil and 40% concentration was recognized as the optimum concentration. Volume concentration above this value tends to reduce in positive LI BDV. Results of positive impulse breakdown voltages at different sizes revealed that at 20 nm size of nanoparticles, the mean lighting impulse breakdown voltages were maximum as compared to base oil and that 20 nm is the optimum size of nanoparticles in this study. The results of negative LI BDV of magnetic fluids with various concentrations and sizes were lower than that of the BD strength of host MO. The lightning impulse breakdown voltages at different electrode distances were also measured. It is concluded that the transformer oil suspended with magnetic nanoparticles has manifested good dielectric characteristics; therefore, it may be a good substitute to mineral oil, with suitable volume concentration and size of nanoparticles, in the future.

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