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COMPARATIVE ANALYSIS OF DIELECTRIC STRENGTH AND ELECTRON VELOCITY IN TRANSFORMER OIL BASED NANOFLUIDS

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Abstract

The growth of nanotechnology has elevated the new challenges and research opportunities in the field of high voltage insulation to prepare the colloidal fluid as an alternative of conventional mineral oil being used as an insulation and coolant in power transformers since long decade. A numerous experiment has been performed to investigate the influence of various types of nanoparticles with different volume concentrations, sizes and shapes on conduction and breakdown phenomena in transformer oil based nanofluids when subjected to short duration of impulse voltages. Because of the complexity in developing the mathematical models for nano-dielectric fluids, less effort has been devoted to simulation approach. In this paper, a 2D-axisymmetry drift diffusion model has been developed by coupling the Poisson's equation with drift dominated charge continuity equations to investigate the influence of nanoparticles on streamer development and electron velocity in transformer oil based nanofluids under the impact of an impulse voltage with different polarities. Three different types of nanoparticles, i.e., Fe_3O_4, TiO_2 and Al_2O_3 with equal concentration have been considered in modelling the nanofluids mathematically. The simulation study shows that the promising augmentation has been observed in breakdown voltage when the transformer oil is modified by nanoparticles. The trapping behaviour or the polarization of the dispersed nanoparticles can effectively hinder the acceleration rate of electrons and prevents the further ionization of liquid dielectric. The alteration in breakdown physics in nanofluids when subjected to impulse voltage of different polarities is also discussed in brief.

Keywords: Breakdown voltage, Nanoparticles, Nanofluids, Polarity, Streamer, Transformer oil.

1. Introduction

The reliability and the operating life of any high voltage equipment installed in electrical network rely on the performance of an insulation system. The rapid growth of high voltage network has brought the new challenges to provide an effective insulation for the different equipment coming across the transmission path from generating stations to the load centres [1, 2]. The petroleum oil is being used as a liquid dielectric in high voltage equipment so far. Because of the low dielectric strength and heat transfer characteristic, the existing mineral oil did not meet with the requirements for extra high voltage applications [2]. Hence the growth of the high voltage power network has demanded intensive research and development for improvement of insulating property of the insulations.

The transformer is one of the most important assets in electrical transmission and distribution network that requires the better insulation property to maintain the continuity and reliability of the power supply. The quality and grade of liquid dielectric will determine the operational consistency and the lifecycle of oil filled power transformers [2]. Hence, with the rapid modernization of electrical power transmission network and miniaturization for oil-immersed transformer, the advancement of transformer oil with favourable electrical and thermal stress withstanding characteristics is comprehensively required [2].

Because of the diminishing availability of traditional insulating oil day by day, the researchers belong to dielectric society and the industrial community focus on conducting an extensive research on nano-dielectric liquids as an alternative of mineral oil [3]. In 1995, Choi at National Laboratory of USA has developed a mixture of liquid dielectric by dispersing the nanoparticles which is called as “nanofluid” or “nano liquid” [4]. It has been proven experimentally that the suspended nanoparticles in base fluid will help in augmenting the electrical and heat transfer characteristics of host fluids.

Many researchers in the literature have conducted the experimental analysis on electrical and heat transfer characteristics of transformer oil based nanofluids by suspending the conducting, semi-conducting and dielectric nanoparticles individually. It has been reported that the factors such as nanoparticle type, concentration, size, shape, humidity, magnitude of applied voltage and its polarity, type of applied voltage etc. have great influence on conduction and breakdown process in nano-dielectric fluids.

Yadav et al. [5], have manufactured the transformer oil based nanofluid by dispersing the different volume fraction of Fe_3O_4 nanoparticles to investigate the electrical characteristic. They have found that the dispersed nanoparticles have augmented the dielectric strength of transformer oil by 34%. Fal et al. [6] have performed BDV test on Fe_3O_4 based nanofluid with different volume concentration of nanoparticles as per IEC standard. They have achieved 1.15 times higher voltage than the pure mineral oil to collapse the liquid filled gap.

Some of the researchers investigated the dielectric strength of modified transformer oil by TiO_2 and Al_2O_3 nanoparticles. Wang et al. [7] have prepared three different types of nanofluids using Fe_3O_4, TiO_2 and Al_2O_3 nanoparticles to present the comparative statistics on influence of concentration on insulating properties of transformer oil based nanofluids. They have performed the experiment on all three nanofluids by applied an impulse voltage of positive polarity. Frascella et al.[8] have tried to investigate the impact of TiO_2, ZnO and Fe_3O_4 nanoparticles on streamer dynamics under the application of positive impulse voltage.

The list of the researchers prepared the nanoparticle-based liquid to evaluate the electrical and cooling performance of host fluids after the modification is available in [1]. Due to a lack of theoretical background in understanding the breakdown physics, the nanodielectric liquids still confronting a lot of challenges [8]. Extensive research work has been conducted experimentally to investigate the behaviour of nanofluids when subjected to heavy electrical stresses but less efforts have been devoted in presenting the electrical behaviour of nanofluids numerically. The objectives of this paper are to analyse the influence of polarity on streamer propagation and electron velocity in transformer oil. The studies have been carried out with and without nanoparticles in transformer oil to confirm the level of augmentation achieved in dielectric strength of transformer oil.

This paper is representing the comparative analysis of dielectric strength and electron velocity with three different type of nanofluids prepared by dispersing Fe_3O_4, TiO_2 and Al_2O_3 nanoparticles diluted with equal concentration.

2. Development of Model

Nowadays, in addition with the experimental procedures, the various finite element based commercialized software has been adopted to study the conduction and breakdown processes in high voltage insulations. COMSOL Multiphysics is one of the commercialized software which is being widely used in the field of high voltage insulation as it provides the flexibility to the users for coupling the various physics applicable to achieve the results.

A two-dimensional axisymmetric model with needle-sphere geometry as shown in Fig. 1 have been developed as per ASTM D3300 [9] to analyse the conduction and breakdown phenomena in transformer oil using COMSOL Multiphysics. The distance of separation between two electrodes is 5 mm. The curvature radius of sphere and needle are 6.37 mm and 40 μm, respectively.

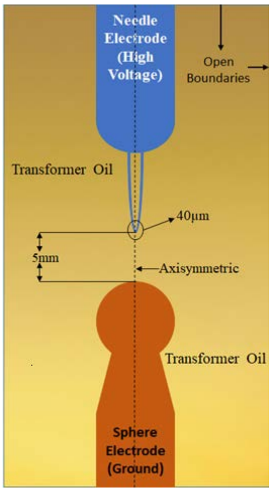


Fig. 1. Needle-Sphere Geometry of simulation in transformer oil.

2.1. Modeling of streamer transmission in transformer oil

The modeling of streamer transmission in transformer oil is essentially required prior to modeling the behaviour of nano-dielectric fluid (NDF). The transition of streamer formation to breakdown in liquid dielectric due to atomic disintegration by the space charges involve the generation, acceleration, and loss of electrons, cations, and anions. To account for these processes, three continuity Eqs. (1)-(3) were coupled with Poisson’s Eq. (4) for developing the hydrodynamic drift-diffusion model [10, 11].

$$\frac{\partial \rho_p}{\partial t} + \nabla \cdot \left(\rho_p \mu_p \vec{E}\right) = G_I\left(\left|\vec{E}\right|\right) + \frac{\rho_p \rho_e R_{pe}}{q} + \frac{\rho_p \rho_n R_{pn}}{q} \tag{1}$$

$$\frac{\partial \rho_n}{\partial t} - \nabla \cdot \left(\rho_n \mu_n \vec{E}\right) = \frac{\rho_e}{\tau_a} - \frac{\rho_p \rho_n R_{pn}}{q} \tag{2}$$

$$\frac{\partial \rho_e}{\partial t} - \nabla \cdot \left(\rho_e \mu_e \vec{E}\right) = -G_I\left(\left|\vec{E}\right|\right) - \frac{\rho_p \rho_e R_{pe}}{q} - \frac{\rho_e}{\tau_a} \tag{3}$$

$$-\nabla \cdot (\epsilon \nabla \varphi) = \rho_p + \rho_n + \rho_e \tag{4}$$

where t is the time, q is the electronic charge, ε is the permittivity, and ρ_p, ρ_n and ρ_e are the density of positive ion, negative ion, and electron respectively in C/m^3. μ_p, μ_n and μ_e are the mobility of positive ions, negative ions, and electrons respectively; φ is the electric potential, $\vec{E}$ the local electric field. R_{pe} and R_{pn} are the ion-ion and ion-electron recombination coefficient respectively and τ_a is the electron attachment time constant.

The generation of lighter free electrons, and heavier positive ions and negative ions are having great connection in interpretation of the streamer dynamics and its processes. The charge density rate source term in Eqs. (1) and (3) can be determined from the Eq. (5).

$$G_I\left(\left|\vec{E}\right|\right) = \frac{q^2 n_0 a \left|\vec{E}\right|}{h} \exp\left(\frac{\pi^2 m^* a (\Delta)^2}{q h^2 \left|\vec{E}\right|}\right) \tag{5}$$

where h is the Planck constant, a is the molecular separation distance, m^* is the effective electron mass and n_0 is the number density of ionizable species. Δ is the liquid phase ionization energy, which is a function of electric field.

Because of the generation of charge carriers, the temperature of the oil increases due to the electrical conduction. The Eq. (6) shows the dissipation of heat due to Joule’s heating.

$$\frac{\partial T}{\partial t} + \vec{v} \cdot \nabla T = \frac{1}{\rho_l C_v} \left(k_T \nabla^2 T + \vec{E} \cdot \vec{J}\right) \tag{6}$$

where,

$$\vec{J} = \left(\rho_p \mu_p - \rho_e \mu_e - \rho_n \mu_n\right) \vec{E} \tag{7}$$

where ρ_l is the oil density, k_T (W/m/K) is the thermal conductivity of the oil, C_v (J/kg/K) is the specific heat, T (K) is the temperature of the oil and v is the velocity (m/s) of the oil, which can be considered negligible.

Table 1 shows the parameters used for mineral oil in the simulation.

Table 1. Parameters of transformer oil [8, 12].

Parameter	Symbol	Value	SI Unit
Ionization Potential	Δ	7.1	eV
Density of ionizable species	n_0	10^{23}	m^{-3}
Intermolecular distance	α	3E-10	m
Electron Charge	q	-1.602E-19	C
Electron Mass	m^*	9.1E-32	kg
Recombination Rates	R_{pe}, R_{pn}	1.645E-17	m^3/s
Mobility of ions	μ_n,μ_p	1E-9	$m^2/V/s$
Electron Mobility	μ_e	1E-4	$m^2/V/s$
Specific heat capacity	C_v	1700	J/kg/K
Density of Oil	ρ_l	880	kg/m^3
Thermal Conductivity	k_T	0.13	W/m/K
Electron attachment TC	τ_a	200	ns
Permittivity	ε	2.2 ε_0	
Planck's Constant	h	6.63E-34	m^2kg/s

The boundary conditions for the simulation are set as following:

- The boundary condition at spherical electrode is set to the zero potential whereas the needle electrode potential is set to DC/double exponential impulse voltage equation.
- The boundary conditions at the electrode surfaces are set to convective fluxes for all the species to represent the charge continuity equations at electrodes.
- The outer boundaries i.e., other than the electrodes are set to zero flux for all species.

2.2. Modeling of streamer transmission in transformer oil based nanofluids

To be able to model the electrodynamics within an electrically stressed transformer oil-based nanofluid it is first necessary to model the charging of the nanoparticles in oil [11]. The effect of attracting electrons to the nanoparticle is called charge. This process takes place until the surface is completely covered with electrons; when this happens, the nanoparticle is saturated and cannot attract more electrons [12]. Once the nanoparticles are saturated with negative charges, the magnitude of saturation charge for nanoparticles can be calculated from Eqs. (8) and (9) [13].

$$Q_{s_{Condcutive}} = -12\pi\varepsilon_1 E_0 R^2 \tag{8}$$

$$Q_{s_{Semiconducting/Insulating}} = -12\pi\varepsilon_1 E_0 R^2 \frac{\varepsilon_2-\varepsilon_1}{2\varepsilon_1+\varepsilon_2} \tag{9}$$

where R is the spherical radius of nanoparticles (5 nm), E_0 is electric field (V/m), ε_1 & ε_2 are the partitivities of base fluid and the nanoparticles, respectively.

Another important factor to be considered with nanofluids prepared by dispersing the nanoparticles is the charge relaxation time constant because of which the conduction and breakdown phenomena gets affected. Shorter the relaxation time, lesser will be the ionization rate as the electrons gets trapped faster and slow down the transmission velocity of the streamer [14]. The charge relaxation time can be calculated from Eq. (10) [4, 12].

$$\tau_r = \frac{2\varepsilon_1+\varepsilon_2}{2\sigma_1+\sigma_2} \tag{10}$$

where, σ_1 and σ_2 are the electrical conductivities of base fluid and nanoparticles.

Table 2 shows the electrical properties and corresponding charge relaxation time for the nanoparticles used in simulation.

Table 2. Electrical properties of nanoparticles [4].

Material	Charge Relaxation Time Constant (s)	Permittivity	Electrical Conductivity (S/m)
Mineral Oil	-	$2.2\varepsilon_0$	1E-12
Fe_3O_4	7.47E-14	$80\varepsilon_0$	1E4
TiO_2	77	$100\varepsilon_0$	1E-11
Al_2O_3	42.5	$10\varepsilon_0$	1E-12

The lighter weight and high velocity of electrons compared to the ions in a dielectric, they will capture or trap by the dispersed nanoparticles faster. The mobility or the movement of the nanoparticles in the oil is given as [14]:

$$\mu_{np} = \frac{|Q_s|}{6\pi\eta R} \tag{11}$$

where kinetic viscosity (η) of transformer oil is 0.02 Pa·s.

To investigate the streamer dynamics in transformer oil based nanofluids under the presence of nanoparticles, the charge carrier continuity and Poisson's equations needs to be modified to include the influence of nanoparticles. The following equations represents the modelling of nanofluids for the streamer progression [12, 14].

$$\frac{\partial\rho_p}{\partial t} + \nabla\cdot\left(\rho_p\mu_p\vec{E}\right) = G_I\left(\left|\vec{E}\right|\right) + \frac{\rho_p\rho_e R_{pe}}{q} + \frac{\rho_p(\rho_n+\rho_{np})R_{pn}}{q} \tag{12}$$

$$\frac{\partial\rho_e}{\partial t} - \nabla\cdot\left(\rho_e\mu_e\vec{E}\right) = -G_I\left(\left|\vec{E}\right|\right) - \frac{\rho_p\rho_e R_{pe}}{q} - \frac{\rho_e}{\tau_a} - \frac{\rho_e}{\tau_{np}}\left(1 - H\left(\rho_{npsat} - \rho_{np}\right)\right) \tag{13}$$

$$\frac{\partial\rho_n}{\partial t} - \nabla\cdot\left(\rho_n\mu_n\vec{E}\right) = \frac{\rho_e}{\tau_a} - \frac{\rho_p\rho_n R_{pn}}{q} \tag{14}$$

$$\frac{\partial\rho_{np}}{\partial t} - \nabla\cdot\left(\rho_{np}\mu_{np}\vec{E}\right) = \frac{\rho_e}{\tau_{np}}\left(1 - H\left(\rho_{npsat} - \rho_{np}\right)\right) - \frac{\rho_p\rho_{np}R_{pn}}{q} \tag{15}$$

$$\nabla\cdot\left(\varepsilon_0\varepsilon_r\vec{E}\right) = \rho_p + \rho_n + \rho_e + \rho_{np} \tag{16}$$

$$\frac{\partial T}{\partial t} + \vec{v}\cdot\nabla T = \frac{1}{\rho_l c_v}\left(k_T\nabla^2 T + \vec{E}\cdot\vec{J}\right) \tag{17}$$

The function $H(x)$ in Eqs. (13) and (15) is the Heaviside unit step function which is defined as:

$$H(x) = \begin{cases} 0 & x \le 0 \\ 1 & x > 0 \end{cases} \tag{18}$$

The permittivity, thermal conductivity, specific heat capacity and density of nanofluid can be found from following equations. For determining the relative permittivity of NDFs, the Maxwell-Garnett equation can be used [15].

$$\varepsilon_{NDF} = \varepsilon_{bf} + 3\left(\frac{a}{b}\right) \tag{19}$$

where, $a = \varphi_{NP}\varepsilon_{bf}(\varepsilon_{NP} - \varepsilon_{bf})$ and $b = \varepsilon_{NP} + 2\varepsilon_{bf} - \varphi_{NP}(\varepsilon_{NP} - \varepsilon_{bf})$, ε_{bf} is the permittivity of a base fluid, ε_{NP} is the permittivity of the nanoparticles and φ is the volume concentration of the nanoparticles in the host fluid. The volume concentration can be computed by [16]:

$$\varphi_{NP} = \frac{w_{NP}/\rho_{NP}}{w_{NP}/\rho_{NP} + w_{oil}/\rho_{oil}} \times 100\% \tag{20}$$

where, w_{NP} and w_{oil} are the weights of nanoparticles and oil respectively whereas ρ_{NP} and ρ_{oil} are the densities of nanoparticles and oil, respectively.

The thermal conductivity, density, and specific heat capacity of the NDFs can be calculated from Table 3.

Table 3. Equations to model the thermal properties of nanofluids [10, 17].

Property	Equation
Thermal Conductivity	$\frac{k_{nf}}{k_f} = \frac{k_{NP} + 2k_f - 2\varphi(k_f - k_{NP})}{k_{NP} + 2k_f + \varphi(k_f - k_{NP})}$
Density	$\rho_{NF} = (1 - \varphi)\rho_f + \varphi\rho_{NP}$
Specific Heat Capacity	$C_{P_{NF}} = (1 - \varphi)C_{P_f} + \varphi C_{P_{NP}}$

3. Results and Discussions

The gap length applied impulse voltage (its magnitude, duration, and polarity), electrode field configuration and its geometry, nanoparticles (type, shape, size, concentration, electrical and thermophysical properties) are the key factors of altering the conduction and breakdown phenomena in any given nano-dielectric fluids.

In the transformer oil without nanoparticles, when the heavy electrical stress is applied, the primary electrons are dislodging from the high voltage stressed electrode due to elimination of its work function and accelerated towards the opposite electrode. During travelling it will collide with the neutral molecules of the mineral oil and successively produce the positive ions and free electrons. This process is known as ionization by collision. The process is being continue until the enough number of electrons are produced due to primary and secondary ionization processes responsible for the initiation and progression of streamer in transformer oil that may lead to breakdown of insulation liquid. The ionization source term in Eq. (5) models the generation of the charge careers due to electric field dependent molecular ionization process in transformer oil when subjected to heavy electrical stress.

The dispersion of nanoparticles in transformer oil will hinder the successive growth of electron avalanche in transformer oil by absorbing the free electrons produced due to ionization by collisions or by the polarization. The process by which the nanoparticles can absorb the electrons from the ionized space is known as charging of nanoparticles. The nanoparticles can trap the electrons to convert them in slow negative charge until they get saturated. The saturation charge for the nanoparticles can be determined from Eqs. (8) and (9). The mechanism of delaying the streamer progression and hence the breakdown will depend upon the type of the nanoparticles dispersed.

This paper will give the comparative analysis over the dielectric strength and electron velocity with and without nanoparticles in transformer oil. Three different types of nanoparticles, i.e., Al_2O_3, Fe_3O_4 and TiO_2 with equal concentration (4%) have been used to prepare the mathematical model of nanofluid to investigate the impact on electron velocity in a dielectric using COMSOL Multiphysics software.

To investigate the streamer dynamics and electron velocity in with and without nanoparticles in transformer oil, a double exponential voltage expressed in Eq. (21) with positive and negative polarities is applied across the needle-sphere electrodes [18].

$$V(t) = V_o \left[e^{\frac{-t}{\tau_2}} - e^{\frac{-t}{\tau_1}} \right] \tag{21}$$

with, $\tau_2 = \frac{T_t}{\ln (2)}, \tau_1 = \frac{T_f}{5}, V_o = V_m e^{\left(\frac{T_f}{1.443 T_t}\right)}$

where T_f is the time in µs at which the impulse voltage wave attains the peak magnitude and T_t is the time in μs at which the wave attains 50% of peak magnitude.

3.1. Breakdown in a pure transformer oil

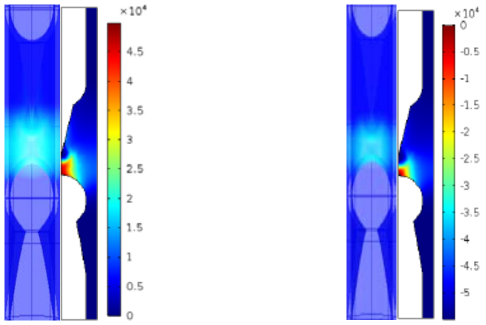
The conduction and breakdown mechanism in liquid dielectrics are quite complicated than the gaseous and solid insulations. The ionization by collision, photoionization, secondary ionization processes and the ionization due to metastable atoms are the basic phenomena behind the occurrence of the conduction that led to sparkover in given dielectrics.

When the transformer oil is subjected to the heavy electrical field stress, the electrons are injected out from the positively stressed electrode due to the elimination of the work function of the metal. These electrons gain the kinetic energy from the applied field and accelerated towards the target electrode. During their travelling towards the opposite electrode, they will collide with the neutral molecules of the transformer oil and releases the more electrons and positive ions when the electrons' kinetic energy is more than the ionization potential required to trap the electron by the neutral molecule is higher. This process is called as ionization by collision and depicted by Eq. (22).

$$AB^+ + e^- \xrightarrow{K.E>V_i} A^+ + e^- + e^- \tag{22}$$

To simulate the liberation of the space charges in pure transformer oil due to molecular ionization and the arc initiation and its propagation, the conduction-convection based drift dominated charge carrier continuity equations (Eqs. (1)-(3)) have been implemented. The Eqs. (1)-(3) determines the concentration and velocity of the emitted positive ions, negative ions, and free electrons due to molecular field ionization of pure transformer oil under the application of heavy electrical stress. The produced positive ions which are left behind the free electrons due to their heavier mass will further produces the additional positive and negative charges due to secondary ionization. Few of the electrons are captured by the ions and forms the negative ions due to electronegative ingredients present in transformer oil. Due to the cumulative ionization a greater number of positive and negative space charges are produced. The positive ions are accumulated across the positively stressed electrode and extend its diameter virtually. This will cause in subsequent reduction of the gap length. Presence of more electrons extensively strengthen the electric field at the head of the streamer and hence increases the velocity of the streamer between the successive collisions. Hence, the breakdown will take place at relatively less voltage and less time.

The conduction process observed in the pure transformer oil is different due to the space charge behaviour when stressed with negative polarity. The positive ions produced by the ionization will act as the potential well which traps or restricts the motion of the electrons. This will reduce the electric field strength at the head of the streamer and also the kinetic energy of the electron until the electric field is strengthen by applying the higher voltage to eliminate the potential well created by the positive space charges. Hence the voltage required to cause the flashover in pure transformer oil is more with negative polarity than the positive voltage. As shown in Fig. 2, the breakdown of pure transformer oil take place at relatively less voltage (+50 kV) when positive impulse of nanosecond rise time was applied. The voltage required to initiate the sparkover with negative impulse voltage is 55 kV which is higher than the positive breakdown voltage value. The colour legend in Fig. 2 shows the distribution of potential across the gap. Furthermore, it has also been observed that the time taken by the streamer to approach the target electrode for the breakdown are 7 ns and 20 ns for positive and negative polarities, respectively.



(a) +50 kV. **(b) -55 kV.**

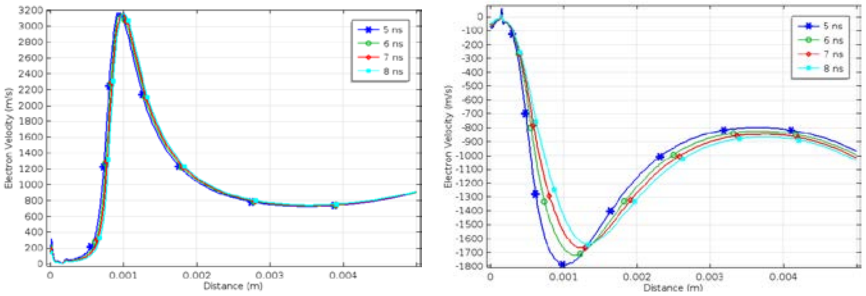
Fig. 2. Potential distribution and streamer propagation in pure TO.

To compare the impact of polarity on electron velocity to confirm the change in breakdown voltage requirement, the same voltage with different polarities was applied. Figures 3(a) and 3(b) show that the velocity with which the electrons are accelerating in the liquid filled gap at different polarities.

From the electron velocity plot, it has been observed that the electrons are accelerated with an average velocity of 3.2 km/s and 1.8 km/s for positive and negative polarities, respectively. The term (μE) of ($\rho * \mu E$) in governing equations Eqs. (1)-(3) and Eqs. (12)-(15) determines the drift velocity of free electrons and heavy ions. The drift velocity of the electrons can be determined by Eq. (23).

$$v = \mu_e \vec{E} \tag{23}$$

where, v is the drift velocity of electrons, μe is the electron's mobility and $\vec{E}$ is the electric field.



(a) +ve polarity. **(b) –ve polarity.**

Fig. 3. Velocity of electrons in pure TO when 50 kV impulse is applied.

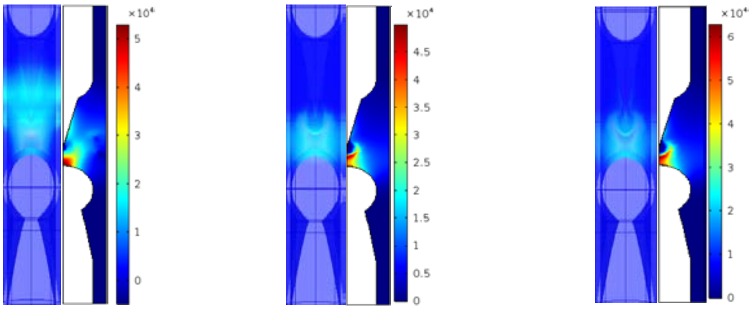
3.2. Breakdown in a transformer oil based nanofluids

The conductivity and the permittivity of the nanoparticles plays a vital role in changing the conduction and breakdown physics in transformer oil modified with nanoparticles. Hence, the classical theory responsible for the breakdown of pure oil is not truly applicable to explain the failure mechanism of the transformer oil based nanofluids. The simulation results show that the nanoparticles effectively change the activities of the space charges and help in augmenting the dielectric strength of transformer oil. It has been reported that the augmentation achieved in dielectric strength is due to very low charge relaxation time constant and polarization of nanoparticles [14].

Numerous investigators have examined that the charged surface of the nanoparticles can trap and discharge the electrons frequently. This charging and discharging process converts the fast-accelerating electrons into slow moving ions and obstruct the streamer transmission [14]. For simulating the impact of polarity on streamer propagation, breakdown voltage and electron velocity, Fe_3O_4, TiO_2 and Al_2O_3 based transformer oil have considered. To represent the impact of nanoparticles on generation of electrons, positive ions, and negative ions and hence on electron propagation, the conduction-convection based drift dominated charge carrier continuity Eqs. (12)-(15) have been implemented. The Heaviside step function in Eqs. (12)-(15) puts a limit for the nanoparticle's charging to include the effect of nanoparticle over the ionization.

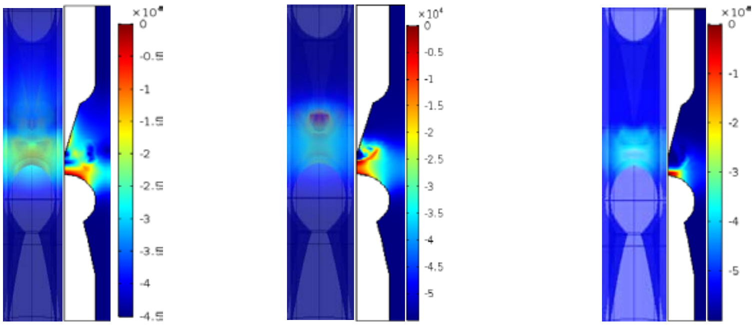
The electrical properties of the nanoparticles are shown in Table 2. Figures 4 and 5 show the propagation of streamer and potential distribution in three nanodielectric fluids under the impact of positive and negative impulse voltages. Table 4 shows the results of breakdown voltage and the electron/streamer velocity in transformer oil with and without nanoparticles at different polarities of applied impulse voltage.

The analysed values depicted that the streamer would take more time to initiate the flashover in nanodielectric fluid compared to pure mineral oil when positive impulse voltage was being applied. Because of slowing down the electron acceleration, the breakdown will take place at higher voltage in nanodielectric fluid compared to pure mineral oil. The dielectric strength of mineral oil modified by Al_2O_3 nanoparticles was found to be higher compared to Fe_3O_4 and TiO_2 based nanofluids in both polarities. Hence it has been proven that the modifying the pure oil by dispersing the nanoparticles can enhance the electrical properties of transformer oil.



(a) Fe_3O_4 based NDF. **(b) TiO_2 based NDF.** **(c) Al_2O_3 based NDF.**

Fig. 4. Potential distribution and streamer propagation in NDF under positive impulse voltages at (a) 10 ns, (b) 15 ns and (c) 25 ns.



(a) Fe_3O_4 based NDF. **(b) TiO_2 based NDF.** **(c) Al_2O_3 based NDF.**

Fig. 5 Potential distribution and streamer propagation in NDF under negative impulse voltage at (a) 7 ns, (b) 20 ns and (c) 20 ns.

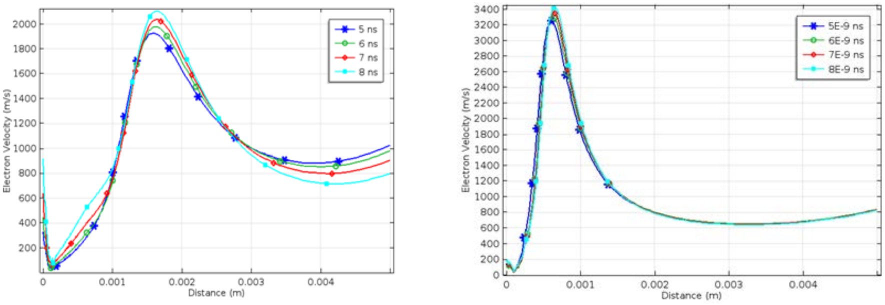
Table 4. Breakdown voltage and streamer velocity.

Sample	Impulse Breakdown Voltage (kV)		Velocity (km/s)	
	+Ve	-Ve	+Ve	-Ve
Pure oil	50	55	3.2	1.8
Fe_3O_4 based NDF	53	45	2.1	2.8
TiO_2 based NDF	50	55	3.2	2.0
Al_2O_3 based NDF	63	60	2.6	2.7

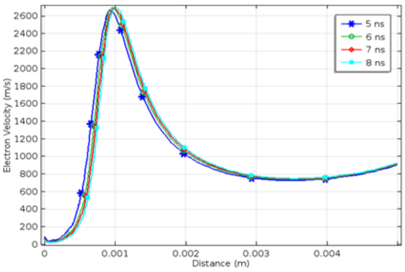
Figures 6 and 7 show the velocity with which the electrons are travelling in nanodielectric fluids at different polarities. Comparison between Figs. 3 and 6 depicts that the electrons are accelerated with comparatively lower speed than the velocity observed in pure oil when positive impulse voltage was applied. The slowing down the electron velocity and hence augmentation of dielectric strength is attributed to the trapping/de-trapping mechanism or polarization of nanoparticles.

The electrical conductivity of Fe_3O_4 nanoparticles is 1E4 S/m that is very high compared to the electrical conductivities TiO_2 and Al_2O_3. The charge relaxation time (Eq. (10)) which indicates that how fast the electrons can absorb from the ionized fluid is inversely proportional to the electrical conductivity. Hence higher the conductivity, lower will be the electron absorption time. The time taken by the Fe_3O_4 nanoparticle is calculated as 7.47E-14 seconds from Eq. (10) which is very small than the streamer propagation time. As an effect, the Fe_3O_4 nanoparticles can trap/absorb the electrons rapidly from the ionized dielectric liquid compared to the nano-dielectric fluids made up of the nanoparticles having less value of electrical conductivity.

Once the electrons are being absorbed or trapped by Fe_3O_4 nanoparticles dispersed in transformer oil by its charged surface, it will convert the rapidly moving electrons into slow moving negative charges. The simulation result in Fig. 6 shows that the electrons are moving with an average velocity of 2 km/s when the transformer oil modified with Fe_3O_4 nanoparticles that is small compared to the velocity of electrons observed in pure transformer oil when positive polarity impulse voltage was being applied. Because of the less speed of electrons, the ionization condition to dislodge the electron from the neutral atom of the liquid is not satisfied. Furthermore, the trapping of electrons will result in production of heavier negative ions. This will further result in reduction of current density (shown in Fig. 8) due to free electrons in liquid dielectric and prevent the successive ionization that can lead to flashover. The term $\rho\mu\vec{E}$ in governing Eqs. (1)-(3) and Eqs. (12)-(15) determines the current density in A/m^2. Where, ρ is the density (C/m^3), μ is the mobility (m^2/(V*s)) and $\vec{E}$ electric field intensity (V/m).



(a) Fe_3O_4 based NDF **(b) TiO_2 based NF**



(c) Al_2O_3 based NDF

Fig. 6. Electron velocity in transformer oil and modified transformer oil with NPs at +50 kV impulse voltage.

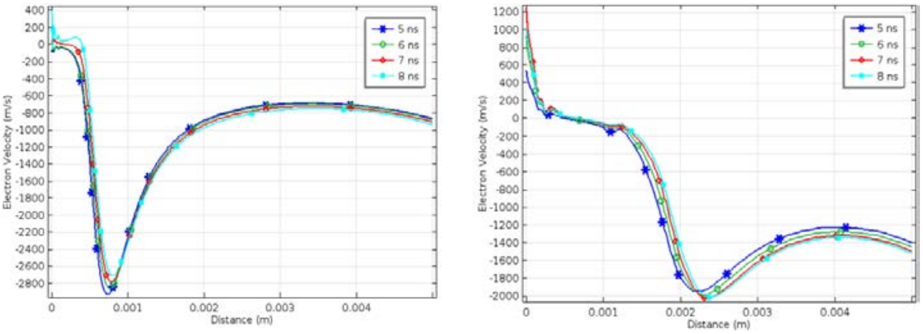
Because of larger relaxation time constants with semi-conducting and insulating nanoparticles, the electron trapping/de-trapping phenomena was failed to explain the augmentation in dielectric strength as seen in highly conducting nanoparticles. Because of the larger time, the Al_2O3 and TiO_2 nanoparticles do not have the enough time to accumulate the charges on their surfaces when exposed to heavy electric field but they will tend to polarize. This polarization will allow to create the potential wells that will trap the fast-moving electrons and reduces their speed.

It can be seen in Fig. 6 that the average velocities of electrons in Al_2O_3 and TiO_2 nanofluid were found to be 2.6 km/s and 3.4 km/s respectively when exposed to positive impulse voltage. It has been further noticed that the streamer is progressing in nanofluid prepared by dispersing TiO_2 nanoparticles is very close to the velocity of the streamer observed in pure mineral oil. Hence, no change is observed in breakdown voltage magnitudes between TiO_2 based nanofluid and pure mineral oil. This is attributed to the large value of charge relaxation time with semiconducting TiO_2 based nanofluid.

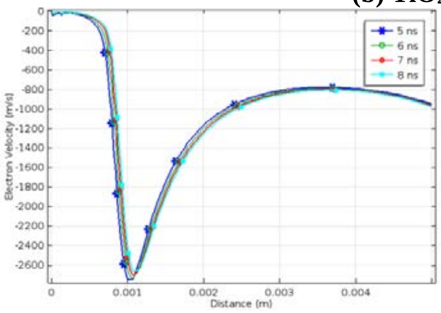
Hence to dislodge the electrons from the neutral molecules to satisfy the breakdown condition, it will need high potential to be apply with positive polarity. The promising enhancement has been observed in breakdown voltage for nanofluids compared to pure mineral oil when the positive impulse voltage was being applied. The magnitude of the voltage being required to cause the complete discharge and hence the breakdown are listed in Table 4. The contradiction has been observed when an impulse voltage with negative polarity was being applied. The breakdown voltage is reduced with Fe_3O_4 and Al_2O_3 based nanofluids compared to pure mineral oil and TiO_2 based nanofluid. When the negative impulse is applied to the nanofluids, a small portion of the positive ions produced by field ionization are neutralized after reaching to the stressed electrode.

The remaining parts of positive ions are retained at negative electrode. Furthermore, a large number of negatively charged nanoparticles also remain close to negatively charged electrode. These will weaken the electric field at the needle electrode and strengthen the field at opposite electrode. The electrons and hence the streamer is progressing with comparatively higher speed due to weakening of the electric field.

Figure 7 depicts that the velocity of the electrons and hence the streamer under the influence of negative impulse voltage in Fe_3O_4 and Al_2O_3 nanoparticles is 2.8 km/s and 2.6 km/s, respectively. Because of this reason the breakdown of Fe_3O_4 and Al_2O_3 based nanofluids takes place at reduced voltages compared to when positive impulse voltage was being applied (shown in Table 4). Whereas the breakdown voltage for TiO_2 based nanofluid was observed higher than the positive breakdown voltage value.

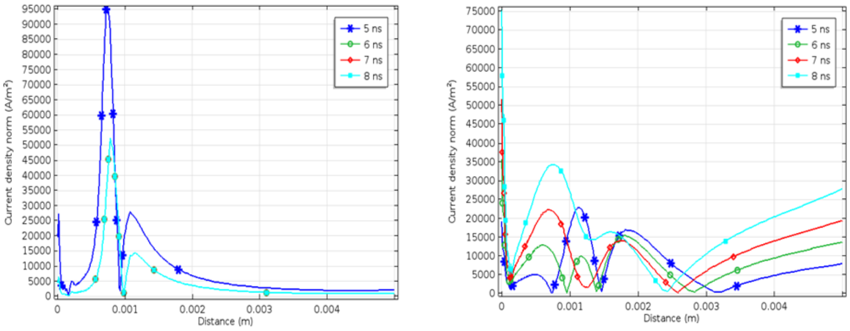


(a) Fe_3O4 based NF **(b) TiO_2 based NF**



(c) Al_2O_3 based NF

Fig. 7. Electron velocity in transformer oil and modified transformer oil with NPs at -50 kV impulse voltage.



(a) Pure MO **(b) Fe_3O_4 based NDF**

Fig. 8. Current density plot under positive impulse voltage.

4. Conclusions

The following conclusions have been derived from the simulation study.

- The breakdown voltage for pure transformer oil under positive and negative impulse voltages are found to be +50 kV and -55 kV, respectively. Whereas the velocity of the electrons in pure transformer oil at ±50 kV was observed to be 3.2 km/s and 1.8 km/s respectively for positive and negative impulse polarity. It has been noticed that the breakdown voltage with negative polarity in a pure transformer oil is found to be higher than the positive breakdown voltage value. The accumulation of the positive ions over the surface of positively stressed electrode causes the virtual reduction of gap length and hence increase the probability of the breakdown at lower voltage stress. Contradictory, the protecting shield produced by the net positive ions during negative polarity hinders the acceleration of the electrons and thus reduces the rate of ionization effectively.
- The positive breakdown voltage for Fe_3O_4, Al_2O_3 and TiO_2 based nanofluids are 53 kV, 63 kV and 50 kV, respectively. However, the negative breakdown voltages are 45 kV, 60 kV and 55 kV, respectively. At positive polarity, the electrons are accelerated in ionized nanofluid with a velocity of 2.1 km/s, 2.6 km/s and 3.2 km/s, respectively. But the acceleration of electrons at negative polarity in nanofluids are 2.8 km/s, 2.7 km/s and 2.0 km/s, respectively.
- The positive impulse breakdown voltage values of Fe_3O_4 and Al_2O_3 based nanofluids are found to be higher than the mineral oil. The augmentation observed in positive impulse voltage application is attributed to trapping/de-trapping phenomena and polarization of nanoparticles.
- The deposition of the negatively charged particles and un-neutralized positive ions close to the negatively stressed electrode weakens the electric field and enhances it at the opposite electrode and hence the streamer is accelerating at faster rate compared to the average velocity observed when positive impulse voltage was applied. This will reduce the dielectric strength and increase the velocity of the electrons when negative impulse voltage is being applied.
- The electrons and hence the electric field wave is propagating in Fe_3O_4 and Al_2O_3 based nanofluids is comparatively lower than the velocity observed in pure transformer oil when subjected to the positive impulse voltage. On the

other side, the electrons are travelling faster in conducting and insulating nanofluids compared to the pure transformer oil under the impulse voltage of negative polarity. Whereas no change in velocities have been noticed between TiO_2 based nanofluid and mineral oil at different polarities.

- The breakdown voltage and electron velocity for pure transformer oil and TiO2 based nanofluid are found to be same. This is because of the lower concentration of TiO2 nanoparticles. The augmentation in dielectric strength can be observed at higher concentration of TiO_2 nanoparticles.
- The conductivity and permittivity of nanoparticles plays a dominant role in changing the conduction and breakdown physics in transformer oil when subjected to high voltages. The conducting nanoparticles (Fe_3O_4) with high electrical conductivity offers extremely low relaxation time constant (7.47E-14 s) to trap the fast-moving electrons in successive ionization than the streamer propagation time. This trapping mechanism will allow in reducing the effective acceleration of electron which hinders the further ionization of liquid dielectric.
- Because of the high relaxation time constants than the streamer propagation time due to higher electrical conductivities, semi-conducting (TiO_2) and insulating (Al_2O_3) nanoparticles tends to be polarized when subjected to heavy electrical fields. The polarization of the nanoparticles produces the potential well over the surface of nanoparticles that can trap the electrons and reduces the electron velocity lower than the ionization potential of neutral molecule of nanofluid and thus hinders the further ionization.

References

1. Bhatt, M.; and Bhatt, P. (2019). A review on electrical characteristics of nanofluid based transformer oil. *Indian Journal of Science and Technology*, 27(12), 1-20.
2. Sumathi, S.; and Rajesh, R. (2020). Improvement on the characteristics of transformer oil using nanofluids. *Current Science*, 118(1), 29-33.
3. Danikas, M.G. (2018). Breakdown in nanofluids: A short review on experimental results and related mechanisms. *Engineering, Technology & Applied Science Research*, 8(5), 3300-3309.
4. Muhammad, R.; Yuzhen, L.; and Chengrong, L. (2016). A review on properties, opportunities, and challenges of transformer oil-based nanofluids. *Journal of Nanomaterials*, 2016, 1-23.
5. Yadav, N.; Jarial, R.; and Rao, U. (2018). Characterization of mineral oil based Fe_3O_4 nanofluid for application in oil filled transformers. *International Journal on Electrical Engineering and Informatics*, 10(2), 338-349.
6. Fal, J.; Mahian, O.; and Zyla, G. (2018). Nanofluids in the service of high voltage transformers: Breakdown properties of transformer oils with nanoparticles, a review. *Energies*, 11(11:2942), 1-46.
7. Wang, Q.; Muhammad, R.; Yuzhen, L.; Chengrong, L.; and Kai, Y. (2015). Preparation of three types of transformer oil-based nanofluids and comparative study on the effect of nanoparticle concentrations on insulating property of transformer oil. *Journal of Nanotechnology*, 2016, 1-6.

8. Frascella, R.; Velasco, J.; Albarracin, R.; and Primo, V.A. (2018). Positive streamer simulation in nanodielectric fluids with Comsol Multiphysics, *IEEE 2nd International Conference on Dielectrics (ICD)*. Budapest, Hungary, 1-4.
9. Standard test method for dielectric breakdown voltage of insulating oils of petroleum origin under impulse conditions, ASTM D3300 – 00, 2000.
10. Zhang, Y.; Ho, S.; and Fu, W. (2018). Heat transfer comparison of nanofluid filled transformer and traditional oil-immersed transformer. *AIP Advances*, 8(056724), 1-5.
11. Hwang, J.G.; O'Sullivan, F.; Zahn, M.; Hjortstam, O.; Pettersson, L.; and Liu, R. (2008). Modelling of streamer propagation in transformer oil based nanofluids. *Annual Report Conference on Electrical Insulation and Dielectric Phenomena*. Quebec, Canada, 361-366.
12. Velasco, J.; Frascella, R.; Albarracin, R.; Burgos, J.C.; Dong, M.; Ren, M.; and Yang, L. (2018). Comparison of positive streamers in liquid dielectrics with and without nanoparticles simulated with finite-element software. *Energies*, 11(361), 1-16.
13. Thabet, A.; Allam, M.; and Shaaban, S. (2019). Slowing positive streamer propagation in silicon and ester transformer oil using multi-nanoparticles technique. *International Journal of Applied Energy System*, 1(1), 15-20.
14. Hwang, J.G. (2010). *Elucidating the mechanisms behind pre-breakdown phenomena in transformer oil systems*. PhD Thesis, Massachusetts Institute of Technology, United States.
15. Rodriguez-Serna, J.M.; Albarracin-Sanchez, R.; Velasco, J.; Frascella, R.; and Primo, V.A. (2019). Streamer simulation in nano-based dielectric fluids at different Fe3O4 nanoparticle concentration. *IEEE 20th International Conference on Dielectric Liquids (ICDL)*, Roma, Italy, 1-4.
16. Yao, W.; Huang, Z.; Li, J.; Wu, L.; and Xiang, C. (2018). Enhanced electrical insulation and heat transfer performance of vegetable oil based nanofluids. *Journal of Nanomaterials*, 2018, 1-12.
17. Nawaz, M.; and Nazir, U. (2019). An enhancement in thermal performance of partially ionized fluid due to hybrid nanostructures exposed to magnetic field. *AIP Advances*, 9(085024), 1-9.
18. Lee, H.; and Lee, S. (2011). Hydrodynamic modelling of discharge analysis in a dielectric medium with the finite element method under lightning impulse. *Journal of Electrical Engineering and Technology*, 6(3), 397-401.