Streaming Electrification of Different Insulating Fluids

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The comparison of different techniques used to assess the charging tendency of fluids is discussed depending on the flow type (planar or centrifugal), volume of oil, and interface material. The charge separation between the insulating fluid and metallic/pressboard interfaces is explained in terms of the electrical double layer formation involving a fixed layer and diffuse layer. Based on the experimental results, the streaming electrification is observed to be a function of various factors such as speed, temperature, electric field, and surface roughness. Depending on the molecular structure of insulating liquids that come into contact with solid insulation at the interface, the streaming current can increase; hence, a suitable additive (benzotriazole, fullerene, Irgamet 39) is selected based on the type of fluid and charge polarity. The degradation of the insulating liquid upon ageing, which increases the streaming current and reclamation of such aged fluids using adsorbents (Fuller's earth, activated carbon, bentonite, and alumina), is a possible method to suppress the static current through improving its dielectric properties. The nanofluids show a higher streaming current compared to base fluid with no change observed even after the reclamation process.

power transformers insulation diagnostics dielectric liquids streaming current flow pattern double layer interfacial zone additives electric field reclamation sulfur

1. Introduction

The most crucial part of the transmission system is the power transformer, and reliable functioning of the electricity supply depends on the insulation lifetime [1]. The distinct insulation types use different types of materials (solid, liquid, and gas) either alone or in combination and thus are categorized as the dry type and gas- and liquid-filled transformers [2]. Among the different types of transformers, the liquid-immersed transformers are used for higher-power-rating transformers in which the insulating liquid functions as a coolant and is combined with cellulosic paper and pressboard material to hold the winding conductors [3]. The cellulosic paper/pressboard insulation is manufactured from wood fibers using the kraft chemical reactions to serve as spacers and provide mechanical protection from the copper conductors [4]. They are mostly made up of a cellulosic polymer and are linked to one another with glycosidic units based on the degree of polymerisation. The dielectric characteristics of insulation (solid and liquid) in the transformer should be continuously inspected because they deteriorate over a longer time of operation. Generally, the insulating liquid is recycled after sludge formation using adsorbents [5], whereas the pressboard insulation is completely replaced.

Static electrification is a key issue that is noticed in liquid-immersed power transformers, with the first case study reported in Japan [6] describing a higher power risk as a result of this phenomenon. An internal flashover may be caused by the forced oil convection employed for the heat transfer, which poses a fire hazard [7]. The pressboard material's surface potential may increase due to surface charge accumulation caused by the oil circulation inside the transformer, which could eventually result in incipient discharges after a prolonged period of time. There are various insulating liquids that have been applied in power transformers from the early stage. The non-flammability of askarels composed of polychlorinated biphenyls (PCBs) allowed them to be used as the liquid inside transformers during the early 1970s. They were typically biphenyl molecules with chlorine atoms replacing the hydrogen atom [8]. The disposal of PCBs into the environment results in soil attachment, contamination of water, and sedimentation that can persist for more years. A common method of trash disposal is the incineration process, which poses a severe health concern by producing dangerous substances such as polychlorinated dibenzofurans; hence, PCBs were eventually banned in 1979 in transformers and other appliances [9]. So, researchers considered using silicon fluid as an insulating medium due to the drawbacks of PCBs as a dielectric medium in transformers. Polydimethylsiloxane (silicon fluid), a sort of synthetic liquid with a good thermal stability, was used successfully in power transformers. Its viscosity is determined by the existence of a methyl group in its chemical structure [10]; during the partial discharge of the silicon fluid, it resulted in a polymerization reaction in which a gelatinous substance was observed to develop on the electrodes. This issue, which limited its use considerably to operating at less than the inception voltage [11], must be taken into account during a transformer's early design stage. Transformer manufacturers began utilizing mineral oils refined with hydrocarbons instead of PCBs and silicon liquid.

Mineral oils are categorized into paraffinic and naphthenic based on the nature of their extraction from crude oil. Owing to the lower oxidation stability associated with paraffinic oils on transformer windings, cooling channels restrict the process of heat transfer with a higher probability of sludge formation. Conversely, naphthenic oil's stronger oxidative stability limits the production of sludges, which increases a transformer's lifespan, and its reduced viscosity enhances the cooling performance [12]. The corrosive sulfur compounds present in mineral oil can cause the insulation to deteriorate and lead to serious transformer failures over time. The mineral oil typically contains compounds with a sulfur backbone that are not corrosive in nature but can draw in free radicals during the oxidation process to produce peroxide [13]. Additionally, mineral oil's lower flash point gives it a higher possibility of fire risks in power transformers; in addition, due to its poor biodegradability, researchers are now considering other dielectric fluids [14]. Prior to actually adopting new insulating fluids in transformers, insulation engineers must concentrate on the design characteristics of the liquid and evaluate how well it performs under various electrical, thermal, and chemical stresses along with the hydrolysis and oxidation reactions that occur primarily during a transformer's operation [15][16].

The National Electrical Code (NFPA 70) specifies that the thermal class of ester fluids makes them a practical alternative substitute for deployment in densely populated areas or commercial establishments. Ester fluid is recommended for non-breathing transformers due to its higher hygroscopicity than that of mineral oil, which causes it to combine with the surrounding atmosphere, thus requiring additional handling and storage precautions [17]. Additional design enhancements should also be undertaken to assure that ester fluids inside a transformer perform effectively while considering its increased necessity for voltages greater than 100 kV [18], thus providing a suitable alternative for transformer insulation due to its improved fire safety and biodegradability [19]. Ester fluid, which has the aforementioned benefits over the conventional insulating liquids, can be used for transmission lines up to 400 kV while taking into consideration the overall cost of installation of the transformer.

Based on their origin and suitability for transformer applications, ester fluids are categorized into two types (natural and synthetic esters). In contrast to synthetic esters, which belong to a family of polyol esters and contain pentaerythritol tetra ester, natural esters contain a glycerol backbone and a variety of fatty acid groups that may be saturated, monounsaturated, or polyunsaturated [20]. The resistance of ester fluids to oxidation and their viscous properties are determined by the ratio of saturated fatty acids to unsaturated fatty acids [21]. Therefore, to meet the rising need for high-voltage insulation systems, the development of insulating fluids with outstanding thermal and dielectric properties is often desired [22]. After being introduced in the early 1990s, nanotechnology has drawn widespread interest in its development. When the nanomaterials were first tested on solid polymers, it was discovered that they offered improved dielectric performance; subsequently, a similar method was applied to liquid insulation in transformers. The higher interfacial area created by nanoparticles with the insulating fluids resulted in an increased dielectric performance; this unique property associated with nanoparticles has led to their application in the power sector for AC and DC power transmission systems. Among the different methods [23][24] used for the dispersion of suitable nanoparticles in insulating fluids, a two-step method is typically used due to its lower cost and easier deployment at the lab scale. Du et al. [25] tested the breakdown voltage of mineral oil with the addition of TiO_2 nanoparticles and inferred a higher magnitude in its breakdown value due to a reduction in the distortion of the electric field caused by moisture content. Fontes et al. [26] examined transformer oil with carbon nanotubes and diamond nanoparticles and observed increases of about 27% and 23% in its thermal conductivity. The addition of ZnO nanoparticles to transformer oil [27] resulted in an increase in the permittivity at a lower concentration. Vegetable oils were altered using different sizes of Fe_3O_4 nanoparticles [28] and a significant increase was observed in the electric potential well for the nanofluids. Raj et al. [29] studied the dielectric properties of ester fluid upon the addition of Al_2O_3 nanoparticles and inferred a higher survival percentage and breakdown voltage of 80% and 64%, respectively. Thus, it is required to understand the electrostatic charging tendency (ECT) associated with different insulating fluids used nowadays for their application in power transformers.

The failure involved in power transformers due to static electrification is not an instantaneous phenomenon because such static charges that accumulate on the pressboard spacers can only lead to surface tracking and puncturing of the transformer insulation after a long time. In addition, because this phenomenon is a complex multivariable problem, there are no exact statistics available on the failure rate associated with power transformers. Different techniques for testing the ECT of insulating fluids were indicated by Sierota et al. [30] that depended on the flow conditions of the pressboard insulation. Wu and Jayaram [31] further examined how the impurities affected the charging tendency of fluid while considering the influence of a DC field. The streaming current was enhanced when energized with a positive DC voltage and resulted in a polarity reversal in a field of 0.52 kV/mm for a negative DC voltage. Arazoe et al. [32] used the filter approach to accomplish the streaming electrification of various insulating fluids with temperature in which the mineral oil and ester fluid exhibited a positive streaming current with polytetrafluoroethylene (PTFE) utilized as a filter; a negative streaming current was observed in silicon oils. Cabaleiro et al. [33] modeled the static electrification phenomenon using a rectangular pressboard duct and inferred that the time taken for the interfacial reaction near the walls was greater than that of the formation of the electrical double layer. El-Adawy et al. [34] calculated the space charge density related to the streaming current after the EDL formation with wall currents and found corrosion as the major result of shear stress and chemical reactions occurring at the interface.

2. Mechanism of Static Electrification

The charge separation at the pressboard and metallic surface contacts occurs due to the forced oil convection used for the heat transfer mechanism inside the transformers. The most basic model is “double layer stripping”, in which charge production occurs when the motion of the insulating liquid shears the double layer at the boundary between the liquid and solid phases. A number of hypotheses on the formation of the electrical double layer and its structure have been put forth by different researchers [35][36][37] in its early stages. The solid–liquid coupling, which is apparently neutral, becomes polarized as a result of physico-chemical interactions when the insulating fluid is brought into contact at its interfaces. This causes the production of charges with a reverse polarity at the interface region. Intermolecular collisions are the primary mechanism of charge production in these interactions. As a result, the collision and impulse processes could result in space charge distribution in both the liquid and the solid insulation to create the electrical double layer (EDL), which is generally used to explain the electrostatic charging [38]. The double layer consists of two regions; the first layer, often referred to as the fixed or compact layer, is located closer to the solid surface and can contain either positive or negative charges according to the electrochemical reactions. The ions within that second layer, often referred to as the diffuse layer, are allowed to migrate into the fluid. There are various studies that explained the mechanism of the charge creation of the liquid with metallic/pressboard insulation [39][40][41]. According to a CIGRE report [42], lowering the surface tension of the insulating liquid could reduce its electrostatic charging tendency upon contact with the pressboard material. The positive ions were drawn to the surplus electrons in the outer metallic structure and aggregated on the surface, while the negative ions were left back and transported by the insulating fluid far away from the compact layer.

The positive charges from the electrical double layer migrate toward the insulating liquid as a result of the streaming electrification phenomenon at the paper/pressboard insulation inside power transformers. This is explained by cellulose’s molecular structure [43], in which the hydrogen ions present in the external structure of individual glucose units have a stronger affinity to the negative ions and thus build up the negative charges on the surface of the paper/pressboard insulation [44]. Harvey et al. [45] determined the charge density away from the double layer based on the relation between the Debye length and the diffuse sublayer thickness. The mass transport of an insulating liquid depends on the laminar flow for a lower Reynolds number, whereas turbulent flow determines the charge transfer for a higher Reynolds number. For the insulating liquid, it is inferred that the diffuse layer thickness is greater than the Debye length and that if the fluid results in a higher conductivity over its longer operation inside the transformer, the limiting case other than the former case can also occur, thereby increasing the streaming current. Despite the fact that these models were established for electrolytes, they later found application in solid–liquid interfaces in transformers. Variables such as temperature, permittivity, and concentration of ions in the insulating liquid affect the characteristics of a double layer. Compared to the electrolytes, the ionic concentration in the insulating liquid is very low when modeling the potential away from the interfaces. Walmsley and Woodford [46] later constructed the pipe flow model to determine the current generated due to the laminar flow and determined the streaming current based on the assumption that the adsorption of ionic species was equal to the ions present nearer to the walls. It was finally concluded that different factors and models along with the rate of adsorption and diffusivity of positive and negative ions determined the magnitude of streaming current.

3. Factors Affecting the Streaming Electrification Phenomenon

The streaming current of an insulating fluid can be influenced by different factors such as velocity, type of fluid, applied electric field, temperature, and surface roughness. Since the rated capacity of transformers has increased in the recent years, the volume of oil used for cooling the transformer winding has also increased, resulting in a higher possibility of static electrification; hence, the various factors impacting the static charges are required to be clearly understood. Radwan et al. [47] investigated the effect of frequency in the applied electric field, temperature, and velocity on static electrification and concluded that current existed under both energization and non-energization conditions. In addition, it has been noted that an increase in the applied electric field reduced the ECT of the fluid inside transformers. The change in the hydrodynamic flow pattern of the insulating liquid could modify the streaming current magnitude with variation in its velocity. This phenomenon could be related to the shear stress and diffusive sublayer thickness along with the friction existing between the insulating liquid and solid pressboard material [48]. The velocity and streaming current follow both a linear and a log-linear relation at the interface between the insulating liquid and pressboard [49]. The formation of oxidation byproducts in the insulating liquid with ageing can alter the flow mechanism governing the streaming current [50]. Based on actual failure experiences, it is recommended to keep the oil flow rate for the heat regulating mechanism in a transformer unit below 3 m/s [51]. Transformers can operate at very high temperatures, which have an adverse effect on the paper/fluid insulation's propensity for charging tendency. In fact, the magnitude of the streaming current develops exponentially in accordance with temperature; these characteristics are mostly governed by the ionic mobility and diffusion coefficient [52]. Additionally, as a result of the fluid's turbulent motion at high temperatures, the charge carriers collect on the pressboard material. The alternate dielectric fluids age more rapidly than the existing mineral oil with a discernible difference beginning at a temperature of about 80 °C. It is inferred that self-contamination of the liquid and leakage of ionic substances from solid materials are the causes of ageing impact on electrostatic charging, which is more severe in the presence of copper and oxygen [53]. The surface roughness of the pressboard insulation inside the transformer scratches and non-uniform surface increased the magnitude of streaming current to 10 times higher than in the uniform condition. Thus, each of the aforementioned elements has an individual or combined effect on the streaming current.

4. Streaming Current in Different Insulating Fluids

4.1. Mineral Oil and Silicone Oil

Mineral oil has been widely used in transformer applications for a very long time due to wide research on its insulation properties. This oil, which is derived from crude petroleum, involves a refining process that can be either naphthenic or paraffinic in nature [12]. Mineral oil was used in experiments on static electrification after major fire hazards were found in transformers in 1980. Kedzia and Brozostek [54] studied the static electrification of transformer oil as a measure of its ageing parameter and found that the impact of pipeline materials led to different leakage currents. In addition, the streaming phenomenon showed a better sensitivity to ageing characteristics and could detect the change in the insulation behavior at its early stages. The mineral oil was further investigated for ECT with transient characteristics [55] in which the migration of water and air injection toward the pressboard interface played a major role in the charging current. The aromatic additives present naturally in mineral oil provided a lower streaming current during the initial transformer operation, but at the same time, the longer ageing of the oil could lead to adverse fire hazards [56]. The static charges in power transformers can lead to partial discharges due to the accumulation of potential on the surface of the pressboard insulation, which usually occurs when the rate of change in the incremental charge is higher than the rate of charge leakage [57]. The impact of free radicals generated in the oil during transformer operation not only affects the physio-chemical properties, but also the static charges with a polarity reversal observed under localized thermal stress [58]. The diverse compounds present in the mineral oil were tested using accelerated thermal ageing under laboratory conditions in which the oxygen and copper catalyst that led to the formation of peroxide was found to be responsible for an increased ECT with ageing [59]. Paillat et al. [60] found that the effect of modifying cellulosic pressboard insulation with fibers from cotton and crystalline reduced the ECT of mineral oil but starch addition and laser-plasma treatments had no desired positive effects. The different factors (speed, temperature, rotation time, and electric field) studied in the electrification of mineral oil indicated that the interfacial charge density affected the breakdown strength [43]. The thermal ageing of mineral oil assessed using turbidity and spectrometric analysis provided a good correlation with the ECT [61]; the dissolved gases formed during the ageing process affected the magnitude of the streaming current. Silicone oil was measured for its streaming electrification using different insulating materials and the researchers concluded that a combination of silicone oil with Nomex paper could be a suitable interface to reduce the impact of ECT in transformers [62]. In addition, the electric charge of silicone was negative and smaller in magnitude compared to the positive charges observed in mineral oil. Similar research performed on the silicone oil [63] indicated a maximum current at 100 °C irrespective of changes in the kinematic viscosity and the silicone oil was less likely to cause a breakdown due to streaming behavior compared to mineral oil.

4.2. Ester Fluid

The alternate dielectrics from ester initially gained importance at the distribution level; now, the increased data available on these fluids regarding its dielectric performance has made them viable for power transformers. Ester fluids were tested for its static discharges initially using a sensor-based prototype along with simultaneous measurement of the charge accumulated at the pressboard surface and the leakage current [64]. Although the ester fluids showed a higher current generation, the increased conductivity could remove the charge accumulated on the pressboard insulation and thus limited the potential build-up across the spacers. This initial study on ester fluids could not determine the reason for the charge generation and concluded that it could be due to conductivity, viscosity, or physio-chemical reactions at the interfaces. Later, the rotating disk method was adopted in a synthetic ester fluid; its performance after being subjected to thermal ageing with the presence of paper and copper was reported [65]. The analysis in the study revealed a lower charging current in synthetic ester upon ageing compared to mineral oil with a higher relaxation time due to its higher volume resistivity. The pipe flow model investigated in a synthetic ester fluid by a similar research group resulted in identical conclusions made when using the rotating disk model [66]. Talhi et al. [50][67] used the spinning disk system to compare the charging tendency between ester fluids and mineral oil. This technique provided a higher charging current with synthetic ester compared to mineral oil and showed a completely different result from the previous methods. The parameters influencing the ECT upon ageing were moisture, dissolved gases, and oxygen diffused in the fluid. The impact of different solids on the ECT in synthetic ester fluid [68] was studied while considering the flow velocities and temperature and showed a higher magnitude than mineral oil [69]. The type of solid pipe (carbon, aluminium, cellulose, or aramid) used for the flowing of the insulating liquid also governed the streaming electrification. The fluid used in the transformer had its interface not only with pressboard insulation, but also with other metallic contacts; the streaming current was compared between mineral oil and natural ester using fiber glass/copper and pressboard/copper [70]. Among the different interface materials, the usage of pressboard/copper showed a higher ECT for natural esters. However, at higher temperatures, the charging tendency of mineral oil exceeded that of the natural ester fluid, indicating that impurities formed in the fluid at higher temperatures could modify the streaming phenomenon. The above research provided an idea that ester fluids are more superior to mineral oil when considering the ageing phenomenon [71]. The comparison of streaming current between synthetic ester and natural ester showed an ECT that was five times higher in the former compared to the latter [72]. In addition, the rate of change in the charge accumulation was very minimal compared to rate of transfer in the charges for both the ester and mineral oil. Based on an evaluation of the charge accumulated on the pressboard material from the ECT, the magnitude level was the same for ester fluid compared with mineral oil and thus could be a promising insulant in transformers up to 500 kV.

5. Effect of Additives on Streaming Current

Over the past century, a number of additives have been claimed to improve the physio-chemical and dielectric properties of an insulating liquid. These included different substances such as inhibitors, antioxidants, and electron scavengers, which reduce the partial discharge inception voltage and the charging tendency of the fluid and improve the breakdown voltage [73]. The different additives (Irgamet 39, benzotriazole, and C60) were used mostly for the reduction in the electrostatic charging tendency in power transformers. Both benzotriazole and Irgamet 39 are triazole-type derivatives of benzene except with a change in the group attached to the external nitrogen ring [74][75]. In addition to reducing the static charges of insulating fluids, these two additives function as a passivator around the copper and pressboard surface for the diffusion of sulfur compounds [76]. C60 is a type of fullerene that is spherical in shape with 60 carbon atoms providing excellent heat conductivity and lubrication performance [77]. Apart from the above-mentioned additives, the suppression of static electrification was initially tested using ionic and non-ionic additives [78]. Based on the experimental results, it was concluded that the chemical structure of the additive played a major role in the static charges, with non-ionic additives containing a polyethylene group showing the lowest streaming current. Further, additives such as alkylbenzene and benzotriazole [79] were investigated for the streaming current in large power transformers. The tests were conducted in the presence of oxygen, which provided a better reduction in the ECT for both of the additives, but the researchers were unsure about their compatibility and reliability with other materials in transformers. The conductivity of an insulating liquid depends on the amount of positive and negative ions present in the compound. Similarly, the streaming current of an insulating liquid depends on the quantity of dissociated ions; thus, a relation was postulated between the current formed at the interface with the activation energy required for the ionic transfer [80]. In the study, it was observed that the streaming current was a function of ionic charges present in the bulk liquid and activation energy involved in the transfer of ions to interfaces. Mohamed EL-Adawy et al. [81] studied the physio-chemical reaction at the interface between the liquid and pressboard material using OLOA 218 and OLOA 219, which led to a modification in the amplitude and polarity reversal of the streaming current. This variation could distinguish the reagent of fluid with the solid material for the streaming current. The optimum concentration of benzotriazole (BTA) of 20 ppm added into the liquid decreased over a longer time interval due to its diffusion into the pressboard material. The streaming current measured under a pressure gradient of 1.85 bar was reduced by almost four times after creating a flow period of 5 h toward the pressboard material [82]. The impact of BTA caused a change in the physio-chemical interaction occurring at the interface along with its dissociation in the insulating liquid [44]. The BTA molecule decomposed into a triazole ring and hydrogen ion upon its addition to the fluid. The unsaturated double bonds present in the structure of the BTA molecules upon dissociation reacted with paper/pressboard insulation, releasing extra electrons and attracting positive ions from the surface, which caused equal amounts of negative ions to diffuse into the liquid [83].

6. Effect of Electric Field on Streaming Current

There have been numerous investigations and databases created for the streaming current of an insulating fluid under an unenergized condition. So, a large experimental model was developed by Westinghouse with shell-type transformers with a 240 MVA capacity in which the static electrification phenomenon was understood. The energization of the insulating liquid could affect the streaming current, which, along with different flow conditions, governed the magnitude of the charge generation [52]. The streaming current under the energization condition increased 1.5 to 2 times when performed using 60 Hz electric stress [84]; the impact of AC voltage stress was not considered, and hence the observed results might have varied when the transformer was energized. Later, Miyao et al. [85] investigated the effects of AC and DC fields on the streaming electrification in transformer oil; they found that lower field regions under AC voltage were influenced by the apparent charge distribution and that for higher fields, the acceleration in the charge was observed at the interfaces. The polarity of the DC field had an influence on the streaming current with a negative conduction current affecting it in lower fields and a positive conduction current affecting it in higher fields. A highly charged fluid in the transformer reached the top of the tank, causing a severe failure. Although the intensity of the discharge had a very minimal effect on the ECT, the situation could become worse for higher discharge intensities [30]. The impact of DC fields on the streaming current was further investigated by Wu and Jayaram [31], who inferred that a positive DC field always enhanced the current magnitude and that in the case of a negative DC field, the current was a function of the field. The calibration and development of the streaming current in a cellular duct of a transformer winding was conducted with a boundary layer and explained the charge transfer mechanism as a function of electric field under different flow conditions [86]. Metwally investigated the effects of solid insulation material on the streaming current of transformer oil [87]; ageing conditions were observed a higher ECT under both AC and DC fields with polarity reversal dominating at lower temperatures. In addition, the conduction in both the fields was inferred to be a function of the square root of the applied voltage. The streaming current was studied in pressboard/paper insulation through a thin insulating pipe that indicated the leakage current from the positive to negative electrode for DC field conditions, with asymmetry and electrophoresis affecting the streaming current under an AC field [88]. Since electrification results with the energization of AC and DC fields became predominant, the impact of mixed fields on the streaming current was studied by Metwally [89]. The level of harmonics had a significant effect on the streaming current; a combined effect of the magnetic field and the electric field increased the ECT of the transformer oil. The AC-superimposed DC voltage in the transformer oil could increase the streaming current due to negative ion dispersion toward the interface [90]. Thus, the different fields can affect the streaming phenomenon of insulating liquids in power transformers.

References

1. Biçen, Y.; Aras, F.; Kirkici, H. Lifetime estimation and monitoring of power transformer considering annual load factors. IEEE Trans. Dielectr. Electr. Insul. 2014, 21, 1360–1367.
2. Metwally, I.A. Failures, monitoring and new trends of power transformers. IEEE Potentials 2011, 30, 36–43.
3. Werle, P.; Brendel, H. Transformers. In Handbook of Power Systems; Papailiou, K.O., Ed.; Springer: Singapore, 2021; pp. 443–509.
4. Prevost, T.A.; Oommen, T.V. Cellulose insulation in oil-filled power transformers: Part I-history and development. IEEE Electr. Insul. Mag. 2006, 22, 28–35.
5. Liu, Q.; Venkatasubramanian, R.; Matharage, S.; Wang, Z. Effect of oil regeneration on improving paper conditions in a distribution transformer. Energies 2019, 12, 1665.
6. Higaki, M.; Kako, Y.; Moriyama, M.; Hirano, M.; Hiraishi, K.; Kurita, K. Static electrification and partial discharges caused by oil flow in forced oil cooled core type transformers. IEEE Trans. Power Appar. Syst. 1979, 98, 1259–1267.
7. Crofts, D.W. The electrification phenomena in power transformers. IEEE Trans. Electr. Insul. 1988, 23, 137–146.
8. Borja, J.; Taleon, D.M.; Auresenia, J.; Gallardo, S. Polychlorinated biphenyls and their biodegradation. Process Biochem. 2005, 40, 1999–2013.

9. Fitzgerald, E.F.; Standfast, S.J.; Youngblood, L.G.; Melius, J.M.; Janerich, D.T. Assessing the health effects of potential exposure to PCBs, dioxins, and furans from electrical transformer fires: The Binghamton State Office Building medical surveillance program. Arch. Environ. Health Int. J. 1986, 41, 368–376.
10. Fernández, I.; Ortiz, A.; Delgado, F.; Renedo, C.; Perez, S. Comparative evaluation of alternative fluids for power transformers. Electr. Power Syst. Res. 2013, 98, 58–69.
11. Kuwahara, H.; Tsuruta, K.; Munemurs, H.; Ishii, T.; Shiomi, H. Partial discharge characteristics of silicone liquids. IEEE Trans. Electr. Insul. 1976, 11, 86–91.
12. Rouse, T.O. Mineral insulating oil in transformers. IEEE Electr. Insul. Mag. 1998, 14, 6–16.
13. Scatiggio, F.; Tumiatti, V.; Maina, R.; Tumiatti, M.; Pompili, M.; Bartnikas, R. Corrosive sulfur induced failures in oil-filled electrical power transformers and shunt reactors. IEEE Trans. Power Deliv. 2009, 24, 1240–1248.
14. Tokunaga, J.; Nikaido, M.; Koide, H.; Hikosaka, T. Palm fatty acid ester as biodegradable dielectric fluid in transformers: A review. IEEE Electr. Insul. Mag. 2019, 35, 34–46.
15. N'cho, J.S.; Fofana, I.; Hadjadj, Y.; Beroual, A. Review of physicochemical-based diagnostic techniques for assessing insulation condition in aged transformers. Energies 2016, 9, 367.
16. Rao, U.M.; Sood, Y.R.; Jarial, R.K. Ester dielectrics: Current perspectives and future challenges. IETE Tech. Rev. 2017, 34, 448–459.
17. Mehta, D.M.; Kundu, P.; Chowdhury, A.; Lakhiani, V.K.; Jhala, A.S. A review on critical evaluation of natural ester vis-a-vis mineral oil insulating liquid for use in transformers: Part 1. IEEE Trans. Dielectr. Electr. Insul. 2016, 23, 873–880.
18. Lashbrook, M. Ester fluids for power transformers at >100 kV. Transform. Mag. 2014, 1, 14–19.
19. Asano, R.; Page, S.A. Reducing environmental impact and improving safety and performance of power transformers with natural ester dielectric insulating fluids. IEEE Trans. Ind. Appl. 2013, 50, 134–141.
20. Liu, Q.; Wang, Z.D. Streamer characteristic and breakdown in synthetic and natural ester transformer liquids under standard lightning impulse voltage. IEEE Trans. Dielectr. Electr. Insul. 2011, 18, 285–294.
21. CIGRE Working Group A 2.35. Experiences in Service with New Insulating Liquids; CIGRE: Paris, France, 2010; ISBN 978-2-85873-124-4.
22. Pierce, L.W. An investigation of the thermal performance of an oil filled transformer winding. IEEE Trans. Power Deliv. 1992, 7, 1347–1358.

23. Li, Y.; Tung, S.; Schneider, E.; Xi, S. A review on development of nanofluid preparation and characterization. Powder Technol. 2009, 196, 89–101.
24. Lv, Y.Z.; Zhou, Y.; Li, C.R.; Wang, Q.; Qi, B. Recent progress in nanofluids based on transformer oil: Preparation and electrical insulation properties. IEEE Electr. Insul. Mag. 2014, 30, 23–32.
25. Du, Y.; Lv, Y.; Li, C.; Zhong, Y.; Chen, M.; Zhang, S.; Zhou, Y.; Chen, Z. Effect of water adsorption at nanoparticle–oil interface on charge transport in high humidity transformer oil-based nanofluid. Colloids Surf. A Physicochem. Eng. Asp. 2012, 415, 153–158.
26. Fontes, D.H.; Ribatski, G.; Bandarra Filho, E.P. Experimental evaluation of thermal conductivity, viscosity and breakdown voltage AC of nanofluids of carbon nanotubes and diamond in transformer oil. Diam. Relat. Mater. 2015, 58, 115–121.
27. Miao, J.; Dong, M.; Ren, M.; Wu, X.; Shen, L.; Wang, H. Effect of nanoparticle polarization on relative permittivity of transformer oil-based nanofluids. J. Appl. Phys. 2013, 113, 204103.
28. Du, B.; Li, J.; Wang, F.; Yao, W.; Yao, S. Influence of monodisperse Fe3O4 nanoparticle size on electrical properties of vegetable oil-based nanofluids. J. Nanomater. 2015, 2015, 560352.
29. Raj, R.A.; Samikannu, R.; Yahya, A.; Mosalaosi, M. Investigation of Survival/Hazard Rate of Natural Ester Treated with Al2O3 Nanoparticle for Power Transformer Liquid Dielectric. Energies 2021, 14, 1510.
30. Sierota, A.; Rungis, J. Electrostatic charging in transformer oils. Testing and assessment. IEEE Trans. Dielectr. Electr. Insul. 1994, 1, 840–870.
31. Wu, H.; Jayaram, S. DC field effects on streaming electrification in insulating oils. IEEE Trans. Dielectr. Electr. Insul. 1996, 3, 499–506.
32. Arazoe, S.; Saruhashi, D.; Sato, Y.; Yanabu, S.; Ueta, G.; Okabe, S. Electrical characteristics of natural and synthetic insulating fluids. IEEE Trans. Dielectr. Electr. Insul. 2011, 18, 506–512.
33. Cabaleiro, J.M.; Paillat, T.; Moreau, O.; Touchard, G. Electrical double layer's development analysis: Application to flow electrification in power transformers. IEEE Trans. Ind. Appl. 2009, 45, 597–605.
34. El-Adawy, M.; Cabaleiro, J.M.; Paillat, T.; Moreau, O.; Touchard, G. Experimental determination of space charge density associated with flow electrification phenomenon: Application to power transformers. J. Electrost. 2009, 67, 354–358.
35. Von Helmholtz, H.L.F. Studies of electric boundary layers. Wied. Ann. 1879, 7, 337–382.
36. Grahame, D.C. The electrical double layer and the theory of electrocapillarity. Chem. Rev. 1947, 41, 441–501.

37. Parsons, R. The electrical double layer: Recent experimental and theoretical developments. Chem. Rev. 1990, 90, 813–826.
38. Metwally, I.A. Characterization of static electrification in power transformers. IEEE Trans. Dielectr. Electr. Insul. 1996, 3, 307–315.
39. Yamada, N.; Kishi, A.; Nitta, T.; Tanaka, T. Model approach to the static electrification phenomena induced by the flow of oil in large power transformers. IEEE Trans. Power Appar. Syst. 1980, 99, 1097–1106.
40. Oommen, T.V. Static electrification properties of transformer oil. IEEE Trans. Electr. Insul. 1988, 23, 123–128.
41. Peyraque, L.; Boisdon, C.; Beroual, A.; Buret, F. Static electrification and partial discharges induced by oil flow in power transformers. IEEE Trans. Dielectr. Electr. Insul. 1995, 2, 40–45.
42. CIGRE Joint Working Group 12/15-13. Static Electrification in Power Transformers, General Session, Paper 15/12-03; CIGRE: Paris, France, 1992.
43. Liu, D.; Du, B.; Yan, M.; Wang, S.; Liu, X. Investigation of electrification and breakdown strength about transformer oil/pressboard. IET Electr. Power Appl. 2017, 11, 386–392.
44. Amalanathan, A.J.; Sarathi, R.; Harid, N.; Griffiths, H. Modeling of Spinning Disk System for Charging Tendency of Ester-Based TiO2 Nanofluids Along With its Interfacial Zone. IEEE Trans. Dielectr. Electr. Insul. 2022, 29, 462–469.
45. Harvey, T.J.; Wood, R.J.K.; Denuault, G.; Powrie, H.E.G. Effect of oil quality on electrostatic charge generation and transport. J. Electrost. 2002, 55, 1–23.
46. Walmsley, H.L.; Woodford, G. The polarity of the current generated by the laminar flow of a dielectric liquid. J. Electrost. 1981, 10, 283–288.
47. Radwan, R.M.; El-Dewieny, R.M.; Aish, T.D.; Metwally, I.H. Factors affecting transformer oil flow electrification in electric power apparatus. In Proceedings of the IEEE Annual Conference on Electrical Insulation and Dielectric Phenomena, Pocono Manor, PA, USA, 28–31 October 1990; pp. 642–647.
48. Kedzia, J.; Willner, B. Electrification current in the spinning disk system. IEEE Trans. Dielectr. Electr. Insul. 1994, 1, 58–62.
49. Oommen, T.V.; Petrie, E.M. Electrostatic Charging Tendency of Transformer Oils. IEEE Trans. Power Appar. Syst. 1984, 103, 1923–1931.
50. Talhi, M.; Fofana, I.; Flazi, S. Comparative study of the electrostatic charging tendency between synthetic ester and mineral oil. IEEE Trans. Dielectr. Electr. Insul. 2013, 20, 1598–1606.

51. Brubaker, M.A.; Nelson, J.K. A parametric study of streaming electrification in a full-scale core-form transformer winding using a network-based model. IEEE Trans. Power Deliv. 2000, 15, 1188–1192.
52. Liu, D.; Du, B.; Liu, F.; Wang, S. Effects of multiple parameters on static electrification and breakdown strength of transformer oil. IET Sci. Meas. Technol. 2016, 10, 597–601.
53. Nelson, J.K. Electrokinetic effects in pumped dielectric fluids. In Proceedings of the IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), Pocono Manor, PA, USA, 17–20 October 1993; pp. 25–61.
54. Kedzia, J.; Brozostek, E. Static electrification in transformer oil as a measure of its aging. IEEE Trans. Electr. Insul. 1984, 19, 101–106.
55. Peyraque, L.; Beroual, A.; Buret, F. Static electrification of pressboard/oil interface and transient phenomena. IEEE Trans. Dielectr. Electr. Insul. 1998, 5, 443–449.
56. Ueta, G.; Tsuboi, T.; Okabe, S.; Amimoto, T. Study on degradation causing components of various characteristics of transformer insulating oil. IEEE Trans. Dielectr. Electr. Insul. 2012, 19, 2216–2224.
57. Massala, G.; Lesaint, O.; Moreau, O. Influence of oil electrification on ac breakdown between metallic electrodes. In Proceedings of the IEEE Annual Report Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), Victoria, BC, Canada, 15–18 October 2000; pp. 89–92.
58. Talhi, M.; Fofana, I.; Flazi, S. Impact of free radicals on the electrostatic charging tendency of transformer oils. Electr. Eng. 2020, 102, 1265–1274.
59. Okabe, S.; Kohtoh, M.; Tsuchie, M.; Amimoto, T. Influence of diverse compounds on electrostatic charging tendency of mineral insulating oil used for power transformer insulation. IEEE Trans. Dielectr. Electr. Insul. 2009, 16, 900–908.
60. Paillat, T.; Onic, L.; Moreau, O.; Bertrand, Y.; Mortha, G.; Charvet, N.; Touchard, G. Influence of pressboard physico-chemical composition on static electrification in power transformers. IEEE Trans. Ind. Appl. 2003, 39, 346–354.
61. Fofana, I.; Bouslimi, Y.; Hemmatjou, H.; Volat, C.; Tahiri, K. Relationship between static electrification of transformer oils with turbidity and spectrophotometry measurements. Int. J. Electr. Power Energy Syst. 2014, 54, 38–44.
62. Nakajima, A.; Miyahara, H.; Ishikawa, T.; Wada, J.; Yanabu, S. Streaming electrification characteristics of silicone oil. IEEE Trans. Dielectr. Electr. Insul. 2008, 15, 519–526.
63. Ishikawa, T.; Yasuda, K.; Igarashi, T.; Yanabu, S.; Ueta, G.; Okabe, S. Effect of temperature on the streaming electrification characteristics of silicone oil. IEEE Trans. Dielectr. Electr. Insul. 2009, 16, 273–280.

64. Paillat, T.; Zelu, Y.; Morin, G.; Perrier, C. Ester oils and flow electrification hazards in power transformers. IEEE Trans. Dielectr. Electr. Insul. 2012, 19, 1537–1543.
65. Liu, Q.; Liu, Z.; Yang, G. Comparison of streaming electrification characteristics between an ester liquid and a mineral oil using rotating disc method. In Proceedings of the IEEE Annual Report Conference on Electrical Insulation and Dielectric Phenomena, Chenzhen, China, 20–23 October 2013; pp. 1026–1029.
66. Huang, Y.M.; Liu, Q. Comparisons of streaming electrification characteristics between an ester liquid and a mineral oil using pipe flow method. In Proceedings of the IEEE International Conference on Dielectrics (ICD), Palermo, Italy, 3–7 July 2016; pp. 1028–1031.
67. Talhi, M.; Fofana, I.; Flazi, S. The electrostatic charging tendency of some environmentally friendly insulating fluids. In Proceedings of the IEEE Electrical Insulation Conference (EIC), Ottawa, ON, Canada, 2–5 June 2013; pp. 378–382.
68. Podesser, J.; Wieser, B.; Muhr, M.; Schwarz, R.; Pukel, G.J.; Lashbrook, M. Static electrification of different solid-liquid couples used in transformers for insulation. In Proceedings of the IEEE 18th International Conference on Dielectric Liquids (ICDL), Bled, Slovenia, 29 June–3 July 2014; pp. 1–4.
69. Zdanowski, M. Streaming electrification of mineral insulating oil and synthetic ester MIDEL 7131. IEEE Trans. Dielectr. Electr. Insul. 2014, 21, 1127–1132.
70. Kolcunova, I.; Kurimský, J.; Cimbala, R.; Petráš, J.; Dolník, B.; Džmura, J.; Balogh, J. Contribution to static electrification of mineral oils and natural esters. J. Electrost. 2017, 88, 60–64.
71. N’cho, J.S.; Fofana, I.; Beroual, A. Studying the Electrostatic Charging Tendency of some environmentally friendly fluids in a spinning disk system. In Proceedings of the International Conference on High Voltage Engineering and Application (ICHVE), Poznan, Poland, 8–11 September 2014; pp. 1–4.
72. Huang, Q.; Chen, Y.; Huang, H.; Wang, Y.; Song, H. Comparison Among Ester Liquids for Streaming Electrification of Power Transformers. In Proceedings of the IEEE 21st International Conference on Dielectric Liquids (ICDL), Seville, Spain, 22 May–2 June 2022; pp. 1–4.
73. Fofana, I. 50 years in the development of insulating liquids. IEEE Electr. Insul. Mag. 2013, 29, 13–25.
74. Qian, Y.; Su, W. Research on influencing factors of corrosive sulfur attacking copper in insulating oil and prevention. IEEJ Trans. Electr. Electron. Eng. 2013, 8, 546–549.
75. Tumiatti, V.; Maina, R.; Scatiggio, F.; Pompili, M.; Bartnikas, R. In service reduction of corrosive sulfur compounds in insulating mineral oils. In Proceedings of the Conference Record of the 2008 IEEE International Symposium on Electrical Insulation, Vancouver, BC, Canada, 9–12 June 2008; pp. 284–286.

76. Wan, T.; Qian, H.; Zhou, Z.; Gong, S.K.; Hu, X.; Feng, B. Suppressive mechanism of the passivator irgamet 39 on the corrosion of copper conductors in transformers. IEEE Trans. Dielectr. Electr. Insul. 2012, 19, 454–459.
77. Sima, W.; Chen, J.; Sun, P.; Zhang, H.; Ye, L.; He, J.; Yin, Z.; Shao, Q. Breakdown characteristics of C60 modified transformer oil. In Proceedings of the IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), Cancun, Mexico, 21–24 October 2018; pp. 125–128.
78. Watanabe, S.; Kawaguchi, S.; Fujil, M.; Tanabe, K.; Ohashi, A. The structure of additives and their relation to streaming current. In Proceedings of the Twenty-First Symposium on Electrical Insulating Materials, Tokyo, Japan, 26 September 1988; pp. 319–322.
79. Watanabe, S.; Tanabe, K.; Fujii, M.; Ohashi, A.; Zerghouni, A.; Touchard, G. The relation between the chemical structure of anti-additives and streaming current. In Proceedings of the 10th International Conference on Conduction and Breakdown in Dielectric Liquids, Grenoble, France, 10–14 September 1990; pp. 212–216.
80. Ieda, M.; Okugo, H.; Tsukioka, H.; Goto, K.; Miyamoto, T.; Kohno, Y. Suppression of static electrification of insulating oil for large power transformers. IEEE Trans. Electr. Insul. 1988, 23, 153–157.
81. Mohamed, E.A.; Paillat, T.; Bertrand, Y.; Moreau, O.; Touchard, G. Physicochemical analysis at the interface between conductive solid and dielectric liquid for flow electrification phenomenon. IEEE Trans. Ind. Appl. 2010, 46, 1593–1600.
82. Moreau, E.; Paillat, T.; Touchard, G. Oil electrification measured on a pressboard coming from a damaged power transformer. In Proceedings of the Annual Report Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), Austin, TX, USA, 17–20 October 1999; pp. 794–797.
83. Nelson, J.K. Dielectric fluids in motion. IEEE Electr. Insul. Mag. 1994, 10, 16–28.
84. Roach, J.F.; Templeton, J.B. An Engineering model for streaming electrification in power transformers. In Electrical Insulating Oils; Erdman, H.G., Ed.; ASTM: West Conshohocken, PA, USA, 1988; pp. 119–135.
85. Miyao, H.; Higaki, M.; Kamata, Y. Influence of ac and dc Fields on Streaming Electrification of Transformer Oil. IEEE Trans. Electr. Insul. 1988, 23, 129–135.
86. Brubaker, M.A.; Nelson, J.K. Development and calibration of a streaming electrification model for a cellulose duct. IEEE Trans. Dielectr. Electr. Insul. 1997, 4, 157–166.
87. Metwally, I.A. Influence of solid insulating phase on streaming electrification of transformer oil. IEEE Trans. Dielectr. Electr. Insul. 1997, 4, 327–340.

88. Huh, C.S.; Jeong, J.I. Streaming electrification of thin insulating pipes under electric field. IEEE Trans. Dielectr. Electr. Insul. 1998, 5, 199–203.
89. Metwally, I.A. Flow electrification of transformer oil effects of mixed fields. IEEE Trans. Dielectr. Electr. Insul. 1998, 5, 518–526.
90. Chen, Q.; Lin, L.; Gao, Y.; Li, J. Flow electrification characteristics of oil-pressboard insulation under ac superimposed on DC electric field. IEEE Trans. Dielectr. Electr. Insul. 2015, 22, 2915–2922.