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Review

Streaming Electrification of Different Insulating Fluids in Power Transformers

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Abstract: This paper presents a detailed review of the streaming electrification phenomena of different insulating fluids for power transformers. 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. The energization process using alternating current (AC) and direct current (DC) impacts the streaming phenomenon depending on its magnitude and polarity. The diffusion of sulfur compounds in the insulating liquid is another major hazard to transformers because the sulfide ions affect the physio-chemical reaction at the interface material, which is responsible for the formation of streaming current.

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

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Citation: Amalanathan, A.J.; Zdanowski, M.; Sarathi, R. Streaming Electrification of Different Insulating Fluids in Power Transformers. *Energies* **2022**, *15*, 8121. https://doi.org/10.3390/en15218121

Academic Editor: Zbigniew Nadolny

Received: 12 October 2022
Accepted: 26 October 2022
Published: 31 October 2022

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.

Considering the aforementioned literature on static electrification failures in power transformers, it is required to understand the streaming electrification formation in different insulating liquids along with different factors that aid the charging phenomenon. Thus, the major objective of the present work was to investigate the streaming phenomenon of insulating fluids by simulating transformers in real time under laboratory conditions and adopting a suitable standardized method for its evaluation. Based on the above statement, the current work investigated the following: (i) the streaming current of different insulating fluids, (ii) techniques used for assessing the streaming current under laboratory conditions, (iii) the impact of additives and energization on the streaming current, (iv) the impact of reclamation on the streaming current, and (v) sulfur diffusion in the streaming phenomenon.

2. Experimental Setup and Precautionary Measures

This section describes the different techniques used to measure the streaming current of insulating fluids. To test the streaming electrification of insulating fluids under lab conditions, various approaches [30] were used according to the different flow conditions (planar flow or centrifugal flow).

2.1. Techniques for the Measurement of Static Current

2.1.1. Flow Loop Device

With the advancements in capacitive-type sensors, power transformer conditions were first simulated with a flow loop device for calculation of the streaming current [35,36], in which the charges allowed for separation at the interface by forcing the insulating liquid with a planar flow toward the pressboard material. The exchange of charges and the motion of ions within the liquids were performed with different electro-mechanical devices (flow meter, motor pump, liquid tank, sensor, and heat regulator). To achieve the appropriate temperature, the flow of the insulating liquid provided by a motor pump was controlled with a flow meter and then directed toward the heat exchanger. The sensor typically comprises pressboards inside a rectangular channel with each of the pressboard layers adhered together and fitted inside a PTFE frame to isolate the pressboards from the electrode, which then receives the data from its outlet. The charges trapped on the surface of the pressboard material were measured by the picoammeter attached to the electrodes. The remaining charges in the fluid were then allowed to move toward the relaxation container in which leakages of currents during the upstream and downstream flow were measured. This method has significant drawbacks, one of which is the substantial amount of oil (20 liters) needed for the testing. The feedback system and the pressboard duct were allowed to dry using a nitrogen gas inlet under a high vacuum condition for a period of 24 h prior to start of the investigation. Additionally, the relaxation time of about 24 h was enforced during the flow of the insulating liquid in the pressboard impregnation. As a result, the processing and conditioning of the liquid and solid insulation took a substantial amount of time. This technique could be modified with a higher area of solid insulation used for testing, thereby improving its accuracy as related to actual power transformers. These shortcomings prompted the development of filtering techniques to assess the insulating fluid's charging tendency.

2.1.2. Ministatic Charge Tester

The Ministatic charge testing device was designed to assess the electrostatics of the fuels used in the jets and was subsequently modified for its utilization for insulating fluids [37]. This technique involves forcing an oil from a plastic syringe (50 mL) through a filter paper so the electrostatic charge separation takes place on the cellulosic paper. Since there are more pores and a larger surface area of the filter paper compared to the actual pressboard/paper insulation in transformers, the current measured cannot be related to the actual mechanism. The charges that are transferred away by the oil from the filtering mechanism are detected by the picoammeter in which the measured current is used to calculate the charge density by dividing the value by the volumetric rate of the fluid flow used in the device. The charge density is dependent on a number of variables (medium of filter, velocity of oil, and temperature) and hence its magnitude cannot be used as an accurate measurement to compare distinct oil samples [38]. As the recorded current is from the filter, the actual current will be negative and needs to be given an inverse relation to determine the charging current involved with the fluid. This technique can provide an understanding of different insulating fluids in the porous structure of solid insulation but cannot be related to actual field conditions. Thus, techniques based on centrifugal fluid motion and rotating models were developed to address the shortcomings of the approaches involved with the Ministatic charge tester.

2.1.3. Couette Charger

The Couette charging system [39] involves coaxial cylinders made of aluminum (inner and outer cylinder) filled with the insulating liquid. The pressboard sheets used for the electrostatic charge separation with the liquid are rolled inside the cylinder, resembling the construction inside a power transformer. This technique is capable of measuring current in both laminar and turbulent flow regimes by altering the rotational speed of the internal cylinder. This method is in contrast to the previous methods because it takes into account the effect of the applied electric field on the insulating fluid's tendency to create a charge separation with the pressboard material under various flow regimes [40]. The absolute charge sensor (ACS), a more sophisticated variant of the Couette charger [41], is used to directly measure the charge density irrespective of the fluid characteristics inside the instrument. Although this method offers a higher accuracy, it is more complicated due to the longer time for conditioning involved and the huge volume of fluid required. So, these large-scale models were supplemented with small models such as the CIGRE test cell [42] and spinning disk system in the measurement of charging tendency. The Couette charge test system involves pressboard stacks arranged in a rolled manner similar to that of transformers and provides an advantage of investigating the streaming current in the presence of an electric field, which is not the case in other techniques.

2.1.4. Spinning Disk System

The charge propensity of the insulating fluid is assessed while taking into consideration the influences of fluid temperature, moisture content, and type of pressboard material along with its thickness and surface roughness. According to CIGRE's spinning disk method [43], an insulating liquid-filled metallic aluminum tank with a disk coated on the surface of a solid pressboard material is rotated. The input torque for the rotation is delivered by a motor with a speed control device along with adjustments provided for immersion of the disk in both the vertical and horizontal axes. Considering the steady-state condition in which charges separated at the interface are assumed to be collected the edge of the aluminum vessel, an electrometer is used to measure these charges. By surrounding the spinning system inside a Faraday cage, the stray currents' interference with the actual measurements is minimized. Using this technique, it is possible to conduct the experiment with different thickness of pressboard material and a varying diameter and velocity of the disc. The measurement of the streaming current is done at the walls of aluminum vessel based on the assumption that actual charges separated at the rotating disk are convected toward the vessel wall. So, the current measurement should be repeated multiple times in order to confirm its accuracy.

2.1.5. Shuttle System with Two Parallel Electrodes

Zmarzły and Frącz [44,45] developed an oscillatory system to study the streaming current of insulating liquids. The measuring system consisted of a metal tank filled with liquid and two parallel electrode plates 2 mm apart. Both plates were made of metal with the top one coated with 0.3 mm-thick pressboard. The upper electrode was put into an oscillatory motion using a stepper motor connected to an eccentric clutch and a set of linear guides. The generated streaming current was measured using an electrometer connected to the bottom plate seated on a PTFE insulator. The tank, transmission tower, and mobile electrode were grounded. The entire structure was placed into a metal casing that acted as a Faraday cage. The system enabled measurement of the streaming current as a time and amplitude function, as well as the oscillation frequency (0.4 to 4 Hz) of the upper electrode. The generated streaming current signals were analyzed in the time, frequency, and combined time–frequency domains. In an oscillatory system, it is not necessary to use a large amount of insulating liquid, as in the case of the flow-through systems discussed earlier. There is also no need to put the measuring electrode in a circular motion, as is the case with the classic rotating disk system or the Couette diagnostic system. Moreover, the electrometric device does not need to be in motion, making it much more precise compared to a system with a rotating electrometer.

2.2. Noise Analyzer for Monitoring the Static Electrification Current

Zmarzły and Kedzia [46] proposed a method for analyzing streaming electrification current noise to identify the ageing properties of transformer oil. To this end, a modification was made to the rotating disk measurement system by placing the electrometric instrument inside the measurement object, which enabled the measurement of small changes in the streaming current and reduced the influence of external interference. The measurement system consisted of a grounded tank filled with oil, a rotating electrometer mounted on a disk-supporting axle, a microprocessor controller, and a measurement computer. The measured signal, which represented the streaming current, was transformed using proper software to determine a broad set of parameters in the time, frequency, and combined time–frequency domains. The authors analyzed the effects of hydrodynamic conditions, temperature, and oil ageing time on the generation of streaming current noise. On the basis of the study, the validity of using this method to detect ageing in insulating oil was demonstrated.

3. Results

This section discusses the charging tendency of different insulating liquids (mineral oil, ester fluid, mixed insulating fluid, and nanofluid) along with their impacts on the additive and reclamation process.

3.1. 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 [47–49] 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 [50]. 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 [51–53]. According to a CIGRE report [43], 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 [54], 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 [55]. Harvey et al. [56] 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 [57] 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.

3.2. 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. [58] 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 [59]. The velocity and streaming current follow both a linear and a log-linear relation at the interface between the insulating liquid and pressboard [38]. The formation of oxidation byproducts in the insulating liquid with ageing can alter the flow mechanism governing the streaming current [60]. 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 [61]. 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 [62]. 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 [63]. 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.

3.3. Streaming Current in Different Insulating Fluids

3.3.1. 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 [64] 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 [42] 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 [65]. 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 [66]. 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 [67]. 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 [68]. Paillat et al. [69] 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 [54]. The thermal ageing of mineral oil assessed using turbidity and spectrometric analysis provided a good correlation with the ECT [70]; 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 [71]. 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 [72] 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.

3.3.2. 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 [73]. 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 [74]. 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 [75]. Talhi et al. [60,76] 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 [77] was studied while considering the flow velocities and temperature and showed a higher magnitude than mineral oil [78]. 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 [79]. 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 [80]. 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 [81]. 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.

3.3.3. Mixed Fluid

Research on mixed insulating liquids was conducted using different chemical composition of ester fluids (10%, 20%, and 50%) and mineral oil [82]. The miscibility of both the liquids was clear and a similar density provided a better stable dispersion. Adding such ester liquids to mineral oil can reduce the gassing tendency and improved the lifetime of paper/pressboard insulation. After comparing the different compositions, 80% mineral oil with 20% ester fluid was found to provide superior dielectric and physio-chemical properties. Zdanowski et al. [83] studied the ECT of hydrocarbon mixtures using a spinning disc system with changes in the composition of toluene and cyclohexane. The compositions did not affect the dielectric properties of the fluid but reduced the ECT of the mixture with increased resistivity. In addition, ethanol and hexane mixtures were studied in terms of their charging tendencies [84] to identify the different parameters that impacted the electrification current. It was found that the diffusion coefficient, viscosity, and density had negligible influences on the ECT, while permittivity and conductivity increased the magnitude of current. Gayathri et al. [85] experimented with the mixture of 80% mineral oil and 20% natural ester fluid in terms of its electro-chemical properties and ECT. It was inferred that the mixed fluid provided a higher charging current than mineral oil but a lower one than ester fluid. Similar to the mixture of ester fluid with mineral oil, a silicone oil mixture [86] was also tested, but it resulted in poor biodegradability, a lower resistance to oxidation, and a high viscosity. The accelerated ageing of the natural ester and mineral oil mixture resulted in a poor oxidation stability [87]; hence, the mixture could be used in sealed transformer equipment without exposure to the external atmosphere.

The synthetic ester mixture with mineral oil was found to be better than natural ester because it offered good oxidation stability and longevity of the paper insulation without many changes to the design aspects of the transformer [88]. Both iso-paraffinic and naphthenic-based oils were studied for ECT when mixed with synthetic ester fluid [89]; a higher charging tendency was provided by paraffinic oil mixtures compared to naphthenic oil-based mixtures. Zdanowski and Maleska [90] studied the streaming of insulating liquid mixtures in terms of retrofilling of power transformers. Fresh and aged transformer mineral oil was used in the tests. The natural esters were Midel 1204 and Envirotemp FR3 [91], whereas the synthetic esters consisted of Midel 7131 and Nycodiel 1255 [92]. Measurements were made using a pipe flow-through system and a rotating disk system. Significant differences in the streaming current characteristics were observed in relation to the type of mineral oil used (fresh or aged). In each case, mixtures containing approximately 80% fresh transformer mineral oil and 20% ester showed the highest levels of ECT. Mixtures consisting of 80% ester and 20% aged transformer mineral oil showed the lowest susceptibility to electrification. Extensive testing of ester–oil mixtures has proven that the retrofilling process does not increase the risk of the insulating system of power transformers threatened by the phenomenon of streaming electrification.

3.3.4. Nanofluids

The use of nanofluids for power transformer applications began in the early 20th century with different techniques adopted for a stable mechanism [93]. Each type of nanoparticle (conductive, semiconductive, and insulative) used had its specific properties enhanced, such as the thermal conductivity and breakdown strength, in the base insulating fluids [94]. Silica (SiO_2) nanoparticles were studied in terms of their ECT in mineral oil with different surfactants such as cetyl trimethyl ammonium bromide (CTAB), oleic acid, and Span 80 [95]. This study was conducted with the aim to understand the impacts of ionic and non-ionic surfactants on the charging current. The streaming currents of nanofluids were greater than those of mineral oil; in particular, a higher magnitude was observed for the ionic surfactant (CTAB) compared to oleic acid and the non-ionic surfactant (Span 80). This behavior was related to the rheological properties of nanofluids and the transition involved in the storage modulus and loss modulus. Similar investigations were performed using synthetic ester fluid [96] that showed the same trend as observed using mineral oil. A higher stability was observed with Span 80 toward synthetic ester along with better inception and flow behavior, which were responsible for the reduction in its streaming current. Anju et al. [97] further evaluated the properties of aluminium nitride (AlN) nanoparticles in a synthetic ester fluid for its electro-rheological properties and found that the streaming current of the nanofluids was higher at increased disk velocities and temperatures. In contrast, nanoparticle concentrations of 0.0025% and 0.005% showed a reduction in the streaming current at higher temperatures compared to the base synthetic ester fluid. The higher thermal conductivity nature of AlN nanoparticles could trap the thermal energy as well as the ionic mobility responsible for the streaming current at lower concentrations, whereas for concentrations higher than 0.005%, the agglomeration of nanoparticles was seen to have a higher charge mobility. TiO_2 nanoparticles that provided better scavenging of the electrons were tested in natural ester fluid with CTAB as a surfactant [98]. The addition of the cationic surfactant (CTAB) resulted in a higher streaming current than that of the natural ester fluid without a surfactant. These cations could introduce more negative ions on the compact layer, leaving an equal number of positive ions to diffuse into the insulating fluid. Based on the results, it was concluded that the conductivity of the nanofluids along with other streaming parameters (Debye length, diffusion coefficient, and relaxation time) governed the ECT of the fluid toward the paper/pressboard interface. The mechanism of the streaming current with TiO_2 nanoparticles in natural ester fluid was further explained based on the interfacial zone of fluid with pressboard material [55]. The surfactant molecules were perpendicular to the TiO_2 nanoparticles and were divided into two different layers. The aligned layer was where the surfactant chains were arranged and the affected layer had no chained molecules. Only a single layer of TiO_2 nanoparticles was present without surfactant, whereas with the addition of the surfactant, the two layers were formed with a strong interfacial zone, leading to higher streaming current. A mixed fluid also was investigated for its streaming current with TiO_2 nanoparticles involving CTAB and oleic acid as surfactants [85]. The results showed a negative streaming current with a higher charging magnitude on CTAB compared to oleic acid. This confirmed that the type of nanoparticle and surfactant could influence the polarity and magnitude of the charging current.

3.4. 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 [99]. 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 [100,101]. 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 [102]. C60 is a type of fullerene that is spherical in shape with 60 carbon atoms providing excellent heat conductivity and lubrication performance [103]. Apart from the above-mentioned additives, the suppression of static electrification was initially tested using ionic and non-ionic additives [104]. 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 [105] 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 [106]. 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. [107] 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 [108]. The impact of BTA caused a change in the physio-chemical interaction occurring at the interface along with its dissociation in the insulating liquid [55]. 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 [109].

The addition of BTA molecules to ester-based nanofluids has also been studied; the interfacial zone was found to affect the streaming current phenomenon. When the TiO_2 nanoparticle were surrounded by a positive charge in the ester fluids, upon the addition of BTA, the triazole ring could easily diffuse, which lowered the charge separation at the interface. However, the addition of a surfactant to nanofluids can inhibit the BTA diffusion by requiring a larger concentration to reduce the magnitude of the streaming current [55]. An optimum amount of 10 ppm in BTA [52] and theophylline concentration [110] could reduce the streaming current of transformer oil. However, the investigations of alternate ester fluids required 130 ppm of BTA for a complete reduction in the static charges. In the case of TiO_2 nanofluids, the additive concentration was observed to be 520 ppm due to electron scavenging of the negative BTA ions [98]. In addition, the activation energy responsible for the diffusion of ions in the nanofluids was very high compared to that of the ester fluid. The ester fluid that was aged with the addition of BTA showed a lower ECT with the disc velocity compared to its influence without BTA [111]. Thus, the impact of BTA for transformers must be considered after numerous investigations on the mass transport because it can diffuse easily toward the solid insulation material. Aksamit et al. [112] studied the static electrification of mineral oil with the addition of a C60 inhibitor and found a minimum charge current for a concentration of 100 mg/L irrespective of the velocity. This concentration level was found to be the same under ageing conditions with a reduction rate of 30% to 90% [113]. When examining the current with a rotational speed at concentrations higher than 64 mg/L, a unique characteristic was observed that could be related to a mechanism other than the double-layer model; since the solid material used in the experiments was not similar to the pressboard material used in the transformers, it could not be related to actual power applications.

Zdanowski [114] presented results confirming the possibility of using fullerene C_{60} to reduce the phenomenon of streaming electrification generated by the flow of insulating fluids used in power transformers. In the tests, fresh and aged transformer mineral oil, as well as the natural ester Midel 1204 and the synthetic ester Midel 7131, were used. The streaming current measurements were taken in a flow-through system with a metal pipe that was 4 mm in diameter and 400 mm long. The effect of the flow velocity (from 0.34 m/s to 1.75 m/s) and C_{60} concentration (25 mg/L, 50 mg/L, 100 mg/L, 200 mg/L, and 350 mg/L) on the change in ECT was analyzed. In addition, the density, kinematic viscosity, dielectric constant, and conductivity of the nanofluid were determined. It was demonstrated that an increase in the C_{60} content intensified the generation of the streaming current in fresh mineral oil across the doping range. In the cases of the other liquids, fullerene C_{60} could be used as an inhibitor in the streaming electrification process. Based on the tests, it was shown that the greatest reduction in the streaming current in the nanofluids occurred at a C_{60} concentration between 100 mg/L and 200 mg/L.

3.5. 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 [62]. The streaming current under the energization condition increased 1.5 to 2 times when performed using 60 Hz electric stress [115]; 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. [116] 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 [117]. Metwally investigated the effects of solid insulation material on the streaming current of transformer oil [118]; 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 [119]. 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 [120]. 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 [121]. Thus, the different fields can affect the streaming phenomenon of insulating liquids in power transformers.

3.6. Impact of Reclamation on Streaming Current

In transformers, the liquid insulant is subjected to a number of stresses that hasten its deterioration. The stress on the insulation is caused by electrical, thermal, and chemical interactions (oxidation and hydrolysis) that lead to acidic compounds, which shortens its lifespan [15]. The sludge that results from these reactions also lowers the tendency of the insulating fluid to transfer heat, thereby increasing the temperature inside the transformer. Adsorbents such as Fuller's earth, activated carbon, bentonite, and alumina are typically used in the reclamation of deteriorated fluid to recover the breakdown and dielectric characteristics [122]. The insulating fluid undergoes a range of chemical reactions during the energization of transformer, after which the deterioration begins. As a result, sludge is formed in the insulating fluid due to acidic derivatives, and polar compounds affect the heat transfer between the surfaces of the coil and core. Therefore, the insulating fluid needs to be rejuvenated to prevent the degraded oil from damaging the transformer's active sections. Regeneration improves the dielectric characteristics of an insulating fluid by adsorbing the acidic compounds, dissolved water, and other impurities that are generated over a long time. In addition to eliminating the impurities formed in the insulating fluid, the restoration process also adsorbs its natural compounds, making it unsafe for use in any new apparatus. Transformers, electrical circuit breakers, and reactors are examples of equipment that benefit from reclamation, whereas regeneration of the insulating fluid from insulation cables, generators, and capacitors is not advised. According to the IEEE C57.637 standard [123], many approaches are used to purify insulating fluids, and descriptions of these procedures include diverse materials, interaction techniques, and filtration process. Additionally, with repeated, continuing treatments, the effects of reclamation diminish and sulfur compounds are added into the fluid [124], which maintenance service engineering personnel should take into account before reusing the fluid for transformer applications. The cost of natural ester was above that of synthetic ester with regard to the retrofilling procedures [125]. In this instance, the alternate fluids provided a more cost-effective solution in terms of retrofilling, design modifications, and timescale.

The reclamation procedures explained above could be effective in reducing the statically induced charges by replacing the oil inside the transformers with a lower charge density. After numerous failures with the transformers in the substation, the concept of reducing static charges was investigated with Fuller's earth [7], which provided a good accuracy when testing at a laboratory scale. After considering the experimental results, the amount of Fuller's earth (3.5 kg/m^3) was chosen along with 0.3% of 2,6-ditertiarybutylparacresol (DBPC) to replace the natural ingredients that were lost during the reclamation process. An acceptance limit of less than 75 $\mu C/m^3$ was observed in the static charges after each experiment. Similar experiments further investigated three single-phase autotransformers by increasing the amount to 5.8 kg/m^3, but this did not reduce the ECT to the acceptable limit allowed in transformers. With the development of ester-based fluids for power transformers, the effect of reclamation on streaming electrification after multiple stresses needs to be understood. Apart from the thermal stress, the electrical stress on the insulating fluid can also modify the dielectric characteristics through the deposition of a carbonaceous substance upon breakdown [126]. Talhi et al. [60] also inferred that rather than reclaiming or reconditioning the degraded oil, the removal of moisture content and dissolved oxygen in mineral oil and synthetic ester fluid could also provide a reduction in the static electrification, along with dielectric and physio-chemical properties. It was inferred that removal of dissolved oxygen, ionization of gas particles, and moisture in the fluid reduced the charging tendency. Considering the above degradation of the insulating fluid upon electrical and thermal stresses, the authors studied its influence on the static electrification associated with ester-based TiO_2 nanofluids [127]. Upon impulse stress, the streaming current showed a reduction of 116% with a polarity reversal for the TiO_2 nanofluid without a surfactant, whereas it showed a reduction of 41% for the TiO_2 nanofluid with a surfactant with no change in its polarity. The oxygen atom, which has an extremely high electro-negativity in nature, breaks from the tetrahedral location in TiO_2 nanoparticles at a certain level of impulse stress, thus causing a drastic reduction in the streaming current. Upon thermal stress, the ester nanofluid with and without surfactant showed a marginal reduction in the streaming current due to the complete depletion of the stability around the electrical double layer of the nanoparticles. The fluid reclamation procedure adopted using bentonite with a one-stage filtering mechanism did not have much of an influence on the reduction in streaming current with nanofluids. This showed that static charges could not be reduced for the nanofluids once there was a depletion in the stable double layer formed around the nanoparticles.

3.7. Influence of Sulfur Compounds on Streaming Current

The corrosive sulfur present in mineral oil is a major problem for liquid-immersed power transformers. There are different derivatives of sulfur compounds (elemental sulfur, thiophenes, disulfides, and mercaptons) that are responsible for the formation of copper sulfide (Cu_2S) on the surface of copper and paper/pressboard insulation [128]. Among the different sulfur compounds, disulphides (dibenzyl disulfide (DBDS)) are mostly responsible for the corrosivity associated with mineral oil over longer operational lifetimes [129]. For the formation of Cu_2S in an insulating fluid, DBDS reacts with copper to form an intermediate DBDS-Cu, which then dissociates into Cu_2S, bibenzyl (BiBz), and dibenzyl sulfide (DBS) [130]. On the surface of on-load tap changer (OLTC) selector contacts, corrosive sulfur species can also result in the creation of silver sulfide where the silver is mostly used to reduce the friction between the contacts [131]. Upon silver sulfide formation, the tap changer contacts have a poor adhesion to Ag_2S, which allows its diffusion into the surrounding insulating fluid [132]. Such sulfide (Cu_2S, Ag_2S) formations within the transformer not only affect the dielectric and physio-chemical properties [133], but also the ECT of the insulating liquid. Okabe et al. [134] investigated the impact of different sulfur compounds such as octyl sulfide, octyl sulfoxide, octyl sulfone, and octyl sulfonic acid on the ECT of an insulating fluid under accelerated ageing conditions. The sulfur compounds resulted in a minimal change at room temperature with sulfonic acid and sulfonium ions, leading to negative and positive charging of the liquid. The addition of Ag_2S to both mineral oil and a mixed fluid were studied at different concentrations for its ECT and rheological properties [135]. Both the fluids exhibited a negative streaming current, with the mixed fluid showing a higher magnitude than mineral oil. Similar to the interaction of nitrogen ions from BTA molecules at the interface, the sulfide ions (S^{2-}) introduced more negative ions at the interface material, resulting in a negative streaming current. Although many passivators were tested for the removal of sulfide formation on copper, silver, and pressboard material [136–138], its influence on the ECT of the insulating liquid in transformers is still less known, and thus more detailed information is required before installing insulating liquids containing sulfur in power transformers.

4. Conclusions and Future Scope

The following conclusions were made based on the extensive database available on the streaming electrification of insulating fluids:

- Different techniques are used for the evaluation of the charging tendency associated with an insulating liquid; each method employs a specific flow pattern, volume of oil, and solid material, which leads to different conclusions. There is still no specific standardized technique for measuring the streaming current of power transformers, and thus a suitable standard should be formulated to relate laboratory investigations to practical applications. When considering the present techniques used for measuring static electrification, the Couette charge test system has the greatest potential to become a standardized method because it evaluates the charging tendency of insulating fluids in the presence of an electric field.
- Various factors such as the speed, temperature, electric field, flow behavior, and surface roughness affect the streaming phenomenon. Mineral oil containing aromatic hydrocarbons has a lower electrostatic charging tendency compared to ester fluids. However, a ranking within the ester liquids is not possible because different grades of natural ester (MIDEL 1215, MIDEL 1204, and FR3) extracted from soyabean and rapeseed exhibited different behaviors to that of a synthetic ester manufactured through an esterification reaction. Among the different insulating liquids, ester fluids showed a higher streaming current than mineral oil and silicon liquid; however, when considering the overall transformer operational lifetime in terms of other physio-chemical and dielectric properties, ester fluids are viable for power transformers with some design modifications.
- Nanofluids, which have gained greater importance in transformers in recent years, have much less available information in terms of streaming electrification. Similar to the testing of the effects of different nanoparticles and surfactants on various dielectric characteristics, the charging tendencies of nanofluids should also be considered by the insulation engineers before their installation in real-time power transformers.
- The additives used for suppressing the streaming current should not exceed 100 ppm, thereby not affecting the other dielectric properties in power transformers. Nanofluids showed a higher streaming current and the requirement for additive concentration was more than 500 ppm with benzotriazole. Therefore, the selection of a suitable additive for suppression of the streaming current is also a major factor to be taken into consideration.
- In practical applications, streaming electrification is noticed in the presence of an electric field, but with advancements in alternative esters and nanofluids, such studies are still within the scope of various researchers in the field of high-voltage technology.
- The reclamation of aged fluid, which is performed to remove degradation byproducts, must also be considered in streaming electrification so that a potential buildup across the pressboard spacers that provide mechanical support for the copper windings in transformers can be avoided.
- The impact of copper sulfide (Cu_2S) and silver sulfide (Ag_2S) diffusion in oil is detrimental to both the pressboard/paper insulation and the copper windings. These two sulfides can be used with both mineral oil and ester fluids when the same adsorbents are reused again for the reclamation process. The interaction of sulfide ions at the electrical double layer can result in different physio-chemical reactions that lead to changes in the ion exchange in the fixed layer and the diffused layer.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Conflicts of Interest: the authors declare no conflict of interest.

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. [CrossRef]
2. Metwally, I.A. Failures, monitoring and new trends of power transformers. *IEEE Potentials* **2011**, *30*, 36–43. [CrossRef]
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. [CrossRef]
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. [CrossRef]
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. [CrossRef]
7. Crofts, D.W. The electrification phenomena in power transformers. *IEEE Trans. Electr. Insul.* **1988**, *23*, 137–146. [CrossRef]
8. Borja, J.; Taleon, D.M.; Auresenia, J.; Gallardo, S. Polychlorinated biphenyls and their biodegradation. *Process Biochem.* **2005**, *40*, 1999–2013. [CrossRef]
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. [CrossRef]
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. [CrossRef]
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. [CrossRef]
12. Rouse, T.O. Mineral insulating oil in transformers. *IEEE Electr. Insul. Mag.* **1998**, *14*, 6–16. [CrossRef]
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. [CrossRef]
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. [CrossRef]
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. [CrossRef]
16. Rao, U.M.; Sood, Y.R.; Jarial, R.K. Ester dielectrics: Current perspectives and future challenges. *IETE Tech. Rev.* **2017**, *34*, 448–459. [CrossRef]
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. [CrossRef]
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. [CrossRef]
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. [CrossRef]
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. [CrossRef]
23. Li, Y.; Tung, S.; Schneider, E.; Xi, S. A review on development of nanofluid preparation and characterization. *Powder Technol.* **2009**, *196*, 89–101. [CrossRef]
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. [CrossRef]
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. [CrossRef]
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. [CrossRef]
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. [CrossRef]
28. Du, B.; Li, J.; Wang, F.; Yao, W.; Yao, S. Influence of monodisperse Fe_3O_4 nanoparticle size on electrical properties of vegetable oil-based nanofluids. *J. Nanomater.* **2015**, *2015*, 560352. [CrossRef]
29. Raj, R.A.; Samikannu, R.; Yahya, A.; Mosalaosi, M. Investigation of Survival/Hazard Rate of Natural Ester Treated with Al_2O_3 Nanoparticle for Power Transformer Liquid Dielectric. *Energies* **2021**, *14*, 1510. [CrossRef]
30. Sierota, A.; Rungis, J. Electrostatic charging in transformer oils. Testing and assessment. *IEEE Trans. Dielectr. Electr. Insul.* **1994**, *1*, 840–870. [CrossRef]

31. Wu, H.; Jayaram, S. DC field effects on streaming electrification in insulating oils. *IEEE Trans. Dielectr. Electr. Insul.* **1996**, *3*, 499–506. [CrossRef]
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. [CrossRef]
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. [CrossRef]
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. [CrossRef]
35. Moreau, O.; Paillat, T.; Touchard, G. Flow electrification in transformers: Sensor propotype for electrostatic hazard. *Electrostatics* **2003**, *178*, 31–36.
36. Paillat, T.; Touchard, G.; Bertrand, Y. Capacitive sensor to measure flow electrification and prevent electrostatic hazards. *Sensors* **2012**, *12*, 14315–14326. [CrossRef]
37. Amalanathan, A.J.; Sarathi, R.; Harid, N.; Griffiths, H. Degradation Assessment of Ester Liquids. In *Alternative Liquid Dielectrics for High Voltage Transformer Insulation Systems: Performance Analysis and Applications*; Mohan Rao, U., Fofana, I., Sarathi, R., Eds.; John Wiley & Sons: Hoboken, NJ, USA, 2021; pp. 85–125.
38. Oommen, T.V.; Petrie, E.M. Electrostatic Charging Tendency of Transformer Oils. *IEEE Trans. Power Appar. Syst.* **1984**, *103*, 1923–1931. [CrossRef]
39. Lyon, D.J.; Melcher, J.R.; Zahn, M. Couette charger for measurement of equilibrium and energization flow electrification parameters: Application to transformer insulation. *IEEE Trans. Electr. Insul.* **1988**, *23*, 159–176. [CrossRef]
40. Washabaugh, A.P.; Zahn, M. Flow electrification measurements of transformer insulation using a Couette flow facility. *IEEE Trans. Dielectr. Electr. Insul.* **1996**, *3*, 161–181. [CrossRef]
41. Morin, A.J.; Zahn, M.; Melcher, J.R. Fluid electrification measurements of transformer pressboard/oil insulation in a Couette charger. *IEEE Trans. Electr. Insul.* **1991**, *26*, 870–901. [CrossRef]
42. Peyraque, L.; Beroual, A.; Buret, F. Static electrification of pressboard/oil interface and transient phenomena. *IEEE Trans. Dielectr. Electr. Insul.* **1998**, *5*, 443–449. [CrossRef]
43. CIGRE Joint Working Group 12/15-13. *Static Electrification in Power Transformers, General Session, Paper 15/12-03*; CIGRE: Paris, France, 1992.
44. Zmarzły, D.; Frącz, P. Measurement of Dielectric Liquid Electrification in the Shuttle System with Two Parallel Electrodes. *Energies* **2021**, *14*, 970. [CrossRef]
45. Zmarzły, D.; Frącz, P. Streaming electrification in the swinging plate system. *IEEE Trans. Dielectr. Electr. Insul.* **2017**, *24*, 3217–3225. [CrossRef]
46. Zmarzły, D.; Kędzia, J. A noise analyzer for monitoring static electrification current. *J. Electrost.* **2005**, *63*, 409–422. [CrossRef]
47. Von Helmholtz, H.L.F. Studies of electric boundary layers. *Wied. Ann.* **1879**, *7*, 337–382.
48. Grahame, D.C. The electrical double layer and the theory of electrocapillarity. *Chem. Rev.* **1947**, *41*, 441–501. [CrossRef]
49. Parsons, R. The electrical double layer: Recent experimental and theoretical developments. *Chem. Rev.* **1990**, *90*, 813–826. [CrossRef]
50. Metwally, I.A. Characterization of static electrification in power transformers. *IEEE Trans. Dielectr. Electr. Insul.* **1996**, *3*, 307–315. [CrossRef]
51. 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. [CrossRef]
52. Oommen, T.V. Static electrification properties of transformer oil. *IEEE Trans. Electr. Insul.* **1988**, *23*, 123–128. [CrossRef]
53. 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. [CrossRef]
54. 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. [CrossRef]
55. Amalanathan, A.J.; Sarathi, R.; Harid, N.; Griffiths, H. Modeling of Spinning Disk System for Charging Tendency of Ester-Based TiO_2 Nanofluids Along With its Interfacial Zone. *IEEE Trans. Dielectr. Electr. Insul.* **2022**, *29*, 462–469.
56. 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. [CrossRef]
57. 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. [CrossRef]
58. 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.
59. Kedzia, J.; Willner, B. Electrification current in the spinning disk system. *IEEE Trans. Dielectr. Electr. Insul.* **1994**, *1*, 58–62. [CrossRef]
60. 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. [CrossRef]

61. 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. [CrossRef]
62. 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. [CrossRef]
63. 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.
64. Kedzia, J.; Brozostek, E. Static electrification in transformer oil as a measure of its aging. *IEEE Trans. Electr. Insul.* **1984**, *19*, 101–106. [CrossRef]
65. 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. [CrossRef]
66. 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.
67. Talhi, M.; Fofana, I.; Flazi, S. Impact of free radicals on the electrostatic charging tendency of transformer oils. *Electr. Eng.* **2020**, *102*, 1265–1274. [CrossRef]
68. 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. [CrossRef]
69. 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. [CrossRef]
70. 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. [CrossRef]
71. 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. [CrossRef]
72. 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. [CrossRef]
73. 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. [CrossRef]
74. 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.
75. 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.
76. 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.
77. 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.
78. Zdanowski, M. Streaming electrification of mineral insulating oil and synthetic ester MIDEL 7131. *IEEE Trans. Dielectr. Electr. Insul.* **2014**, *21*, 1127–1132. [CrossRef]
79. 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. [CrossRef]
80. 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.
81. 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.
82. Fofana, I.; Wasserberg, V.; Borsi, H.; Gockenbach, E. Challenge of mixed insulating liquids for use in high-voltage transformers. 1. Investigation of mixed liquids. *IEEE Electr. Insul. Mag.* **2002**, *18*, 18–31. [CrossRef]
83. Zdanowski, M.; Kędzia, J. Research on the electrostatic properties of liquid dielectric mixtures. *J. Electrost.* **2007**, *65*, 506–510. [CrossRef]
84. Zdanowski, M.; Wolny, S.; Zmarzły, D.O.; Boczar, T. ECT of ethanol and hexane mixtures in the spinning disk system. *J. Electrost.* **2007**, *65*, 239–243. [CrossRef]
85. Gayathri, R.; Sundari, P.D.; Thakur, S.; Sarathi, R. Investigation on the dielectric performance of titania nanoparticles and surfactant added mixture of mineral and natural ester oil. *Mater. Res. Express* **2019**, *6*, 125020. [CrossRef]
86. Ranga, C.; Kumar Chandel, A.; Chandel, R. Performance analysis of alternative solid dielectrics of power transformers with a blend of mineral and silicon oils. *IETE Tech. Rev.* **2018**, *35*, 331–341. [CrossRef]

87. Raof, N.A.; Yunus, R.; Rashid, U.; Azis, N.; Yaakub, Z. Effects of palm-based trimethylolpropane ester/mineral oil blending on dielectric properties and oxidative stability of transformer insulating liquid. *IEEE Trans. Dielectr. Electr. Insul.* **2019**, *26*, 1771–1778. [CrossRef]
88. Lyutikova, M.; Korobeynikov, S.; Rao, U.M.; Fofana, I. Mixed Insulating Liquids with Mineral Oil for High Voltage Transformer Applications: A Review. *IEEE Trans. Dielectr. Electr. Insul.* **2022**, *29*, 454–461. [CrossRef]
89. Poovamma, P.K.; Pattanshetti, V.V.; Ahmed, T.A.; Sudhindra, A. Charging tendency of mineral oils and synthetic ester mixtures. In Proceedings of the IEEE International Conference on Dielectric Liquids, Trondheim, Norway, 26–30 June 2011; pp. 1–4.
90. Zdanowski, M.; Maleska, M. Streaming Electrification of Insulating Liquid Mixtures. *Arch. Electr. Eng.* **2019**, *68*, 387–397.
91. Zdanowski, M. Electrostatic Charging Tendency Analysis Concerning Retrofilling Power Transformers with Envirotemp FR3 Natural Ester. *Energies* **2020**, *13*, 4420. [CrossRef]
92. Zdanowski, M. Streaming Electrification of Nycodiel 1255 Synthetic Ester and Trafo EN Mineral Oil Mixtures by using Rotating Disc Method. *Energies* **2020**, *13*, 6159. [CrossRef]
93. Xuan, Y.; Li, Q. Heat transfer enhancement of nanofluids. *Int. J. Heat Fluid Flow* **2000**, *21*, 58–64. [CrossRef]
94. Rafiq, M.; Lv, Y.; Li, C. A review on properties, opportunities, and challenges of transformer oil-based nanofluids. *J. Nanomater.* **2016**, *2016*, 1–23. [CrossRef]
95. Amizhtan, S.K.; Amalanathan, A.J.; Babu, M.S.; Sarathi, R.; Kumar, G.; Sangwai, J.S.; Edin, H.; Taylor, N. Experimental Study and ANN Analysis of Rheological Behavior of Mineral Oil-based SiO2 Nanofluids. *IEEE Trans. Dielectr. Electr. Insul.* **2022**, *29*, 956–964. [CrossRef]
96. Amizhtan, S.K.; Amalanathan, A.J.; Sarathi, R.; Srinivasan, B.; Gardas, R.L.; Edin, H.; Taylor, N. Impact of Surfactants on the Electrical and Rheological Aspects of Silica Based Synthetic Ester Nanofluids. *IEEE Access* **2022**, *10*, 18192–18200. [CrossRef]
97. Anju, P.; Aryanandiny, B.; Amizhtan, S.K.; Gardas, R.L.; Sarathi, R. Investigation on the Electrical and Rheological Properties of AlN-Based Synthetic Ester Nanofluids. *IEEE Access* **2022**, *10*, 37495–37505. [CrossRef]
98. Amalanathan, A.J.; Sarathi, R.; Harid, N.; Griffiths, H. Investigation on flow electrification of ester-based TiO2 nanofluids. *IEEE Trans. Dielectr. Electr. Insul.* **2020**, *27*, 1492–1500. [CrossRef]
99. Fofana, I. 50 years in the development of insulating liquids. *IEEE Electr. Insul. Mag.* **2013**, *29*, 13–25. [CrossRef]
100. 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. [CrossRef]
101. 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.
102. 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. [CrossRef]
103. 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.
104. 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.
105. 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.
106. 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. [CrossRef]
107. 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.
108. 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.
109. Nelson, J.K. Dielectric fluids in motion. *IEEE Electr. Insul. Mag.* **1994**, *10*, 16–28. [CrossRef]
110. Radwan, R.M.; El-Dewieny, R.M.; Metwally, I.A. Investigation of static electrification phenomenon due to transformer oil flow in electric power apparatus. *IEEE Trans. Electr. Insul.* **1992**, *27*, 278–286. [CrossRef]
111. Amalanathan, A.J.; Sarathi, R.; Harid, N.; Griffiths, H. Impact of benzotriazole on the degradation performance of ester fluid. In Proceedings of the IEEE Electrical Insulation Conference (EIC), Virtual Event, 7–28 June 2021; pp. 610–613.
112. Aksamit, P.; Zmarzły, D. C60 as flow electrification inhibitor in mineral insulating oil. *J. Electrost.* **2011**, *69*, 195–199. [CrossRef]
113. Aksamit, P.; Zmarzly, D.; Boczar, T. Electrostatic properties of aged fullerene-doped mineral oil. *IEEE Trans. Dielectr. Electr. Insul.* **2011**, *18*, 1459–1462. [CrossRef]
114. Zdanowski, M. Streaming Electrification of C_{60} Fullerene Doped Insulating Liquids for Power Transformers Applications. *Energies* **2022**, *15*, 2496. [CrossRef]
115. 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.

116. 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. [CrossRef]
117. 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. [CrossRef]
118. Metwally, I.A. Influence of solid insulating phase on streaming electrification of transformer oil. *IEEE Trans. Dielectr. Electr. Insul.* **1997**, *4*, 327–340. [CrossRef]
119. Huh, C.S.; Jeong, J.I. Streaming electrification of thin insulating pipes under electric field. *IEEE Trans. Dielectr. Electr. Insul.* **1998**, *5*, 199–203.
120. Metwally, I.A. Flow electrification of transformer oil effects of mixed fields. *IEEE Trans. Dielectr. Electr. Insul.* **1998**, *5*, 518–526. [CrossRef]
121. 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. [CrossRef]
122. Safiddine, L.; Hadj-Ziane Zafour, A.; Fofana, I.; Skender, A.; Guerbas, F.; Boucherit, A. Transformer oil reclamation by combining several strategies enhanced by the use of four adsorbents. *IET Gener. Transm. Distrib.* **2017**, *11*, 2912–2920. [CrossRef]
123. IEEE C57.637. *IEEE Guide for the Reclamation of Mineral insulating Oil and Criteria for Its Use*; IEEE Std C57.637-2015 (Revision of IEEE Std 637-1985); IEEE SA Standard Association: New York, NY, USA, 2015; pp. 1–38.
124. Velásquez, R.M.A.; Lara, J.V.M. Corrosive Sulphur effect in power and distribution transformers failures and treatments. *Eng. Fail. Anal.* **2018**, *92*, 240–267. [CrossRef]
125. Smolka, T.; MacArthur, T.L.; Frotscher, R.; Mattos, R. Natural/synthetic esters usage from an OLTC Perspective. In Proceedings of the TechCon®—NZ 2018, Sydney, Australia, 16–18 April 1–20.
126. Mahidhar, G.D.P.; Somasundaram Karthikeyan, A.; Sarathi, R.; Taylor, N.; Edin, H. Dielectric properties of mixed mineral and synthetic ester oil. *IET Sci. Meas. Technol.* **2020**, *14*, 704–714. [CrossRef]
127. Amalanathan, A.J.; Harid, N.; Griffiths, H.; Sarathi, R. Impact of adding activated bentonite to thermally aged ester-based TiO_2 nanofluids on insulation performance. *IET Nanodielectrics* **2021**, *4*, 63–74. [CrossRef]
128. Scatiggio, F.; Tumiatti, V.; Maina, R.; Tumiatti, M.; Pompili, M.; Bartnikas, R. Corrosive sulfur in insulating oils: Its detection and correlated power apparatus failures. *IEEE Trans. Power Deliv.* **2007**, *23*, 508–509. [CrossRef]
129. Akshatha, A.; Rajan, J.S.; Ramachandra, H. Study of degradation of sulphur compounds and depletion of metal passivators during thermal ageing of mineral oil. *IEEE Trans. Dielectr. Electr. Insul.* **2015**, *22*, 2786–2797. [CrossRef]
130. Amimoto, T.; Nagao, E.; Tanimura, J.; Toyama, S.; Fujita, Y.; Kawarai, H.; Yamada, N. Identification of affecting factors of copper sulfide deposition on insulating paper in oil. *IEEE Trans. Dielectr. Electr. Insul.* **2009**, *16*, 265–272. [CrossRef]
131. Holt, A.F.; Facciotti, M.; Amaro, P.; Brown, R.C.D.; Lewin, P.L.; Pilgrim, J.A.; Wilson, G.; Jarman, P. An initial study into silver corrosion in transformers following oil reclamation. In Proceedings of the IEEE Electrical Insulation Conference (EIC), Ottawa, ON, Canada, 2–5 June 2013; pp. 469–472.
132. Samarasinghe, S.; Ma, H.; Martin, D.; Saha, T. Investigations of silver sulfide formation on transformer OLTC tap selectors and its influence on oil properties. *IEEE Trans. Dielectr. Electr. Insul.* **2019**, *26*, 1926–1934. [CrossRef]
133. Amizhtan, S.K.; Amalanathan, A.J.; Sarathi, R.; Vinu, R. Impact of DBDS and Silver Sulfide on the Performance of Thermally Aged Mineral oil Impregnated Pressboard Material. *IEEE Access* **2022**, *10*, 9618–9627. [CrossRef]
134. Okabe, S.; Kohtoh, M.; Amimoto, T. Investigation of electrostatic charging mechanism in aged oil-immersed transformers. *IEEE Trans. Dielectr. Electr. Insul.* **2010**, *17*, 287–293. [CrossRef]
135. Amalanathan, A.J.; Sarathi, R.; Sarkar, B.; Gardas, R.L.; Harid, N.; Griffiths, H. Impact of silver sulfide on rheology and streaming electrification of mineral oil and mixed fluid. *J. Electrost.* **2022**, *119*, 103747. [CrossRef]
136. Samarasinghe, S.; Ma, H.; Ekanayake, C.; Martin, D.; Saha, T. Investigating passivator effectiveness for preventing silver sulfide corrosion in power transformer on-load tap changers. *IEEE Trans. Dielectr. Electr. Insul.* **2020**, *27*, 1761–1768. [CrossRef]
137. Cong, H.; Pan, H.; Qian, D.; Zhao, H.; Li, Q. Reviews on sulphur corrosion phenomenon of the oil–paper insulating system in mineral oil transformer. *High Volt.* **2021**, *6*, 193–209. [CrossRef]
138. Amalanathan, A.J.; Sarathi, R.; Harid, N.; Griffiths, H. Investigation of the Effect of Silver Sulfide on the Dielectric Properties of Mixed Insulating Liquid. In Proceedings of the IEEE International Symposium on Electrical Insulating Materials (ISEIM), Tokyo, Japan, 13–17 September 2020; pp. 343–346.