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Alternative Dielectric Fluids for Transformer Insulation System: Progress, Challenges, and Future Prospects

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ABSTRACT Ester-based dielectric fluids have gained widespread popularity for applications in high voltage apparatus. Synthetic and natural esters have been subjected to research for decades vis-à-vis mineral insulating oils around the world. Although many researchers favor the application of ester fluids, utilities are still uncertain and application of these alternatives remains a challenge. The intent of this survey is to present recent research progress and highlight the state of the art of key aspects that should be emphasized in future research. The contemporary research scenarios pertaining to the performance of ester fluids versus mineral oils, miscibility, and retrofilling of insulating fluids are discussed. In addition, pre-breakdown phenomena, usage of esters in on-load tap changers, environmental and fire resistance properties, and use of esters in cold climates are also discussed. Importantly, challenges and future aspects that should be investigated to improve the existing knowledge of ester dielectric fluids for applications in transformer technology are highlighted.

INDEX TERMS Transformer, dielectric fluids, insulating materials, ester fluids.

I. INTRODUCTION

Transformers are among the most important equipment in an electrical power network. Their performance has a noticeable effect on the reliability of the power network. Operating in variable temperatures and loading conditions, transformers are expected to serve successfully for the full theoretical designed life. Oil/paper insulation plays a vital role in determining transformers' performance and life. The insulation system in a transformer is a composite insulating medium composed of oil and paper. Insulating oil is expected to serve as an insulant, coolant, protective barrier for the core, and diagnostic medium for the transformer.

A wide range of liquid dielectrics are available naturally or synthesized chemically and then pre-processed for application in transformer insulation technology [1]. Liquid dielectrics are classified into organic and inorganic chemical compounds [2]. Organic compounds may be natural or agricultural oils such as soybean oils, coconut oils, etc., which are fatty acids generated in seeds and flowers [3, 4]. These agricultural oils are ester compounds and are generally referred to as natural esters. Inorganic compounds are chemically developed or synthesized; these include mineral oils, silicone oils, synthetic liquids, nanofluids, and mixed insulating fluids. Mineral insulating oils are hydrocarbons derived from crude petroleum while silicone oils are halogen-free synthetic compounds that are products of polymerization [5]. Synthetic liquids are chemically formed substitutes for hydrocarbons such as polychlorinated biphenyls (PCBs) and synthetic esters. To date, research on insulating oils for transformers has gone through several critical stages and the shortfalls and advantages of various insulating fluids have been reported. A detailed report on the progress of insulating oils over 50 years was published in 2013 in [1].

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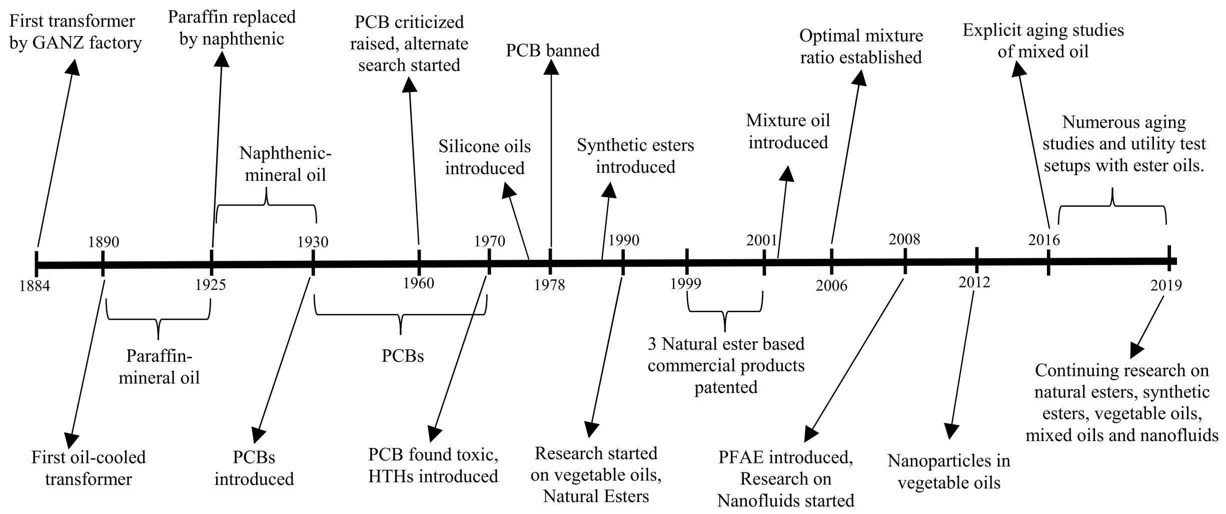

FIGURE 1. **Timeline: Development of transformer insulating fluids.**

In the recent past, ester-based dielectric fluids, both natural and synthetic, have gained considerable popularity among global research communities and industries interested in liquid dielectrics. In particular, the biodegradability of ester-based dielectric fluids is an important characteristic. Hence, there is real scope and demand to improve the existing knowledge and literature on these new insulating fluids. This article seeks to summarize potential and contemporary issues concerning ester dielectric fluids. It will emphasize the aspects that are of key concern to researchers and industry. After a critical survey, the authors identified the aspects of the usage of ester fluids in transformers listed below, which should be further investigated.

- The miscibility and retrofilling aspects of the new insulating oils.
- The workability of ester fluids in regions with cold climates.
- The application of ester fluids in on-load tap changers (OLTCs).
- Pre-breakdown phenomena of ester fluids and the effect of insulation age on streamer behavior.
- Environmental performance and fire-related aspects.

The citations considered in this study provide technical data relevant in testing the hypothesis that ester fluids can be applied in transformers. The above-mentioned factors were found to have significant potential for future research and should help improve knowledge of the application of ester fluids. This study provides information on the performance of various insulation oils in the development of oil-filled transformers since their inception. The disadvantages of traditional mineral oils that highlight the need for alternatives are discussed. The contemporary research scenarios pertaining to ester dielectric fluids and challenges in using them to replace mineral oils are also addressed. Recent research progress on mixed insulating fluids versus mineral oils and ester fluids is reported. In addition, a detailed state-of-the-art review and potential future scope for all the individual issues identified above are provided.

II. EVOLUTION OF TRANSFORMER INSULATION OILS

Over the years, various kinds of insulating fluids have been used in transformers to cater to regular industry needs and respect environmental regulations. The evolution of liquid dielectrics from the beginning of transformer technology to the present state is summarized in Figure 1.

From the inception of oil-filled transformers, mineral insulating oils (derivatives of crude petroleum) were adopted for insulation and cooling purposes. Mineral oils are extracted from either paraffin or naphthenic-based crude oils. Until 1925, paraffin-based mineral insulating oils were used; they were replaced by naphthenic-based ones because of the high pour point of the paraffin-based oils [6]. Although mineral oils were used predominantly, their low fire resistance caused problems and led the industry to search for an alternative.

In 1930, PCBs were found to have high fire resistance and better dielectric properties than mineral oil. Until the 1960s, PCB was used as a transformer insulating fluid. However, environmental issues were raised [7], and in the 1970s, the public started to oppose their use, as new discoveries led to claims that PCBs were extremely toxic organic environmental pollutants [8]. It was then revealed that PCBs have dangerous emission profiles in certain combustion conditions. In 1978, the regulatory commissions outlawed the use of PCBs due to their toxicity [9]. This increased industry's desire for eco-friendly insulating fluids. In the 1980s, industry started to search for new alternative insulating fluids. Furthermore, in 2009, equipment containing PCBs higher than a set value was incinerated in some parts of Europe [1].

Meanwhile, high-temperature hydrocarbons (HTH) were found to have good thermal performance but their high viscosity called for major changes in cooling system design, which reduced industry's interest [5]. In 1970, silicon oils were introduced to replace PCBs due to their good thermal performance and nontoxicity, but their high cost limited use to some special transformer applications [10].

Synthetic esters, which are synthesized from alcohols and acids, were introduced by researchers during the 1990s [11]. Synthetic esters were found to have high dielectric strength; they are biodegradable, less viscous, and have a higher fire point [8]. At the same time, due to strict environmental regulations and the global interest in green technologies and sustainable fuels, researchers started studying vegetable oils and natural esters in the 1990s [11]. In 1999 and 2001, three commercial products were patented for use in transformers based on different vegetable oils (sunflower oil, canola oil, soybean oil) [12]–[14]. It was reported that natural esters' oxidation stability is low and their application was initially restricted to sealed transformers. Later, efforts were made to improve their oxidation stability by using suitable nanoparticles [15]. Investigations of the characteristics and performance of blended insulating fluids are reported in [16], [17]. In 2006, it was confirmed that a mixture of 80% mineral oil and 20% synthetic ester improves insulating systems' operating performance [18]. In 2008 and 2012, palm fatty acid ester (PFAE) oils were proposed because of their low viscosity and high relative permittivity. Further, ester oil's physical properties and loading/cooling capabilities were modified by dispersing nanoparticles [19], [20]. At the same time, several agricultural oils were investigated worldwide to study their feasibility for application in transformers. It was recently reported that an 80:20 mixture ratio of mineral oil and synthetic esters is optimal for application in transformers [21], [22].

III. NEED FOR ALTERNATIVE INSULATING FLUIDS

Conventionally, cooling and insulation for transformer technology have been done by mineral oil originating in crude oil. In view of the expected future oil crisis, the cost of crude oil is increasing, and thus the availability of crude oil stocks will be questionable [1]. Although the dielectric properties of mineral oils are widely accepted, the demand for high insulating levels requires higher dielectric performance, particularly dielectric breakdown strength [5]. The typical value of breakdown voltage for fresh mineral oil is around 50 kV (according to manufacturers). The demand for higher voltage levels is increasing daily; eventually it becomes problematic for the insulating medium to provide effective insulation and cope with higher temperatures. Also, in the event of arcing or short circuits, the rise in temperatures must be withstood by the insulating oil. This particular situation creates a need for high flash points and fire points in insulating oils. The typical value of the flash point for new mineral oil is in the range of 180 °C to 220 °C, according to the manufacturers [21].

Transformer insulation systems should not be allowed to interact with moisture and environmental air, but moisture is unavoidable. For sealed transformers, moisture is created by cellulose insulation paper; for non-sealed units, it is emitted by cellulose and also enters from the external environment the through breather configuration. The rate of hydrolysis is higher in mineral oil than in ester fluids, leading to the generation of acids, furanic compounds and carbon dioxide in oil. Similarly, oxygen ingress works with gases liberated from insulation paper due to temperature and expedites oxidation. Oxidation involves the generation of acids and water in oil. This water expedites hydrolysis and hampers the polymerization of cellulose papers [23]. The severity of oxidation and hydrolysis in mineral oils tends to increase sludging and induce catastrophic failures and premature aging of transformers if the oil is not properly maintained by reclaiming it when required. If oil spills or is disposed of in water bodies, the chemistry of mineral oils affects the environment more permanently than biodegradable liquids.

High operational temperatures in transformers may lead to fires, creating an element of risk for the operating personnel and surrounding equipment. This may also result in large financial loss and poor asset management and risk assessment. Considering these disadvantages of mineral oils, industries should plan for high budgets and invest in good insurance plans to cover any loss incurred. These issues with mineral oils have compelled industry to seek an alternative for use in oil-filled transformers. The challenge is to identify appropriate alternatives that have good dielectric and thermal properties and are biodegradable and nontoxic with good chemical stability. The new insulating oils must also prove their compatibility with other materials that are used in transformers and satisfy environmental and safety regulations. Importantly, the alternatives must also exhibit an optimal balance between initial investments and maintenance costs. In several experimental studies around the world, one possible alternative for mineral oils has been found to be ester-based oils. The properties of mineral oil and ester fluids are presented in Table 1.

IV. RESEARCH PROGRESS ON ESTER DIELECTRIC FLUIDS

Since the 1990s, numerous studies have reported on the performance of the new insulating fluids in comparison to mineral oils. Most researchers support the use of these new oils as potential replacements for mineral oil. The research outcomes and performance of these new oils have been reviewed. Significant review reports surveying the use of natural and synthetic esters in comparison to mineral oils are summarized in Table 2.

A. PERFORMANCE OF ESTER FLUIDS: RECENT PROGRESS

Most research into alternative dielectric fluids has focused on investigating aging performance, degradation aspects, and aging markers in comparison to mineral oil. It is established in the literature that esters are potential candidates for applications in oil-filled transformers. However, industry hesitates to use these new insulating fluids, because of the unavailability of dedicated condition-monitoring methodologies and a lack of information on pre-discharge events and breakdown phenomena, and retrofilling and miscibility of these new oils. Furthermore, the performance of these new oils in cold climates has not yet been examined in the literature.

TABLE 1. Comparative properties of synthetic esters, natural esters, and mineral oil [1], [5], [24].

Property	Mineral oil	Synthetic ester	Natural ester
Source	Crude petroleum	Chemical synthesis, natural synthesis	Natural and synthesized
Type	Hydrocarbons	Acids and alcohol	Fatty acids
Nature of liquid	Naphthenic/paraffinic	Diester, dimer acid ester, etc.	Ester
Availability	Expected crisis in future	Abundant	Abundant
Cost	Increasing with reduced availability	High	High
Interfacial tension (mN/m) ASTM D971	40 to 45	35 to 39	36
Acidity (mgKOH/g) ASTM D974	0.01	0.06 to 0.2	0.02
Color ASTM D1500	Colorless/ transparent	Colorless/ transparent/pale green	Pale yellow
Density (kg/m^3) @20 °C ASTM D1298	0.83 to 0.89	0.90 to 1.00	0.87 to 0.92
Viscosity (cSt) @40 °C ASTM D445	3.0 to 16.0	14 to 29	16 to 50
Pour point (ºC) ASTM D97	−30 to −63	−40 to −60	−10 to −33
Flash point (ºC) ASTM D92	110 to 175	250 to 310	310 to 343
Fire point (ºC) ASTM D92	110 to 185	300 to 322	300 to 369
Thermal conductivity (W/m K) @20 °C ASTM D2717	0.135	0.165	0.17
Specific heat (kJ/kg K) @25 °C ASTM D2766	1.63 to 2.0	1.80 to 2.30	1.50 to 2.38
Coefficient of thermal expansion (/°C) ASTM D1903	7×10^{-4} to 9×10^{-4}	6.5×10^{-4} to 10×10^{-4}	5.5×10^{-4} to 7×10^{-4}
Gassing tendency (µl/min) ASTM D2300	−10 to +24	+19 to +30	−22 to −80.5
Absorbance (Abs) ASTM D6802	0.02213	0.09674	0.02973
Resistivity (Ω-m) ASTM D1169	10^{13}	10^{13}	10^{13} to 10^{14}
Breakdown voltage (kV) ASTM D1816	45 to 55	75 to 80	80 to 85
Dielectric constant IEC 60247	2.4 @25 °C 2.4 @90 °C	3.0–3.5 @20 °C 2.8–3.0 @90 °C	3.3 @25 °C 2.8 @90 °C
Dissipation factor (%) ASTM D924	0.02@25 °C 0.09@90 °C	0.0006 to 0.001 @25 °C 10^{-4} – 0.03@90 °C	0.08 @25 °C 0.64 @90 °C

TABLE 2. Summary of significant reviews reported in the literature on ester fluids for use in transformer insulation systems.

Reference	Year *	Highlights of review
[5]	2012	• The authors summarize the physicochemical, electrical and environmental properties of commercial ester fluids (natural and synthetic), silicone oils, mineral oils and some vegetable oils.
[11]	2014	• The authors highlight the manufacturing process and use of various vegetable oils in transformer applications. • Critical properties and performance of vegetable oils are summarized in comparison to mineral oils. • Discussions are confined to various vegetable oils that are available worldwide.
[25]	2014	• Various properties of oils are comprehensively reported on, with a focus on the relevant literature and standards covering oil properties. • The authors confine the survey to natural esters and mineral oils.
[26]	2014	• Advantages and challenges in adopting natural esters for transformer insulation technology are highlighted. • The authors restrict the survey to natural esters and mineral oils while listing the challenges related to transformer materials and designing for natural-ester-filled transformers.
[27]	2015	• The research progress associated with the physicochemical, electrical properties of ester fluids (natural and synthetic) is discussed. • The feasibility of using *Pongamia pinnata* oil is investigated in comparison to mineral oil.
[24]	2015	• The properties of commercial ester fluids (natural and synthetic), mineral oils and some vegetable oils are summarized, along with a critical literature survey. • The authors reported the deterioration of ester-based oil/paper insulation versus mineral oils.

* *The year until which detailed published literature is publications considered for review.*

Moreover, environmental performance and regeneration methods have not been emphasized. All of these aspects could potentially aspects expedite the application of ester fluids and improve knowledge of this issue.

Recent research progress in general, with a special emphasis on the above-mentioned aspects, is discussed in this section. The majority of researchers are interested in investigating the feasibility of various vegetable oils for use in transformers. Vegetable oils have proven to have high breakdown voltage and good dielectric properties. The higher rate of oxidation in ester fluids is a major concern, which is quantified using the area under the absorbance spectral curves of ultraviolet-visible infrared spectroscopy. In the recent past, various researchers emphasized different plant-based natural esters, while some authors continued the investigation of natural esters in comparison to mineral and synthetic esters. PFAEs have become one of the popular plant-based oils in the field of alternative oils [28]. The feasibility of palm-based neopentyl glycol diester for use in a transformer was investigated and reported in [29]. Properties such as flash point, pour point, viscosity, dielectric strength, acidity and moisture were analyzed in comparison to mineral oil and natural esters. It was reported that high-molecular-weight aging products, produced with aging in esters, are responsible for increased viscosity. The acidity of palm-based neopentyl glycol diester is lower than that of natural esters, which also proves the potential hydrolytic stability of this new oil.

Tokunaga *et al.* investigated the performance and estimated service life of solid insulation in PFAE-filled transformers [30]–[32]. They claimed that the lifetime of solid insulation in PFAE is 7.3 times higher than in mineral oil. The deterioration rate of paper impregnated and aged in mineral oil was observed to be almost 4 times higher than that of paper in PFAE. Research on natural-ester-filled transformers indicates that evidence of carbon dioxide is the potential aging marker for solid insulation in nitrogen-sealed natural-ester-filled transformers. Investigations of the key properties of *Jatropha curcas* oil as a dielectric liquid are reported in [33]. The impact of esterification on the properties of *Jatropha curcas* oil is also discussed and it was observed that, after esterification (alkali base catalyzed), this oil could also be a substitute for mineral oils. Similarly, performance analyses of Karanja oil [34], edible oils [35], [36], camellia and rapeseed oils [37], and waste vegetable oil [38] have been reported recently, and the superiority of vegetable oils over mineral oils and their feasibility for use in transformers were highlighted. Condition monitoring information of in-service vegetable oils is important information to industry and a real-time monitoring history for a service period of 10 years with vegetable-oil-filled transformers is documented in [39]. These condition monitoring data include significant parameters such as dissipation factor, interfacial tension, acid number, water in oil, dielectric strength, and dissolved gas analysis. It was found that natural esters generate similar traces of dissolved gas to mineral oils but with a higher concentration of ethane.

In addition, the sealing of a natural-ester-filled transformer must be maintained effectively in order to sustain longer service periods.

Natural esters are attracting attention across the industry, and several utilities have started using natural esters for sealed transformers due to their characteristics (renewability, biodegradability, availability and safety) [40]. The performance of natural esters in sealed transformers is good; it is questionable in breather transformers because of the high oxidation rate. However, researchers have worked to understand and improve the oxidation stability of natural esters. Various antioxidants were considered in different proportions and the effects on aging markers were reported. Different oil properties have been correlated with different particle volume fractions of antioxidants to track the properties of oils with various proportions of antioxidants. The addition of more antioxidants to natural esters appears to reduce the dielectric properties of the oil [41]. Propyl gallate and citric acid were also investigated for use as oxidation inhibitors in natural esters and the influence of these inhibitors on oil performance is reported in [42]. Oil oxidation induction time and discharge inception voltage have been studied to evaluate the impact of oxidation stability and breakdown voltage on partial discharge. In [42], the authors also demonstrated mathematical methods to determine the optimal concentration of inhibitors required for the natural-ester-filled transformers to improve the oil's oxidation stability and dielectric strength. Bandara *et al.* evaluated the performance of natural-ester-based oil paper/pressboard insulation; their studies aimed to understand the aging aspects of natural-ester-filled transformers in high-moisture environments and the dielectric response of insulation [43]–[45]. They found that at first the rate of degradation of pressboard in natural esters is higher than that in mineral oil, but later it is controlled. The hydrolytic degradation of pressboard in mineral oil becomes prominent after midlife, whereas degradation rates slow down with aging in natural esters. This is because esters consume more moisture during hydrolysis and maintain the dryness of solid insulation, thus slowing the aging of cellulose. They also mentioned that hydrolytic deterioration of natural-ester-based oil/paper insulation has no major impact on oil viscosity. Degradation of oil/paper insulation is mainly attributed to colloidal particles and soluble particles. These decay products, along with moisture, play an important role in hampering the oil's dielectric strength. The effects of cellulose particles [46], water bubbles [47], and metal particles [40] on oil performance were investigated in different proportions with natural-ester-based oil/paper insulation. Those studies focused on the conductivity aspects of cellulose decay content, metal particles, and moisture generated with respect to the insulation degradation and corresponding effect on breakdown voltage. It is already established that the rate of degradation for cellulose insulation paper is lower in ester fluids than in mineral oils. This has been explicitly verified through direct paper characterizations by subjecting ester-based oil/paper insulation to vigorous thermal aging [48]–[54]. Direct measurements such as degree of polymerization, moisture on paper, cellulose crystal size, relative crystallinity of cellulose, expansion/shrinkage properties of cellulose pressboard, tensile strength, furan analysis and molecular properties have been reported. Esters seem to arrest the deterioration rate of cellulose insulants and thus prove superior to mineral oils in terms of cellulose degradation index under the studied laboratory conditions.

B. RETROFILLING AND MISCIBILITY

Mineral oils and ester dielectric fluids have the property of miscibility: they may be mixed to any proportions. The challenge is to study the behavior of mixed oil and investigate the optimal proportion of mixing for use in transformers. Mixed oil is expected to have better electrical, dielectric and operational properties than mineral oil while being cheaper than ester fluids. In 2002, the dielectric properties, moisture behavior and performance of insulation paper were investigated and reported for various proportions of mineral oil and ester oil [16], [17]. It was also reported that the addition of esters to mineral oil improves the mineral oil's performance while indicating the unavailability of standard procedures for mixing oils [55]. The properties of mineral oil and the performance of insulation paper are found to be improved with the addition of esters to mineral oil, but determining the proportion that would lead to optimal performance is a challenge. Dielectric strength is considerably improved, thus reducing the risk of malfunction due to insulation failure [56]. The critical parameters, including kinematic viscosity, dielectric strength and electrostatic charge tendency, were investigated in [18], [57]. The results indicated that 20% of mineral oil replaced with synthetic esters is an optimal mixture for use in transformers. The interesting behavior and properties of mixed oils attracted the attention of researchers interested in mixed insulating fluids, and research progressed toward long-term aging studies. The aging behavior of mixed oil is investigated by subjecting it to accelerated thermal stresses; the results supported the use of mixed oil [58]. Oxidative aging studies of a blend of synthetic ester and mineral oil (20:80) investigated absorbance, dissolved decay products, and interfacial tension, and proved that the addition of esters slows the rate of degradation of mineral oil significantly [21]. Long-term degradation-monitoring curves based on interfacial tension and absorbance have been investigated for mixed oil in comparison to mineral oil, synthetic esters and natural esters [59]. Degradation-monitoring curves are investigated through an explicit thermal aging process. The rate of deterioration of esters is slower than for mineral oil and the addition of ester fluids to mineral fluids retards degradation. The thermal properties of oil with different proportions of synthetic esters and mineral oil were reported in [60], including measurements of thermal expansion, thermal conductivity, viscosity, density, and specific heat. Micro-level degradation aspects of cellulosic insulation paper aged in 80% mineral oil and 20% synthetic esters have been reported using Fourier-transform infrared spectroscopy, flash point measurement, X-ray diffraction analysis, and dilatometry [61], [62]. It was reported that the reduction in cellulose crystal size and shrinkage of cellulose fibers can be prevented by introducing ester compounds into mineral oil. It was also reported that the environmental and fire properties of mineral oil could be improved by the addition of esters. Stability analyses of mixed oil by thermal, electrical and breakdown stressing are presented in [22]. Oil absorbance and pressure varied proportionally with the addition of esters.

Gassing tendency is reported to increase with the addition of ester compounds to mineral oil. Some authors recommend blended oil (80:20) for applications in transformers to achieve an effective techno-economical balance. Recently, the performance of mixtures of olive oil and Jatropha oil with mineral oil in different proportions has been investigated [63], [64]. The physicochemical, dielectric, and electric properties were reported for different ratios of mineral oil and olive oil. It appears probable that the performance of mineral oil can be improved by adding vegetable oils. The addition of olive oil up to 15% and of Jatropha oil up to 20% to mineral oil improves the mineral oil's performance. Recently, the dielectric properties and heat-dissipating ability of blends of mineral oil with olive oil and sunflower oil were investigated and the study confirmed the use of mixed oil for non-cold-climate regions [65].

C. PRE-BREAKDOWN PHENOMENA

The dielectric strength of insulating materials is generally characterized by withstanding voltages before application in electrical equipment. This characterization is classified based on the type of voltage used for testing: impulse waves and power frequency waves. Impulse voltage testing also serves for basic insulation level (BIL) testing and is normally used to test the insulation systems of large power transformers. Insulation engineers designing a transformer insulation system normally use BIL with an additional safety margin. Breakdown and pre-breakdown phenomena are significant topics that must be researched to understand the breakdown process. Research on these topics pertaining to mineral oils has continued for years, and critical reviews of studies are documented in [66], [67]. It is known that the pre-breakdown process and characteristics of breakdown events are attributable to the chemical composition of the insulation liquid. Hence, there is a real need to understand the breakdown phenomena associated with new insulating liquids in comparison to mineral oils. Although several researchers have investigated these aspects of ester-based insulating fluids, there is still scope for research on the pre-breakdown and breakdown phenomena of new insulating fluids. This section summarizes work done on these phenomena with ester fluids.

Breakdown for synthetic esters and natural esters is evaluated at different electrode gap distances, and a relationship between breakdown voltage and gap distance has been established [68]. It is reported that streamer inception voltages are comparable to those found with mineral oil, but streamer propagation is faster in ester-based oils. The stopping lengths of streamers in esters and mineral oil are compared at various electrode geometries in [69] for positive and negative streamers. The authors observed that conductivity and stopping lengths of positive streamers are greater than for negative streamers. The stopping lengths in natural esters are found to be longer than those in mineral oils, especially with negative polarity. Discharge velocity and discharge spectra for mineral oil and ester fluids are studied and reported in [70]–[72]. The slow and fast discharges have been explained based on inception voltage and applied voltage, and that slow discharges are reported to develop below acceleration voltages while fast discharges develop above acceleration voltages.

Generally, slow or fast streamers accompany breakdown in dielectric liquids. Slow streamers are seen in 1st and 2nd modes, while fast streamers are observed in 3rd and 4th modes. The mode of streamer propagation depends on the magnitude of test voltage and field stress. Breakdowns in dielectric fluids are usually noticed with slow (2nd mode) and fast (3rd mode) streamers; the 1st mode is difficult to trace and the 4th mode requires high local field stress. Although several streamer characteristics have been described in the literature, streamer acceleration voltage is the most significant parameter associated with streamer propagation. Acceleration voltage is defined as the voltage at which propagation mode switches from 2nd to 3rd mode (or slow to fast). An increase in voltage beyond the acceleration voltage increases streamer propagation velocity to several times the existing velocity.

With an increase in propagation velocity, streamers' shape and light also change. The spatial shapes and oscillography of streamers have been investigated and analyzed in accordance with propagation velocities, electrode gaps, and acceleration voltages in mineral oil and synthetic esters [73], [74]. Synthetic esters were found to be inferior to mineral oils in resisting the growth of a streamer. Researchers also investigated the light emission properties and shape of streamers [75], [76] and reported that, for small electrode gaps, some streamer characteristics such as spatial shape, emission (light), and average propagation velocities are similar in mineral and ester fluids.

However, oscillography revealed minor differences in the intensities of light emitted for streamers generated in mineral oil, natural esters, and synthetic esters. This may be attributable to the fact that different oils have different chemical bonds (composition), which lead to changes in the absorbance and transmittance of light. Several researchers found that ester fluids are inferior to mineral oils at retarding streamer propagation. Hence, there is a need to further investigate the development and propagation aspects of streamers in ester-filled transformers. Streamer propagation in small gaps has been investigated for natural and synthetic esters in comparison to mineral oil in [77]–[80], and it is reported that esters have less resistance to the propagation of fast energetic streamers (3rd mode) than mineral oils due to the difference in the number of impulses supplied to the electrode setup. It is also reported that the frequency of occurrence of the

TABLE 3. Summary of research progress on pre-breakdown phenomena in esters.

S. No.	Reference	Electrode configuration (type and gap distance)	Insulating oils used*	Critical measurements reported
1.	[68–70]	Point plane, 15 mm to 100 mm	MO, SE and NE	Propagation length Discharge velocity, optical measurements
2.	[71]	Point plane, 10 mm		Discharge spectra analysis
3.	[77]	Point plane, 10 mm gap		Streamer modes
4.	[78]	Point plane, 10 mm and 20 mm		Propagation velocity, streamer modes, inception voltage
5.	[79]	Point plane, 20 mm		Light wave forms for negative and positive polarities
6.	[73]	Point plane, 15 mm and 20 mm	MO and SE	Streamer modes, streamer propagation for positive and negative streamer
7.	[74]	Point plane, 2 mm to 30 mm		Streamer charge, stopping length, streamer velocity for positive and negative streamers
8.	[81]	Point sphere, 25 mm		Light intensity, propagation velocities
9.	[72, 75]	Point sphere, 25 mm	MO, NE and SE	Breakdown voltage (BDV) and spectra for positive streamers
10.	[85]	Point plane, point-bar, 37.5 mm	MO, rapeseed oil, and SE	Stopping length, density of streamer branches
11.	[86]	Needle plane, 50 mm	Modified palm oil and MO	Streamer shape, stopping length, streamer velocity, BDV
12.	[87]	Needle plane, 25 mm, 50 mm, and 100 mm	NE, MO, and rapeseed oil	Stopping length, velocity for both polarities
13.	[88]	Needle plane, 50 mm, 100 mm	MO, soybean oil, and rapeseed oil	Streamer velocity, stopping length, BDV
14.	[89]	Point plane 20 mm, 25 mm, 30 mm	MO, olive oil, rapeseed oil, and synthetic ester	Streamer shape, streamer velocity, BDV, stopping length, streamer current, and voltage
15.	[90]	Needle sphere, point sphere, sphere-sphere 10, 15, 25, 40 and 50 mm	MO and NE	BDV, breakdown field strength

* *MO: mineral oil, SE: synthetic ester, NE: natural ester.*

light waves associated with the streamers produced in ester fluids is higher than the frequency of the pulses produced in the case of mineral oil. The high number of pulses in ester fluids is due to the esters' high moisture absorption, which results in more water bubbles at high electric stress and thus more weak points (water bubbles) [81]. The quick inception and fast propagation of streamers in esters must also be taken into consideration in designing ester-filled transformers. The main parameters affecting the inception and propagation of streamers in oil-filled transformers include streamer shape, stopping length, streamer velocity, streamer current, and light emission. Electrode geometry, internal temperature, hydrostatic pressure, chemical composition of the liquid, additives in oil, aging products in oil, and aging of oil/paper insulation also influence streamer parameters. These issues concerning effects on streamer development, including the analysis and modeling of streamers, which will be useful for researchers and designers, are documented in [82], [83]. Recently, rapeseed oil, soybean oil and modified palm oil have been investigated for streamer characteristics in comparison to mineral oils [84]–[89]. The emphasis was on streamer shape (horizontal and vertical) for point plane electrode configuration under positive and negative polarities. Parameters including stopping length, streamer velocity, and breakdown voltage were investigated under different experimental conditions. Stopping lengths appear to be shorter for pressboard/natural ester interfaces than with mineral oil. It was also observed that streamer patterns for negative polarity are thicker than for positive polarity in natural ester and mineral oil. In [90], inhomogeneity differences in breakdown voltage between natural ester and mineral oils with different electrode arrangements representing different fields in homogeneity factors and different gap distances are reported. Various electrode and conductor arrangements reported in the literature on oil breakdown voltage studies were also documented. The effect of impurities on breakdown phenomena of ester/cellulose-based oil/paper insulation is reported in [91] and [92] to examine the influence of wet/dry cellulose particles and of copper during surface discharge activity. The impact of moisture in oil and pressboard, with dry and wet oil cellulose insulants was investigated. It was found that ester fluids provide good resistance to impurities in bridging the gap between insulation and electrode compared to mineral oil. The higher hydrolysis rate in ester fluids than in mineral oil reduces the degradation of cellulose and the possibility of decay products with aging. A summary of the research progress on dielectric and pre-discharge phenomena in ester-based fluids is presented in Table 3.

D. APPLICATION IN ON-LOAD TAP CHANGERS

On-load tap changers (OLTCs) are mechanical devices that handle voltage and current between taps. The combined operation of movable contacts while constituting active terminals has made transformer tap changers an important element of power transformers. Insulating fluid is used in OLTCs for insulation and immediate arc quenching during switching operations. The performance of alternative insulating fluids in OLTC tanks should be studied. Like oil in the main tank, the oil in OLTCs is in contact with cellulose, metal and sealing material. The degradation of insulating liquid in conventional oil-switching OLTCs is mainly attributable to characteristic spark discharges and gassing. The consequences of these sparks and gases are similar to those in the transformer main tank. Nevertheless, the tendency to find prolonged arcs, acids, and other toxic by-products of the degradation of oil in OLTC tanks is higher than in the main tank. The conventional non-vacuum OLTC filled with ester fluids is found to be inferior in terms of degradation rate [93]–[96]. Fast switching arcs also lead to the production of excess concentrations of free gases with ester fluids. However, managing two different insulating fluids is a challenge for engineers and involves an element of risk with the use of mineral oils. It is reported that vacuum switching tap changers are suitable for ester-filled OLTCs to avoid fast oil degradation. In vacuum switching technology, the switching mechanism is encapsulated in a vacuum medium within the diverter, which buffers the impact of arcing on oil degradation. Other than arcing, factors such as the physicochemical parameters of oil, pyrolysis of paper, and degradation of oil/paper insulation remain the same as in conventional tap changers. However, some special factors concerning the use of esters in OLTC should be investigated:

1) Discharge behavior (arc breaking)

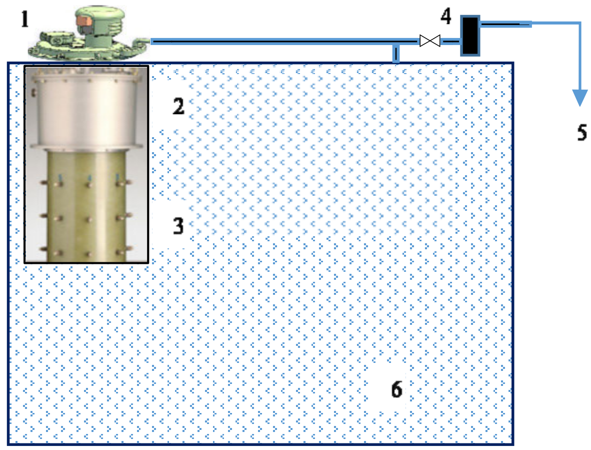

FIGURE 2. Schematic solution for transformers with common household of OLTC and main tank oil.

2) Switching potential (arc breaking limits)
3) Material compatibility (gaskets, metals)
4) Mechanical and thermal limits (lubrication, heating/cooling)
5) Gassing tendency (free gases)

Despite the above-mentioned factors, electrical insulation is the fundamental factor. The details of voltage and thermal limits for OLTCs with ester fluids and mineral oils have been investigated and the limiting values are reported in [97]. The performance of ester fluids in tap changers accommodated in the main tank (common household) is reported in [98]. The dissolved gases generated in vacuum switching tap-changer units are much lower than in the main expansion tank. Considering the high flash point, high breakdown voltage, and low dissolved gases, OLTC units may be accommodated within the main tank [98]. Such a common household tank design reduces the cost of OLTC units and facilitates reduced maintenance activities. This is because the costs of pipes, breather, protection relay, and level indicator of oil of the OLTC are avoided in a common household design. The optimal schematic solution for a common household design of tap changers in the main tank is sketched in Figure 2. Note that, for the OLTC configuration to be accommodated in the transformer main tank, a pressure relief device must be mounted on top of the OLTC to regulate and detect excess pressure. This pressure relief device must be coordinated with the breather configuration through a Buchholz relay. Sealing solutions, various design solutions, limiting values and specifications, material compatibility, retrofilling aspects and common household options for OLTCs with ester fluids were

TABLE 4. Some observations on the application of ester fluids in OLTCs.

Parameter	Remarks	Mineral oil	Natural ester	Synthetic ester
Oil applicability	Conventional OLTC chamber	Acceptable	Questionable	Questionable
	Vacuum-type OLTC chamber	Yes	Yes	Yes
Pressure limit [98]	For sealed units (bar absolute)	0.7 to 1.8		
Hermetic sealing	For tap changer	Not required	Required	Not required
Material compatibility	Gaskets	Normal	Flour polymer	Flour polymer
	Uncoated electrodes (nuts and bolts)	Soft edges must be avoided, facilitating uniform field distribution (in common household)		
Common household	-	Questionable	Acceptable	Acceptable
Anti-abrasion coating	For diverter and pre-selector units in common household	-	Required	Not required
Pressure rise	Protective device	-	Required	Required
Dissolved gas analysis	-	-	Less CO_2	More CO_2
			More C_2H_6 under non-faulty conditions.	

recently documented in [98]. The compatibility of materials was researched and reported in [97], [99], and gaskets made of nitrile rubber were found not to be suitable while several other rubber mixtures tend to become brittle and hard with synthetic esters. Gaskets made of flour polymer rubber have been found to be compatible with ester fluids. Materials used for OLTCs must be capable of withstanding high thermal, electrical and mechanical stresses simultaneously. Various factors affecting the workability of ester fluids in OLTCs are summarized in Table 4.

The gassing tendency of ester oils in tap changers has also been analyzed, and it is reported that acetylene and hydrogen are key gases for partial discharges and the concentration of hydrogen increases with the increase in energy density. Also, ethane is traceable in significant concentrations even under non-faulty conditions. Ethane is the key gas responsible for thermal aging/oxidative decomposition of esters [100], [101]. A performance analysis considering the workability of ester fluids in OLTCs is reported in [102].

E. APPLICATION IN COLD CLIMATES

The performance of the new insulating oils at low temperature is one of the important aspects that must be taken into consideration. Low temperatures in cold countries alter the cooling performance, which is greatly affected by the viscosity and pour point of the insulating oil. In countries where the temperature regularly drops to less than 0 °C, the following abnormalities are likely to be encountered.

Decrease in oil fluidity: The viscosity of the oil increases (or the oil freezes, in some cases), reducing the longitudinal gradient and hampering the free circulation of oil. This greatly affects the oil's heat transfer behavior. Voids are not expected during solid/liquid phase transition.

Increase in internal temperature: As the oil circulation slows down or ceases, the internal heat generated within the winding-core assembly is locally arrested, impairing the solid insulation system. This local heat accumulation leads to high internal temperature gradients and severe hot spots.

Failure of cooling systems: Because the external temperature is much lower than the ambient temperature (excess snowfall and freezing in some cases), the effective cooling surface varies significantly. This contributes to the reduced heat dissipation scenarios discussed above and further impairs the cooling mechanism.

Increase in internal operating pressure: Local freezing and thawing of oil with reduced longitudinal gradients and simultaneous local heating introduce variations in internal pressure. Furthermore, the gases generated during operation increase the internal pressure. This high pressure can cause deformations of the tank or cooling tubes. This effect is generally particularly strong for sealed transformers. In the case of breather transformers, the operational efficiency of the breather configuration may also be reduced due to external freezing.

Impact on useful life: High internal temperature accelerates the deterioration of solid insulation and thus of insulation oil. These situations cause hot spots and local discharges and reduce the effectiveness of the insulation system.

Reduction in the relative moisture content: Moisture in liquids, under fast-decreasing temperature transients, results in free water that may lead to electrical breakdown [103]. For example, at room temperature, an absolute moisture content of about 30 ppm is considered safe for mineral oils. At a temperature of about −20 °C, the absolute moisture content should be less than 3 ppm [104]. These factors have led engineers and researchers to investigate two interesting transformer operating modes in studying freezing and thawing aspects: (i) below-normal temperatures (less than 20 °C to 25 °C); and (ii) above-normal temperatures (more than 20 °C to 25 °C). However, these modes can be investigated under different loading conditions (0% to 100%) and durations based on the objectives of the study. The former condition is commonly known as a "cold start" of a transformer. A cold start happens when a transformer is removed from service at a low ambient temperature and then is returned to service some time later. After the transformer is removed from service, its internal temperature decreases exponentially until it reaches the ambient temperature, which is expected to be very low. Here, oil fluidity in the cooling system will be reduced and oil may or may not flow throughout the operating time. The latter condition is also known as a "steady state." It involves operating the transformer with a temperature and oil fluidity different from those at the ambient temperature (20 °C to 25 °C). The oil temperature will be higher and fluidity is expected to increase with operating time. Few investigations of this kind have been reported and there is scope for further research on ester-based dielectric fluids. Rapp et al. [105] evaluated the dielectric performance of natural esters verified after 120 hours of freeze-thaw cycles at 0 °C, −30 °C, and −40 °C, compared with that of control samples at 25 °C. The rise in temperature at various locations (core steel, winding, and top oil) for a transformer energized with a full load at −30 °C was also investigated. It is reported that pour point is not an effective indicator of the fluidity of natural esters; instead, solidification temperatures should be adopted. The results proved that a transformer can be energized at the solidifying temperature without experiencing any adverse effects. Natural-ester-based dielectric fluids have relatively higher solidification temperatures than petroleum-based fluids. Moore *et al.* reported on comparative cold start procedures with mineral oils and natural esters [106]. They found that the cold start procedure for natural-ester-filled transformers is the same as for mineral-oil-filled transformers. No issues related to the oil's physical or dielectric characteristics were noticed during the excitation or start-up process. Experimental investigations on the cold start and cold storage of synthetic-ester-filled transformers while simulating cooling sequences to extreme low temperatures are reported in [107]. The conclusion was that synthetic esters are capable of withstanding operations at extremely low temperatures and cope even under sudden load fall conditions in cold climates. Storage produced no abnormal conditions with ester-filled transformers. The authors investigated the cooling aspects of cold start and steady state conditions for ester-filled transformers under different loads for temperatures ranging from −50 °C to −30 °C. Temperature rises at different loads are reported in [108]. The properties of some commercially available ester fluids with pour points lower than −30 °C are summarized in Table 5.

With an emphasis on a complete cold start of the transformer [109], two different test conditions were investigated: (i) with a 40% load at −50 °C; and (ii) with a full load at −40 °C. The time required for complete activation of the radiators was reported to be approximately 14 hours in test condition (ii) for the transformer in question. The oil heat dissipation process with a cold start is presented in [110], in which the authors reported thermal calculations for a temperature range of from −40 °C to 40 °C. However, one of the most important questions in case of a cold start is the time required to activate radiators for various insulating fluids.

F. ENVIRONMENTAL AND FIRE PROPERTIES

Among the major concerns with insulating fluids are their renewability and biodegradability and their respect of environmental regulations in case of accidental fires or spillage. Mineral oils are not biodegradable and have a poor emission profile, which means they are hazardous to humans and aquatic life (in the event of spills). Hence, alternative oils must respect environmental regulations and should not be hazardous. Along these lines, several researchers have investigated the environmental and fire-related performance of ester-based dielectric fluids. This section covers studies of these factors in ester dielectric fluids compared with mineral insulating oils. The environmental aspects include major parameters such as biodegradability, toxicity, and sustainability while the fire properties include flash point, fire point, and emission profile of the insulating fluid. Oommen *et al.* [117] highlighted the biodegradability of ester-based insulating liquids for safe transformer insulation. McShane [118] discussed the environmental performance of ester fluids and presented an attempt to enhance the oxidation stability of these fluids in order to increase the biological oxygen demand. When the fluid is disposed of after complete usage or during a spill, oil should not pollute the environment; rather, it should be completely biodegradable. Biodegradability is the measure of biological oxygen demand (BOD), which is the amount of oxygen available for micro-organisms to utilize in their food chains, as a result of which the oil's structure is damaged and it is biodegraded. Hence, higher BOD indicates good biodegradability of the fluid. Thomas [119] and Boss *et al.* [120] evaluated the environmental performance of ester dielectrics in comparison with mineral oils and found ester dielectrics to be environmentally friendly; the biodegradability of esters makes green transformer technology possible. Bertrand and Hoang [121] demonstrated esters' nontoxicity, low oxidation stability, and biodegradability, and showed that the by-products of thermal aging present acceptably low risk. They also suggested that more research on

TABLE 5. Comparative properties of some commercial ester fluids with low pour points.

Property	Remarks	MIDEL			NYCODIEL		
		SE* (7131) [111]	SE* (ICE) [112]	NE** (1204) [113]	SE * (1233) [114]	SE* (1244) [115]	SE * (1258) [116]
Biodegradability		Readily biodegradable	Readily biodegradable	Readily biodegradable	90% (28 days OECD 301B)	83% (28 days OECD 301B)	84% (28 days OECD 301B)
DC resistivity (G-Ohm.-M)	@ 90 °C (IEC 60247)	>20	–	–	10	7.5	10
Dissipation factor (tan delta)	@ 90 °C (IEC 60247)	–	–	<0.03	0.01	0.01	0.01
Breakdown voltage (kV)	2.5 mm gap (IEC 60156)	>75	>75	>75	65	>70	>70
Viscosity (mm²/s)	@ –50 °C (ISO 3104)	–	4970	–	–	–	–
	@ –20 °C (ISO 3104)	1440	422 (at –30 °C)	–	400	650	1150
	@ 40 °C (ISO 3104)	29	7.7	37	16.1	21.6	27.2
	@ 100 °C (ISO 3104)	–	–	8.3	3.81	4.6	5.2
Color		125 (ISO 2211)	–	0.5 (ASTM D1500)	80 (ISO 2211)	60 (ISO 2211)	50 (ISO 2211)
Density (kg/dm³)	@ 20 °C	0.97 (ISO 3675)	0.915 (ISO 3675)	0.92 (ISO 3675)	0.95 (ISO 12185)	0.98 (ISO 12185)	0.97 (ISO 12185)
Flash point (°C)	(ISO 2719)	260	198	>260	248	255	255
Fire point (°C)	(ISO 2592)	316	220	>350	284	304	310
Pour point (°C)	**(ISO 3016)**	**–56**	**–75**	**–31**	**<–65**	**–45**	**–60**
Acidity (mg KOH/kg)	(IEC 62021)	< 0.03	<0.03	< 0.04	0.01	0.01	0.01
Oxidation stability	Acidity (mg KOH/g)	0.02 (164 h, IEC 61125)	–	0.07 (48 h, IEC 61125)	0.09 (164 h, IEC 61125)	0.08 (164 h, IEC 61125)	0.04 (164 h, IEC 61125)
	Sludge (% mass) IEC 61125)	<0.01 (164 h)	–	–	0.004 (164 h)	0.007 (164 h)	0.002 (164 h)

*SE: synthetic ester, **NE: natural ester.*

TABLE 6. Summary of fire characteristics of mineral oils and natural and synthetic esters.

	After ignition	3 minutes later	After extinguishing	Remarks [122]
Mineral oil				• Ignition temperature is relatively low (180 °C) • Ignition is easy • White oxide film is left after burning • Poor emission profile
Natural ester				• Ignition temperature is high (370 °C) • Ignition is difficult • Completely turned to ash after burning
Synthetic ester				• Ignition temperature is high (320 °C) • Ignition is difficult • Completely turned to ash after burning

aging will help define the optimal combination and quantities of additives to obtain a balance between biodegradability and oxidation stability. Generally, antioxidants/inhibitors are added to transformer fluids to restrict the rate of oxidation. The types of inhibitors and their effects on ester aging have been less studied.

Emission profile is an important marker related to the environmental performance of any insulating fluid. It indicates the nature and type of gases released and the behavior of flames when the fluid is subjected to combustion. Insulating fluids' fire point and flash point refer to the maximum temperature at which an insulating fluid may be safely used without significant risk of fire. Ideally, fluids should only ignite at high temperatures and the gases liberated should not damage health and safety. Mineral insulating oils are combinations of hydrocarbons and release hazardous gases when ignited, unlike ester oils. Conversely, ester oils are combinations of acids and alcohols obtained from a biological process and are not environmentally harmful. Arazoe *et al.* [122] investigated the burning/fire characteristics of various insulating fluids and found that esters are more difficult to ignite than mineral oils. A summary of fire/burning characteristics is presented in Table 6.

Amin *et al.* [123] and Redond *et al.* [124] tested the environmental performance and behavior of esters and mineral oils in contact with soil and water according to the Organization for Economic Co-operation and Development (OECD) testing standards and found that ester dielectrics outperformed mineral insulating oils in terms of environmental standards. The safety, non-toxicity, eco-friendliness, and sustainability of ester-based insulating oils proved that esters are a better alternative for a safer and greener transformer insulating technology. Ester fluids are a better choice of liquid insulation in places where environmental regulations are restrictive. Recently, changes in the flash point of various insulating fluids with respect to degradation of oils have been reported [62]. Changes in the flash point of mineral oil (MO), natural ester (NE), and synthetic ester (SE) as a function of thermal aging are illustrated in Figure 3.

The superior fire performance of ester-based oils has been verified for different mixtures of mineral oil, synthetic esters and natural esters [62]. Their dielectric properties, calorific values, fire point, and flash point have been reported as a function of different mixture ratios [125]. Flash point is verified by open cup and closed cup methods for different oil proportions with synthetic esters, natural esters, and mineral oils. It is reported that the difference in the open cup and closed cup flash points increases with greater synthetic ester content. Moreover, the addition of esters to mineral oil improves the dielectric and fire properties. Flash points and fire points are reported to be improved with the addition of

TABLE 7. Environmental properties of ester fluids and mineral oil [1], [5], [24].

Property	Mineral oil	Synthetic ester	Natural ester
Biochemical oxygen demand 5-day SM5210B (ppm)	6	24	250
Biodegradability [129, 130] • 21-day CEC – L –33 • OECD 301 classification • IEC 61039 classification	 <30% Not biodegradable Not biodegradable	 80% Readily biodegradable Fully biodegradable	 97% to 99% Readily biodegradable Fully biodegradable
Toxicity	Yes	Low	No
Health and safety	Unacceptable	Questionable	Acceptable
Sustainability	No	Yes	Yes
Fire risk assessment class (IEC 61039)	O (fire point 110–185 °C)	K (fire point > 300 °C)	K (fire point > 300 °C)
Emission profile	Unacceptable	Questionable	Acceptable

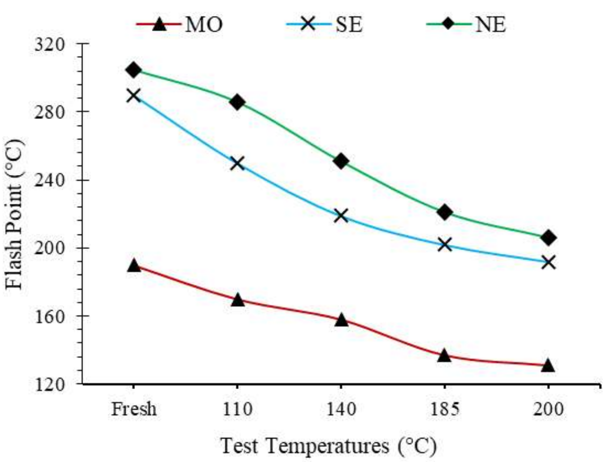

FIGURE 3. Variation of flash point with thermal aging [62].

esters. Recently, different cooling modes for mineral oil and synthetic-ester-filled transformers were investigated for different winding models, as reported in [126]. Natural esters and synthetic esters are known for their fire-resistant properties, and the potential of natural ester fluids to protect against fires has been investigated by researchers and is reported in [127], with the details of thermal properties, heat radiation, and internal pressure. A natural-ester-filled transformer is able to withstand an external fire without burning for 30 minutes, which is ample time to extinguish the fire.

The environmental properties of mineral oil, synthetic esters and natural esters are tabulated in Table 7.

V. FUTURE RESEARCH: CHALLENGES AND PROSPECTS

The majority of the research on ester dielectric fluids has focused on understanding their degradation behavior and compatibility with cellulose insulation. Although research studies support the use of these fluids as alternatives to mineral oils, there are several challenges that should be investigated. These challenges that should be addressed to improve our knowledge of ester fluids are listed below.

Some utilities around the world are already using ester fluids in oil-filled apparatus. Long-term in-service experience data concerning the condition monitoring of ester-filled transformers may be useful. This real-time information on insulation behavior will be helpful in establishing the limits of potential aging markers. Such information will also be helpful in understanding and developing diagnostic tools for ester-filled apparatus. The miscibility of esters with mineral oils has been proven, and the addition of esters improves the dielectric performance of mineral oil: the blend thus formed is better than mineral insulating oils. Hence, more investigation on retrofilling of ester fluids would be informative if utilities wish to retrofill existing units with mineral oils. The behavior of mineral-oil-filled (impregnated and aged) solid insulation systems when retrofilled with ester fluids must be reported. Real-time condition monitoring information and retrofilling studies could lead to increased use of ester fluids for oil-filled apparatus.

Failure rates in tap changers are higher than in transformers, albeit with less serious consequences. The application of ester fluids in OLTCs is an interesting challenge for future research. However, very few studies have reported on this topic. Detailed dissolved gas analyses of ester-filled tap changers have been reported. With the rapid change in potential of the active terminals in tap changers, the degradation of insulating fluids differs from that of oil in the tank. Hence, the degradation behavior of oil in the tap changers should be studied. The diagnostic parameters and dielectric properties of alternative oils in OLTCs should be examined. With frequent unwanted discharges and arcs in tap changers, the deterioration of oil is expedited due to regular electrical stressing. Note that the role of cellulose insulants in the degradation of tap changer oil is not significant. The influence of low-energy and high-energy discharges on the functional behavior of ester fluids in the absence of cellulose insulants should also be investigated. Carbon deposits usually build up on tap changer terminals, leading to increased contact resistance, which in turn leads to further heating and carbon buildup in the active parts. This issue must be better understood to ensure the effective functionality of ester fluids in tap changers.

The majority of research on pre-breakdown phenomena has been carried out on point plane electrodes, while little work has been done on sphere plane electrodes. Most such research sought to understand streamer behavior and properties including streamer velocity, streamer length, streamer shape, charge and current. The influence of aging factors and other diagnostic/operational parameters on streamer propagation has not yet been investigated. Several researchers have reported on the impact of moisture and metal particles on breakdown phenomena. However, cellulose particles and other decay particles also have a major impact in real-time conditions. The effect of electrode geometry (gap length, shape, tip radius) has been reported by several authors, but without considering the aging of the oil and cellulose insulants.

The workability of synthetic and natural esters compared with mineral insulating oils is another area of research. Some significant observations that are related to the workability of ester fluids have been summarized in Table 8.

In [4], methods for improving the workability of natural esters are reported, including dispersion of pour point using Poly(methyl methacrylate). Natural esters suffer from low lightning impulse resistance, so several researchers have attempted to improve the resistance of natural esters by using azobenzene and dimethylaniline as additives [4], [130]. Additives designed to address specific concerns require detailed investigation to understand their compatibility with dielectric fluids in operating environments. Therefore, there is scope for research on additives and chemical scavengers to improve the performance of dielectric fluids. Moreover, resistance to oxidation and high viscosity are major concerns related to natural esters that should be further investigated. However, the change in viscosity with aging of an alternative fluid with a very low pour point in comparison to natural ester, synthetic ester and mineral oil is presented in [131].

End-of-life criteria for alternative insulating fluids is another important concern for the industry. The degradation of ester fluids presents an absence of colloidal particles at low and moderate aging [132]; however, soluble particles are seen with aging of ester fluids. The application of fuller's earth for ester fluids is still questionable, and several authors have reported on the use of different adsorbents for treatment of ester dielectric fluids. Still there is a lot of scope for research on additives and adsorbents that are compatible with alternative dielectric fluids.

TABLE 8. Workability observations of various insulating oils in transformers [1], [4], [5], [24].

Property	Mineral oil	Synthetic ester	Natural ester
Suitability for cold climates	Acceptable	Acceptable	Questionable
Miscibility	-	Miscible in all proportions	Miscible in all proportions
Soluble particles with aging	Yes	Yes (with greater aging)	Yes (with greater aging)
Colloidal particles with aging	Yes	No (with lower/ moderate aging)	No (with lower/ moderate aging)
Key gases produced after aging	H_2 and C_2H_2	CO and CO_2	CO and CO_2
Oxidation stability	Acceptable	Acceptable	Questionable
Absorbance	Increases rapidly with age	Increases moderately with age	Initially high
Antioxidants	Required	Required	Strongly required
Gelling	No	No	Partially yes (for breathing units)
Cellulose degradation	Faster	Slower	Slower

Enhancement of the dielectric, thermal, and physical properties of the new alternative fluids by adding nanoparticles is another fruitful new topic of research [133]. It has been reported that the smart liquids developed with some specific nanoparticles can be customized according to the choice of applications in oil-filled apparatus [1], [24]. Several researchers have investigated dielectric strength, viscosity, pour point, oxidation, dielectric properties, thermal properties, and streamer propagation in nano-based ester fluids [134]–[136]. A significant improvement is noticed with the addition of different nanoparticles. Nevertheless, further research should emphasize the aging behavior of these nanofluids and their compatibility with other transformer materials. Recently, a laboratory-based synthesis of trimethylolpropane ester-based dielectric fluids aimed to improving their properties while maintaining an equilibrium between flash point, oxidation stability, pour point, and viscosity [137]. However, the service behavior of these oils and the effect of various additives on oil must still be examined.

Importantly, with the increase in demand for green energy, bulk power is being integrated into the electrical grid via distributed generation. Distributed generation involves concepts like various renewable sources, vehicle to grid, hybrid and plugin electric vehicles, etc. Power from distributed generation is involved in non-linear fast switching actions that affect grid parameters. Hence, the reliability of future insulation systems must be improved to deal with frequent switching transients.

VI. CONCLUSION

In this article, progress in research and the state of the art of key aspects that must be addressed concerning the possible usage of ester dielectric fluids are presented, followed by proposals for future research. A critical emphasis on recent progress, miscibility, and retrofilling of ester fluids was noted. In addition, a review of pre-breakdown behavior, the use of esters in on-load tap changers, environmental and fire properties, and use of ester dielectric fluids in cold climates was presented. Future challenges related to alternative dielectric fluids were described. This survey will be useful for researchers and practitioners interested in alternative dielectric fluids for possible applications in high-voltage oil-filled apparatus.

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