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REVIEW

Natural esters as sustainable alternating dielectric liquids for transformer insulation system: analyzing the state of the art

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Abstract

The remarkable development in high-voltage direct current and high-voltage alternating current transmission systems calls for a renewed assessment of dielectric liquids for insulation systems of transformers. The function of liquid insulation used in high-voltage equipment is cooling and insulation. It should have several features like high dielectric strength, low viscosity, high flash point, very low moisture or water content, high specific resistance and many more. Petroleum-dependent synthetic and mineral oil has been conventionally applied as dielectric fluids in transformers during previous some decades that disturbs the environment on account of their low biodegradability and low fire point which have persuaded the exploration of substitutes. The application of alternate insulating fluids is increasing gradually, with safety and environmental apprehensions at the lead of the grounds for shifting from mineral oil. Esters-based dielectric fluids have been used in dielectric industry for roughly four decades, with synthetic esters having initially been proposed to replace harmful polychlorinated biphenyls or PCBs in late 1970s. Ester-based liquids found applications in distribution transformers without any significant design modifications in standard mineral oil designs, although could not be applied at high-voltage levels. From this finding, dielectric society and manufacturers have boarded on a search for an evident insight of the elementary differences between esters and mineral oil and how to adapt designs to allow the application of esters at high-voltage levels. Synthetic and natural esters have been exposed to research for years vis-a'-vis mineral oil around the globe. Even though several investigators are in favor of ester liquids use in high-voltage equipment, manufacturers and utilities are yet averse, and use of these alternative fluids stays a challenge. This paper will present an analysis of the published research results during the past few decades from various researchers, emphasizing the variations in dielectric performance between esters and mineral oil. This knowledge transfer is timely as it presents challenges and prospective attributes that would be considered further to enhance the accessible information of ester dielectric fluids for application in transformers.

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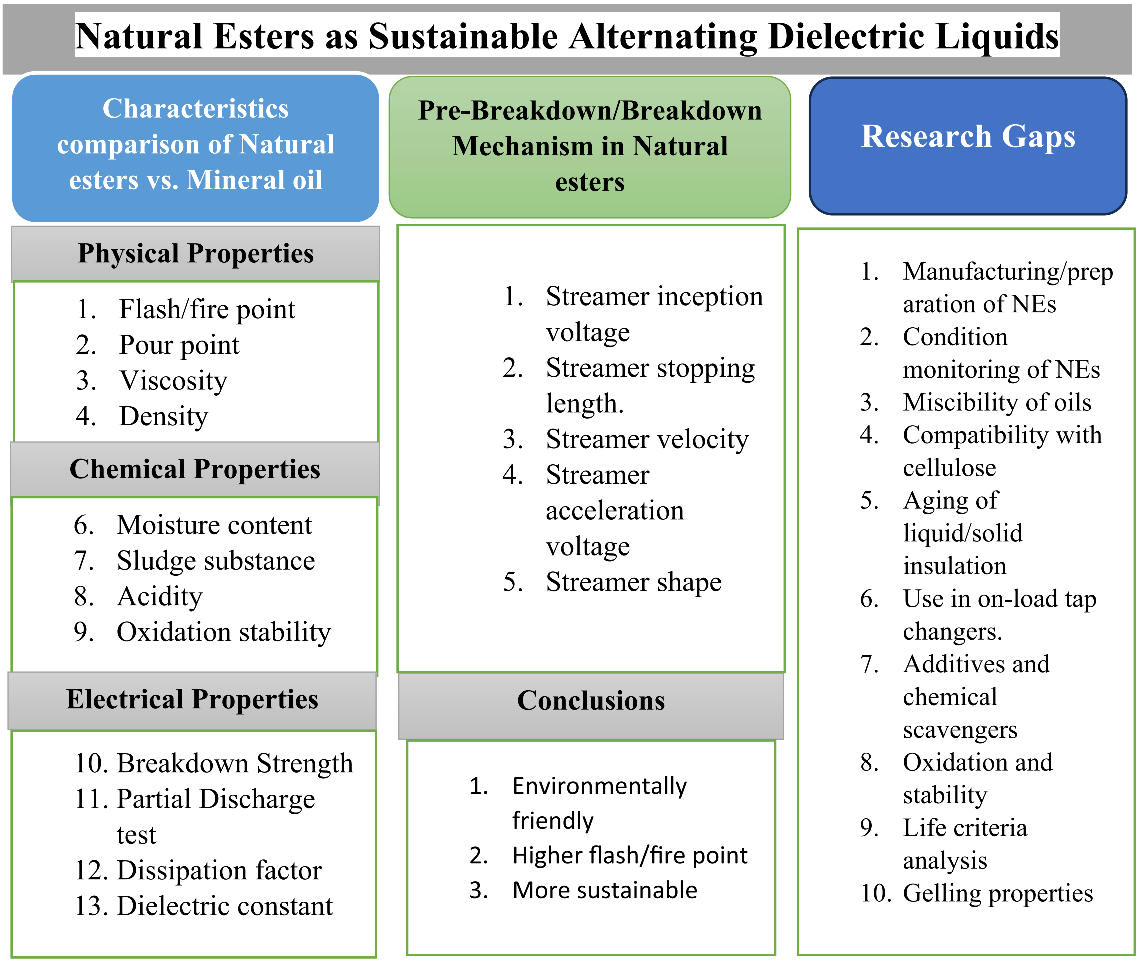
Graphical abstract



Natural Esters as Sustainable Alternating Dielectric Liquids

Characteristics comparison of Natural esters vs. Mineral oil

Physical Properties

1. Flash/fire point
2. Pour point
3. Viscosity
4. Density

Chemical Properties

6. Moisture content
7. Sludge substance
8. Acidity
9. Oxidation stability

Electrical Properties

10. Breakdown Strength
11. Partial Discharge test
12. Dissipation factor
13. Dielectric constant

Pre-Breakdown/Breakdown Mechanism in Natural esters

1. Streamer inception voltage
2. Streamer stopping length.
3. Streamer velocity
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5. Streamer shape

Conclusions

1. Environmentally friendly
2. Higher flash/fire point
3. More sustainable

Research Gaps

1. Manufacturing/preparation of NEs
2. Condition monitoring of NEs
3. Miscibility of oils
4. Compatibility with cellulose
5. Aging of liquid/solid insulation
6. Use in on-load tap changers.
7. Additives and chemical scavengers
8. Oxidation and stability
9. Life criteria analysis
10. Gelling properties

Keywords Natural esters · High voltage · Dielectric liquids · Insulation system · Transformer

Introduction

The insulation system in transformers is a complex insulating medium which includes oil and cellulose. This composite insulation is significant for the life and performance of a transformer. Insulating oil in transformer is used to function as insulant, coolant, protective barrier for the core and diagnostic instrument for high-voltage (HV) equipment (Rafiq et al. 2016b). Fluid dielectrics are categorized into organic and inorganic chemical compounds. Organic compounds include natural/agricultural oils. They are usually described as natural esters (NEs). Inorganic compounds include mineral oils (MOs), silicone oils, synthetic esters (SEs), nanofluids and combined dielectric fluids. The complete history on the advancement of dielectric fluids can be found in (Fofana 2013). MO has been used as insulating liquid due to its low cost, high efficiency, good thermal cooling capacity, good pouring point at low temperatures and availability in the transformer market (Rafiq et al. 2020b). Despite its previously mentioned advantages, the disadvantage of MO includes high fire risk, low biodegradability as well as its scarcity in future. Synthetic ester fluids have been used in applications where fire safety was the major concern. Bio-based hydrocarbons (BIO) insulating fluid which is an instance of a new attempt in terms of environmentally friendly and sustainable liquid which are being used as insulation purposes in HV equipment (Rozga et al. 2022; Lu et al. 2014). These developed insulating fluids have very trivial sulfur and have great resistance to oxidation. These insulating liquid (BIO) performed superior in terms of acceleration voltage as compared to synthetic esters (Stuchala and Rozga 2023; Lu et al. 2017) and similar to MO (Rozga et al. 2023). A comparison of the impregnation conduct of BIO was made with traditional MO by using a pressboard with thickness of 0.5 mm and 3 mm as a sample. The result indicated that both tested oils presented similar behavior of the dissipation factor for various samples and temperatures, and hence, they indicate a similar impregnation behavior. Consequently, it could be concluded that the same diagnostic approach could be used for this new developed oil (Münster et al. 2017).

Nevertheless, in latest times users are recognizing that ester-based fluids might suggest a more typical substitute to MO. In specific space-inhibited urban locations, ester-based fluids may even become the preferred option, with the flammability and potential environmental impact of MO presenting the design of advanced installation enormously demanding.

In recent years, ester-based dielectric liquids (natural and synthetic), as an alternative insulation liquid, have grown considerably prevalent among international dielectric research society including various universities, research centers, manufacturers and utilities of transformers. More specifically, their higher fire safety and biodegradability is the focus. And so, there is genuine scope and requirement to enhance existing understanding and literature on these insulating liquids. This article attempts to sum up the various studies on natural esters, their potential and contemporary issues as well as targets to point up the main problems and the contemporary literature on recovering these disadvantages of NEs. It will focus on various key concerns of researchers, utilities and industries related to the application of ester-based liquids.

Application of natural ester-based liquids in transformer industry

Mineral oil is extensively applied as a dielectric channel in electrical equipment like transformers, capacitors, cables and bushings which has been obtained from petroleum crude oil since 1940s. The fundamental undertaking of dielectric fluid is the impregnation of all kinds of hollow gaps in an aspect where electrical strength is as high as possible. Moreover, in transformers, dielectric fluid functions as cooling medium. Accordingly, dielectric fluids must show the following necessary characteristics: (a) sound electrical properties, in specifically high BDS, (b) high aging resistance, particularly hindrance from oxidation, (c) adequately low viscosity affirming oil circulation and heat transference, (d) compatibility with solid materials of electric apparatus, and (e) flame impeding features are also significant in certain applications. The desired qualities of good dielectric fluids for transformers are given in Fig. 1.

Given that anticipated potential oil emergency, price of crude oil is rising, and hence its accessibility might be uncertain. However, the dielectric traits of MOs are extensively acknowledged, and they have presented satisfactory insulation and cooling performance but the advent of HV transmission levels such as HVAC and HVDC, conduct demands for insulation system of transformers are on a rise. The alternate insulating liquid material development is guided by multiple aspects, e.g., higher electrical insulation obligations and additional safety and economic concerns.

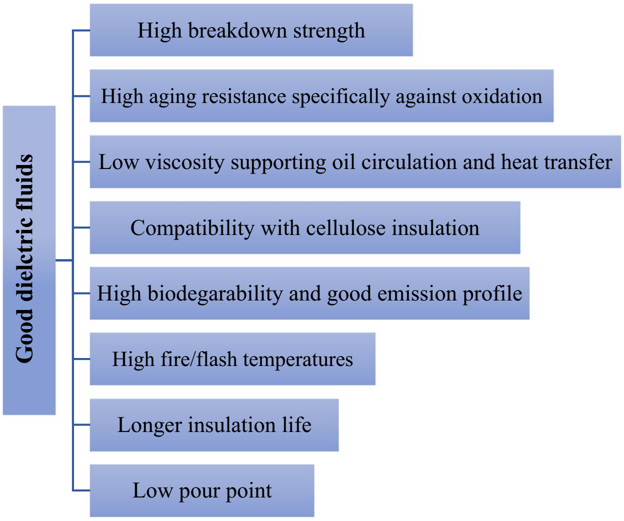

Fig. 1 Desired characteristics of good dielectric fluids for transformers

It is becoming imperative for dielectric channels to supply efficient insulation and contend with elevated temperatures with rising voltage levels. Additionally, in terms of short circuits or arcing, increase in temperatures should be tackled by the insulating medium. This certain instance embarks on a demand for *elevated flash points and fire points* for dielectric liquids.

Moisture and atmospheric air are the biggest enemies of insulation arrangement of a transformer, but moisture is inexorable. This moistness is formed by cellulose insulation in closed transformer units but in non-sealed units, it is introduced from exterior atmosphere via breather. The *rate of hydrolysis* is greater in MO as compared to ester liquids, expediting the production of acids, furanic combinations and CO_2 in oil. Likewise, oxygen admittance works with the gases released from cellulose insulation due to temperature and accelerated oxidation. This oxidation introduces the creation of acids and moisture in MO. This water speeds up hydrolysis and slows down polymerization of papers (Gilbert et al. 2010). This extremity of hydrolysis and oxidation in MOs will result in sludging and will lead to *premature aging of insulation system* and ultimately failure of transformer.

The MO can produce toxic elements caused by oxidative instability. Dumping and cleanup afterward a leakage and apparatus breakdown are challenging tasks. Seepage of MO can be hazardous to the environment if spillage or leakage occurs in water bodies.

Excessive functional temperatures in HV equipment may result in fires, posing a serious threat to the personal and nearby apparatus. This may lead to capital loss and imperfect asset management. The previously described disadvantages and issues associated with MOs have urged researchers, utilities, manufacturers and industries to look for alternatives for usage in oil-immersed transformers. The task is to find a suitable substitute which can exhibit mandatory dielectric and thermal characteristics. Moreover, it should be biodegradable, nontoxic and chemical stable. This new insulation liquid should manifest compatibility with other substances applied in transformers and meet the requirements posed by ecological and protection protocol. More critically, this substitute should also demonstrate optimum balance between preliminary capital spending and maintenance expenditures.

Development history of transformer liquid insulation

The main object of fluid insulation is to offer essential insulation and cooling in transformer. It is therefore required to have elevated insulating strength, thermal conductivity, chemical stability and ought be capable to sustain its characteristics at higher temperatures and electric stresses for a persistent eras (Rafiq et al. 2015a, b,c). Over the past years, several types of insulating liquids have been used in transformers to meet the industrial and environmental regulation requirements. The development history of various liquid insulation for transformer is reviewed in (Rafiq et al. 2020a, b, c, d).

Petroleum-based liquid insulation (mineral oil) was an insulating liquid, which was used for application HV apparatus, although it was not preliminary option as cooling medium. According to sources, a preliminary oil-filled transformer was produced in 1890 (Harlow 2004). MOs are obtained either from paraffin/naphthenic-based crude oils. Paraffin oils were commonly employed until 1925 but later naphthenic-based oils dominated due to great pour point of paraffin oils (Rouse 1998). The preliminary crude oil extracted liquid was premised on low viscosity paraffin oil which presented excellent dielectric conduct; contrarily, it manifested a great pour point that obstructs its use in HV apparatus at subdued temperatures. Moreover, unsolvable sludge developed due to oxidation could dwindle its heat removal capacity and lifespan. Thus, paraffin oils were replaced by naphthenic-based oils which presented low pour point temperatures and manifested greater oxidation stability. Key disadvantage associated with petroleum-based oils was their extreme flammability. A casual spillage can simply cause combustion. Fire codes typically require that HV apparatus used indoor structures should be filled with less flammable liquid. These liquids are also ecological toxin, and their insulating traits are rapidly deteriorated by marginal extent of moisture. Mineral oils are generally used in transformers as liquid insulation. However, their low fire resistance (low flash point) initiated problems and resulted in search of substitutes.

The researchers initiated to form non-flammable liquids for specific applications and presented non-inflammable liquids like PCB (polychlorinated biphenyls) or askarel. Alternatives like PCBs were introduced in 1930s, due to their better fire resistance and dielectric properties than MO. They were developed as an ideal dielectric liquid to be used at delicate premises, e.g., markets, hospitals, near water channels, etc. PCBs presented better insulating performance and were non-combustible. They were used as insulating liquid until the 1960s, but environmental issues (toxic pollutants) were associated with them hindered their applications in 1970s (Berger et al. 1997). This put huge pressure on the industries to look for eco-friendly dielectric liquids. In the 1980s, dielectric society initiated the eye for new substitute dielectric liquids.

The HV equipment using PCBs was replaced with suitable liquids, e.g., MO and extreme fire point liquids (HFP) like SEs and silicone liquids. Silicone liquids were introduced in the mid-1970s. They remained expensive and were badly biodegraded. On the other hand, synthetic esters were presented in 1977. They showed greater fire/flashpoint temperatures and better biodegradability as compared to MO (Borsi 1990, 1991; Yamagishi et al. 2004).

To conclude, the present advancement of dielectric fluids for transformers is renewable, sustainable and eco-friendly NEs which are introduced as alternative of MO. They have remarkable fire point and smaller volatility. They also have lower pout point, great humidity tolerance and improved working at high temperatures and they are not noxious and highly biodegradable. Natural esters were developed in the early 1990s in the USA as green and eco-friendly substitutes of conventional MO and silicone fluids. The first natural ester-filled prototype transformer was prepared in 1996; nonetheless, industrial development of transformer occupied with natural easters was commenced in 1999 (Contreras et al. 2019; McShane et al. 2006). The timeframe of development of transformer liquid insulations and their respective advantages and disadvantages are summarized in Fig. 2. The academia and utilities are making efforts to investigate various kinds of natural esters as dielectric insulation which are compatible for applications in colder atmospheres and at higher voltages.

Approach for literature search

This literature analysis delivers an imperative study of cutting-edge research into natural esters as sustainable alternating dielectric liquids for transformer insulation system

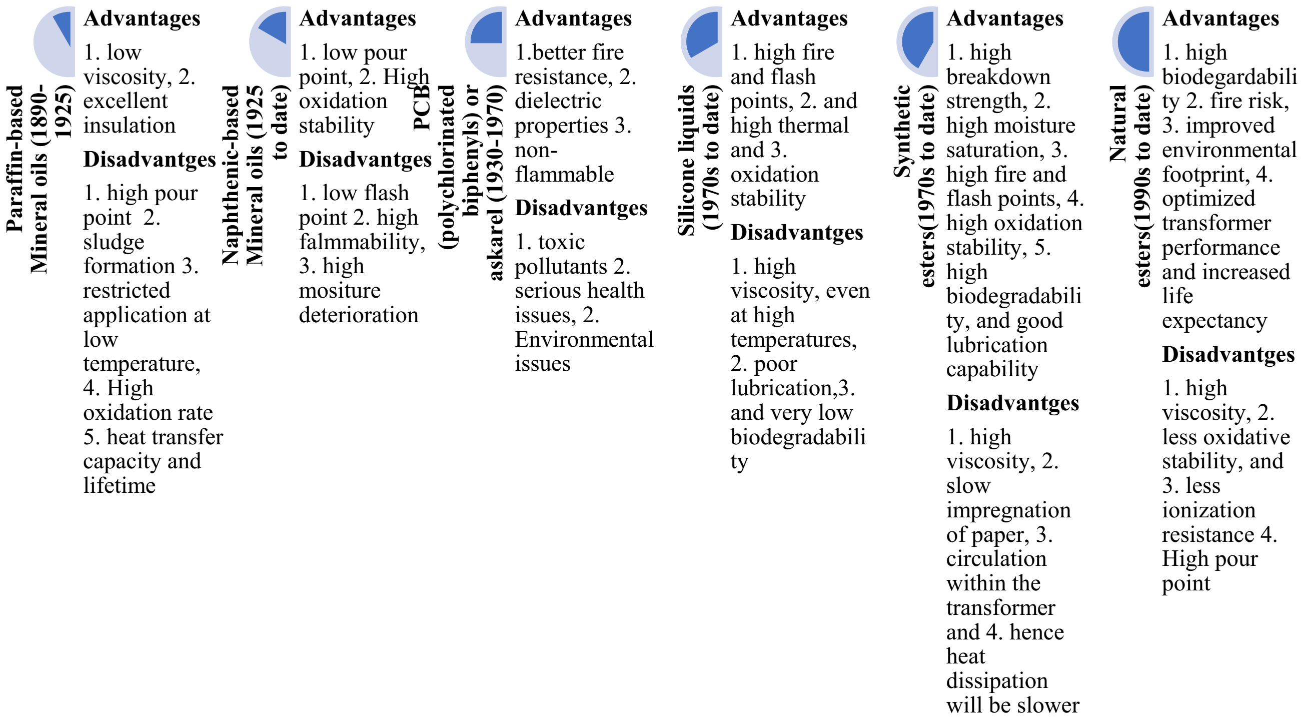

Fig. 2 Timeline of development of transformer liquid insulations and summary of their advantages and disadvantages

and the following sections provide the exploration stages used to complete this methodical analysis of the literature. A broad literature evaluation may deliver valuable knowledge in terms of vital information of potential of natural esters applications in HV transformers, their breakdown phenomenon and suggest imminent research guidelines. The following key actions have been conducted for the literature compilation.

Initial survey

This phase involves primary exploration in Springer and Direct Science gateways. In this exploration, leading journals encompassing "natural esters in transformer" and "vegetable oils in transformer" keyword in heading and keywords were designated. Keywords associated to the exceeding subject were also looked for and linked information was obtained from respective magazines.

Substance selection approach

A five-stage exploration technique (Fig. 3) was applied to look for editorials for this analysis. Initially, two main scientific archives (Thomson Reuters Web of Science [WOS] and Scopus) were used for keyword hunt. Then, a blend of keywords and expressions were chosen regarding accessible scientific statistics and data of the research group. Since 25 August 2023, titles, summaries and keywords were hunted in mentioned records. Most of the research regarding this topic was conducted between 2010 and 2023. Hence, this timespan was used for search. In the light of chosen keywords, a whole of 468 articles were retrieved in the above databases as shown in Fig. 4.

Selection and conclusive collection of papers

Later, a manual selection technique was used in accordance with abstracts, titles and keywords. The emphasis of this work was peer-reviewed journal articles, conference papers dissertation and various reports. During the 4th phase, the annexation principles were used to titles and some articles were omitted. Later, required articles were strained in reference to their abstracts. Consequently, in the last stage, after analysis of the complete texts of the remainder articles, papers that were openly and indirectly associated to the subject were chosen for this broad investigation. The intention of this analysis is to present inclusive knowledge concerning natural esters as sustainable dielectric fluids for transformers. This study also reviews the challenges which need to be addressed for application of natural esters in transformer on broad range. Ultimately, this study implies the prospective trails for adoption natural esters as sustainable, renewable, biodegradable, non-toxic and sustainable alternating dielectric fluids for transformer insulation system.

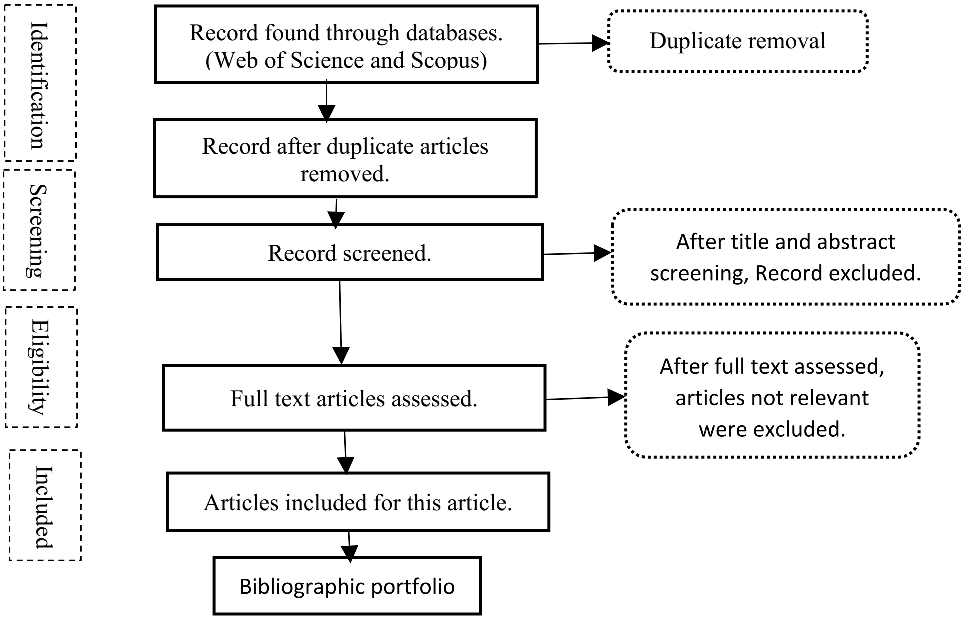

Fig. 3 Flowchart for screening the retrieved articles in this study

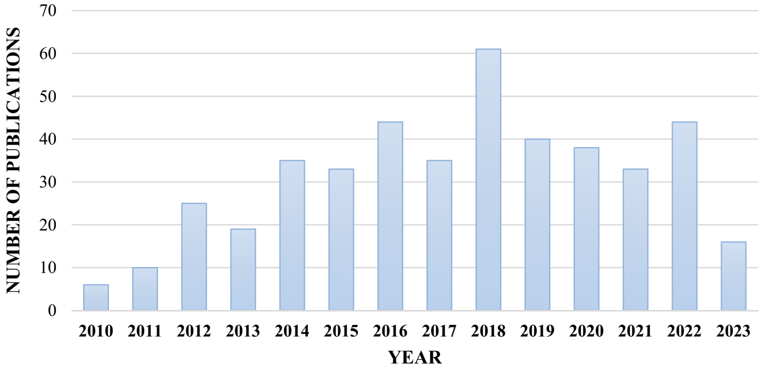

Fig. 4 Number of publications related to natural esters in transformer during 2010–2023

Research on natural ester fluids

The latest development of dielectric liquids for HV application is the eco-friendly natural esters. Natural esters dielectric liquids, also identified as vegetable oils or bio-based liquids, are naturally produced from living entities, and derived from plant yields, generally soybean, sunflower, rapeseed, etc. (Oommen 2002). Initially in the 1990s, NEs were produced and presented in America as a "green" and eco-substitute for environmental apprehensions of traditional MOs and silicone oils. Liquid-filled transformers use enormous volumes of dielectric fluid. The MO refined to transformer grade oil is the most frequently applied transformer liquid that has been in use for than a century. During latest times, ecological apprehensions have been induced on the application of inadequately biodegradable liquids in transformers in sensitive spheres, where spatters from leaks and apparatus breakdown might infect the environment. Research efforts were initiated in the mid-1990s to build an entirely biodegradable dielectric liquid. VO was deemed the utmost prospective contender for a totally biodegradable dielectric fluid. The researchers rapidly realized that natural esters needed further enhancement to be applied as transformer fluid. Several investigations have been reported on the use of NEs as alternatives to MO, since the 1990s. These studies favor the use of natural esters as prospective substitutes for MO. The performance of these new liquid insulations has been evaluated.

Performance evaluation of vegetable oil vs. mineral oil: recent progress

MOs, applied as insulating and cooling fluid in transformers, are acquired by petroleum extraction. The concluding traits of customary MO depend on the chemical structure. MO has a few demerits, e.g., poorer biodegradability, dearth in future and presence of poly nuclear aromatic hydrocarbons that are not eco-green. As petroleum reserves to be vanishing in the upcoming, demand fosters to prepare substitutes that are price effective, instantly available. Consideration is given to NEs as a substitute to MO due to exceeding cited disadvantages of MO. Ester oil is categorized into two classes i.e., natural ester and synthetic ester. NE is extracted from vegetable seed oil. Agriculture esters provide the decent amalgamation of high-temperature traits stability, biodegradability, price as alternate to MO. VOs are natural ester molecules with triglyceride composition, created from chemical link of three fatty acids to one glycerol molecule (McShane 2002). The application of NEs is growing due to its benefits over MOs, e.g., biodegradability and low flammability. For synthetic esters, great temperature abilities and biodegradability are most significant, it has appropriate dielectric characteristics, biodegrade much faster than MO and hydrocarbon liquids. Biodegradability is the capability to decay naturally by the process of biological organisms. Extremely biodegradable oils include natural esters, synthetic esters or mixtures of these core reserves. Biodegradable liquids denote outstanding prospective saving for utilities. NEs are extremely reactive to oxygen existing in the atmosphere. Thus, it is generally effective in hermetically closed transformer units.

It is confirmed from the literature that NEs are likely contenders for applications in oil-immersed transformers. But the manufacturers, utilities and industries are still cautious to apply these new dielectric liquids, due to non-availability of devoted condition-monitoring methods and deficiency of knowledge regarding pre-breakdown and pre-discharge events, and retro-filling and miscibility issues of these new liquids. Moreover, the literature is still lacking information regarding the functionality of these liquids in cold conditions. The advantages and disadvantages of NEs are summarized in Fig. 5.

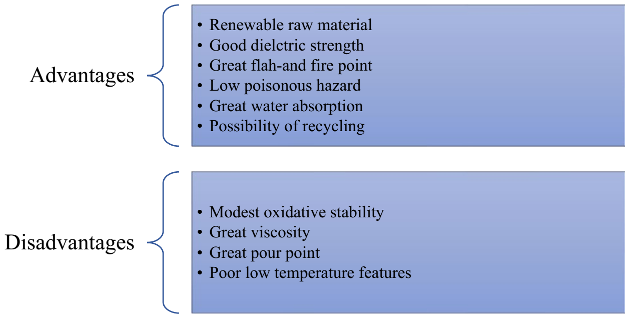

Fig. 5 Summary of advantages and disadvantages of natural esters as transformer liquid insulation

Various important characteristics of transformer oil

Various important characteristics which are desired to be used as transformer liquid insulation include physical traits, chemical features and electrical attributes which are presented in the following section.

Physical properties

Flash and fire point

The smallest temperature at which the fluid may develop a vapor close to its surface that will "flash," or momentarily ignite when exposed to an open flame. Flash point (FP) is counted to be a usual sign of the flammability or combustibility of a fluid. The temperature which is necessary to originate spontaneous ignition causes generates vapors to develop flammable blend. The flammability in transformers is very critical for the safety of power systems. There are multiple examples of transformer explosions resulting into flames in the event of liquid leakage. Fire and flash points are measures of liquid's opposition to provoke a fire. One of most significant advantages associated with NEs is their higher fire and flash points than MO. Fire and flash point are vital for transformer for their indoor applications for safety measures. Flash and fire point are temperatures which imply flammable nature of fluid insulations. Fluid insulations with greater flash point and fire point will have good fireproof attributes. The research studies conducted to investigate the flashpoint and fire point of natural esters as compared to other transformer oils are reviewed in Tables 1 and 2 separately. All the different authors agree that flash and fire point are generally higher in NE rather than MO, but the difference will depend on the type of used oils.

Pour point

It specifies the smallest temperature at which dielectric liquid will flow. Pour point is the lowest temperature at which dielectric liquid simply initiates to pour/flow, when investigated under recommended specifications. It is significant in cold conditions to confirm that the fluid will flow and perform its objective as an insulating and cooling medium. Transformer oil stops circulating when the oil temperature is beneath the pouring point. Low pour point signifies a good insulating liquid. A greater value of pour point indicates the presence of wax substance in oil sources to enhance viscosity. Pour point is a useful measure to identify how dielectric liquid will perform under low-temperature conditions particularly, whereas this is critical to startup a transformer

Table 1 Review of research conclusions on flash point of various transformer liquid insulations

Reference(s)	Author (s)	Year	Standard	Oil types	Findings
McShane (2001)	C. Patrick McShane et al	2002	–	VOs, MO	The FP of VO was 123% higher than MO
Bashi et al. (2006)	S M Bashiet al	2006	ASTM D92	Palm oil (RDB), MO	Flash point for VO (< 220 °C) is higher than MO (145 °C)
Abdelmalik (2014)	A.A. Abdelmalik	2014	–	Alkyl ester of palm kernel oil	Flash point of VO was higher 6 °C than MO
Raof et al. (2016)	N.A Raof	2016	ASTM D 92 by using manual Cleveland Open Cup apparatus	Palm-based oil, MO	Flash point of enhanced by 94% as compared to MO
Beroual et al. (2017)	Beroual et al	2017	Pensky-Martens (PM) closed-cup approach according to ASTM D93	Vegetable oil, SO, MO	Flash point of VO was 123% higher than MO
Menkiti et al. (2017)	Menkiti et al	2017	–	Terminalia catappa kernel oil, MO	The flash point enhancement for VO was 71% as compared to MO
Subburaj et al. (2020)	S.K. Subburaj et al	2020	ASTM D92	Palm oil, olive oil, MO	Flash point of VO (palm and olive) is much higher than that of MO
Das (2023)	A.K Das	2023	ASTM D92	VO (coconut oil), SO (MIDEL eN1215), MO	VO shows a flash point of 290 °C and consequently satisfy the requirement of fire-safe fluid

Table 2 Summary of research studies on fire point of various transformer liquid insulations

Reference(s)	Author (s)	Year	Standard	Oil types	Findings
Bashi et al. (2006)	S M Bashiet al	2006	ASTM D92	Palm oil (RDB), MO	Fire point for VO (< 220 °C) is higher than MO (185 °C)
Subburaj et al. (2020)	S.K. Subburaj et al	2020	ASTM D92	Palm oil, olive oil, MO	The fire point of VO (palm and olive) is much higher than that of MO
Das (2023)	A.K Das	2023	ASTM D92	VO (coconut oil), SO (MIDEL eN1215), MO	VO shows a fire point of 329 °C and thus satisfies the requirement of fire-safe fluid

in enormously cold environments. When the temperature of dielectric liquid drops beneath the pour point, it stops convention flow and impedes the cooling of the transformer. Natural esters have higher pour point than MO; however, SEs have pour point quite close to the customary MO. A plain and economical answer to this issue is to add pour point depressants (Rapp et al. 1999). Jaya Sree et al. employed two SEs and one MO with pour point below − 50 °C to investigate the impact of water on breakdown failure probability and it was concluded that the performance of low pour point insulating fluids under certain conditions is identical to the conventional transformer liquids (Thota et al. 2022). They also studied the pre-breakdown and breakdown assessment of the above-mentioned insulating liquids with various tip radii under AC stress and concluded that conduct of these liquids is complying with the theoretical principle on pre-breakdown phenomena (Jayasree et al. 2021, 2023). The research studies conducted to investigate the pour point of NEs as compared to other transformer oils are summarized in Table 3. All the different authors agree that pour point is generally lower in NE rather than MO, but the difference will depend on the type of used oils.

Viscosity

This is the interior friction force that opposition to flow dielectric liquid. Good dielectric fluid has small viscosity. When the temperature of dielectric liquid decreases, the viscosity of oil will increase. The viscosity of dielectric liquid affects the capacity to transport the heat by conduction; therefore, cooling of transformer by conduction is the main heat eliminating process. A smaller value of viscosity enables a high rate of heat transfer in transformers (Yao et al. 2018). The viscosity represents fluid-flow

Table 3 Summary of research studies on pour point of various transformer liquid insulations

Reference(s)	Author (s)	Year	Standard	Oil types	Findings
McShane (2001)	C. Patrick McShane et al	2002	–	VOs, MO	The pour point of VO was 58% lower than MO
Raof et al. (2016)	N.A Raof	2016	ASTM D 97 Petrotest Instruments	Palm-based oil, MO	Pour point of VO enhanced by − 72% as compared to MO
Menkiti et al. (2017)	Menkiti et al	2017	–	Terminalia catappa kernel oil, MO	The pour point enhancement for VO was − 106% as compared to MO
Beroual et al. (2017)	Beroual et al	2017	–	Vegetable oil, SO, MO	Pour point of VO was − 63% lower than MO
Beroual et al. (2017)	Beroual et al	2017	–	Vegetable oil, SO, MO	Pour point of VO was − 63% lower than MO

features, and therefore is an including feature for heat transfer capacity of insulating fluid. If the oil has greater viscosity, heat transfer capacity is substantially decreased and vice versa. Viscosity decides the flow character of oil within the transformer which is indirectly linked to the cooling capability of oil. Viscosity is a measurement of flow resistance of oil on smooth surface. Fluid with low viscosity will have great heat removal ability. For better heat transfer, free circulation of oil is necessary which is likely with reasonable viscous oil. Viscosity is inversely proportional to temperature. The research studies conducted to investigate the viscosity of natural esters as compared to other transformer oils are summarized in Table 4. Most of the studies show that viscosity of NE is generally than MO, but the difference will depend on the type of used oils.

Density

The density of transformer oil is one of the most significant aspects of its physical properties. It has an enormous impact on the operation of transformers. The specific density of oil will change based on the producer and area where the oil will be principally used. It is defined as ratio of the masses of the substance to the volume of the substance. Simply expressed, it is the ratio of the weight of the oil to the volume/amount of oil. The temperature of oil influences the density of transformer oil. As the temperature rises, the density of oil reduces. Density of transformer oil is believed to be a scale for determining its other properties, e.g., viscosity and specific internal friction coefficient. The research studies conducted to investigate the density of natural esters as compared to other transformer oils are summarized in Table 5. Most of the studies indicated that relative density of NE is generally similar, but the difference will depend on the type of used oils.

Chemical features

Sludge substance

The dielectric liquid includes sludge compounds and existence of these compounds limits its circulation in transformer that is crucial for cooling purpose. Consequently, for better cooling, sludge contents must be smallest.

Moisture content

Water content in dielectric fluid not only influences its insulating characteristics but also affects paper insulation badly. Cellulose absorbs the maximum extent of water due to its hygroscopic characteristics. High moisture reduces the dielectric strength and enhances dielectric loss of dielectric fluid. Moisture accumulates in the transformer with the passage of time predominantly absorbed by the solid insulation, but it can last in various other forms. These can involve dissolved water in the oil, free water suspended as droplets in the dielectric fluid. A trivial segment of moisture is found in the dielectric fluid, most of it is diffused in the paper (cellulose) insulation. Moisture existence in transformer can result in the frequent issue of oxidation; however, in severe instances, arcing and flashovers can happen, preceding to dielectric breakdown. The summary of research studies on moisture content of natural esters in comparison with other transformer oil types is presented in Table 6. Most of the studies show that moisture absorption for NE is generally lower than MO, but the difference will depend on the type of used oils.

Acidity

Acidity of dielectric fluid deteriorates dielectric features and produces rust in iron parts of transformer. Acidity is the number of acidic ingredients present in insulating liquid. The acidity increases as oil ages through a function.

Table 4 Summary of research studies on viscosity of various transformer liquid insulations

Reference(s)	Author (s)	Year	Standard	Oil types	Findings
McShane (2001)	C. Patrick McShane et al	2002	–	Vos, MO	The viscosity of VO was 243% higher than MO
Bashi et al. (2006)	S M Bashiet al	2006	ASTM D88/D445	Palm oil (RDB), MO	Viscosity for VO is higher than MO at temperatures of 0 °C, 40 °C and100 °C
Jeong et al. (2012)	Jeong et al	2012	–	Vegetable oil, MO	The viscosity of VO was higher than MO
Abdelmalik (2014)	A.A. Abdelmalik	2014	–	Alkyl ester of palm kernel oil	Viscosity of VO of about 4 times lower than that of MO
Devi et al. (2016)	K.G Devi	2016	REDWOOD viscometer	Coconut oil, Pongamia pinnata oil and palm oil, MO	The viscosity of palm oil was 17% lower than MO
Raof et al. (2016)	N.A Raof	2016	ASTM D 7042 by using automatic Stabinger Viscometer™ SVM 3000	Palm-based oil, MO	The viscosity (at 40 °C) of VO enhanced by 163% of MO
Mariprasath et al. (2017)	T. Mariprasath et al	2017	ISO 3104 using red wood viscometer	Karanja oil, MO	The viscosity (at 100 °C) of VO was 157% higher than MO
Menkiti et al. (2017)	Menkiti et al	2017	–	Terminalia catappa kernel oil, MO	The viscosity (at 40 °C) enhancement was 103% of VO as compared to MO
Beroual et al. (2017)	Beroual et al	2017	–	Vegetable oil, SO, MO	Viscosity (at 40 °C) of VO was 304% higher than MO
Subburaj et al. (2020)	S.K. Subburaj et al	2020	ASTM D 2162–06	Palm oil, olive oil, MO	The viscosity of VO is greater than MO. Thus, consideration must be given for designing of tubes of transformers
Das (2023)	A.K Das	2023	ASTM D445	VO (coconut oil), SO (MIDEL eN1215), MO	The mean value of 12 mm^2/s was described as the concluding viscosity of VO which is marginally larger than that of MO but smaller than half of that for SO

Table 5 Summary of research studies on density of various transformer liquid insulations

Reference(s)	Author (s)	Year	Standard	Oil types	Findings
Bashi et al. (2006)	S M Bashiet al	2006	ASTM D1298	Palm oil (RDB), MO	Relative density for VO is almost like MO at 15 °C temperature
Beroual et al. (2017)	Beroual et al	2017	–	Vegetable oil, SO, MO	Density (at 20 °C) of VO was almost like MO
Das (2023)	A.K Das	2023	ASTM D1298	VO (coconut oil), SO (MIDEL eN1215), MO	The result showed that density of vegetable oils is almost like MO

Observation of acid value during working is a significant agent to verify secure working and functioning of transformer. Acidity is utilized to evaluate the existence of free organic and inorganic acids in oil. Corrosion and deformation rise with upsurge in the acid substance of the oil. The acidity of oil is utilized as quality control for liquid insulation formulation, and it suggests the relative volume of acidic constituents existing in the oil by extent of base titrated. The summary of research studies on acidity of natural esters in comparison with other transformer oil types

Table 6 Summary of research studies on moisture content of various transformer liquid insulations

Reference(s)	Author (s)	Year	Standard/ Method	Oil types	Findings
Bashi et al. (2006)	S M Bashiet al	2006	ASTM D3277	Palm oil (RDB), MO	Moisture content in % for VO (0.08) is lower than MO (0.1)
Mariprasath et al. (2017)	T. Mariprasath et al	2017	IEC 60814 Karl Fischer titration	Karanja oil, MO	Water matter of Karanja oil is greater than that of MO
Beroual et al. (2017)	Beroual et al	2017	–	Vegetable oil, SO, MO	Water content of VO is kore than SO and less than MO
Subburaj et al. (2020)	S.K. Subburaj et al	2020	IEC 60814	Palm oil, olive oil, MO	The water content noted in ppm for MO was 27, for palm oil 88 and for olive oil 110
Das (2023)	A.K Das	2023	% RH Probe	VO (coconut oil), SO (MIDEL eN1215), MO	Moisture content (%) noted for VO was 6.7, for SO 6.9 and for MO 2

is presented in Table 7. A high acid value for NE does not mean a high degradation neither the oil nor the cellulose. In fact, this means the solid insulation is drying and fatty acids are forming due to hydrolysis reactions.

Oxidation stability

Oxidation stability of insulating fluids is a critical parameter as it is extremely required that fluid must not be oxidized with passing of time. The consistency of insulating fluids is substantially affected by oxidation and aging process. The oxidation of dielectric fluid is a significant factor as it results in the forming of by-products, e.g., acids and sludge, conversely initiate problems in the HV equipment by reducing the insulating traits of solid dielectric substance (Saha and Purkait 2017). In line with their relative oxidation stability, SOs are identified as greatly stable insulating fluid, followed by SEs, then MOs and lastly NEs (Raymon et al. 2013). Breakdown of chemical bonds happens because of oxidation of dielectric fluid. Oxidation of dielectric liquid generates carbon dioxide (CO_2) and carbon monoxide (CO). Moreover, oxygen produce per oxides that originates free radicals (Crine 1986).

Electrical properties

It is required for every type of transformer oil to withstand AC voltage, lightning impulse and switching impulse voltages. Natural esters dielectrics have demonstrated comparable properties to MO (Mahanta 2020). They have satisfactory dielectric and excellent fire safety characteristics. Moreover, they are biodegradable as they have an organic structure and most notably, they are more reasonable and readily accessible. An enormous number of studies were carried out with natural esters as an alternative of MO in transformers by researchers from different parts of the world. Majority of these investigations were stated from US, UK, China, Japan, Malaysia and Europe. Oommen et al. investigated the vegetable oils as dielectric fluid in distribution transformers. The newly developed dielectric fluid suited the challenge of environmentally friendly liquid for transformers. Several other qualifying assessments were conducted including standard approval tests for ordinary transformer oils. The results showed that the biodegradable fluid might be used as suitable alternate transformer fluid (Oommen et al. 2000).

Table 7 Summary of research studies on acidity of various transformer liquid insulations

Reference(s)	Author (s)	Year	Standard	Oil types	Findings
Beroual et al. (2017)	Beroual et al	2017	–	Vegetable oil, SO, MO	Acid index of VO is a little higher than MO
Mariprasath et al. (2017)	T. Mariprasath et al	2017	IEC 60021	Karanja oil, MO	The acidity of Karanja oil is higher than that of MO
Subburaj et al. (2020)	S.K. Subburaj et al	2020	IEC 62021	Palm oil, olive oil, MO	VOs exhibit a greater extent of acidity than MO. On the other hand, these are greater molecular fatty acids; these do not react with cellulose applied in transformers
Das (2023)	A.K Das	2023	–	VO (coconut oil), SO (MIDEL eN1215), MO	The VOs exhibited a higher amount of acidity than MOs

AC dielectric strength

Dielectric strength (DS) is the highest electric field strength that a fluid may naturally endure without collapsing and converting electrically conductive. This is a major feature which establishes the viability of a dielectric fluid. Dielectric strength is a physical quantity that relates only to the electrode systems of uniform electric field distribution. A higher DS implies that it has greater resistance to electrical charges. It is the amount of applied voltage at which sparking gets started between two electrodes submerged in oil parted by a given gap distance. The amount of applied voltage at which this happens is called breakdown voltage (BDV measured in volts). BDV is the competence of the liquid to endure dielectric stresses. Degradation of DS generally implies the existence of moisture and polar element contamination from external sources and/or insulation aging. The DS is potential gradient at potential gradient at which this happens (stated in volts per meter, kV/mm, etc.). The summary of research studies on AC BDS in comparison with other transformer oil types is presented in Table 8.

Impulse BDV test

Over voltages are generated by direct/indirect lightning strikes or by switching operations in electric power systems. They generate transient stresses to the insulation, much greater than the stresses due to operational voltages. Lighting overvoltage is a natural phenomenon, whereas switching over voltages originates in the system due to switching operations. The study of lightning and switching surges is critical for insulation system of HV equipment.

The impulse strength of an insulation indicates its competence to withstand HV transients for a short period, e.g., those it might be subjected to through lightning strikes. The standard lightning impulse (LI) denotes simulating lighting shots and typically employs 1.2-µs surge for a wave to attain a 90% amplitude and fall to 50% amplitude after 50-µs. The LI BDV is usually assessed by IEC 60897 standard. The wave form of standard switching impulse (SI) is 250/2500 µs, where 250 µs and 2500 µs mean front time and wave tail, respectively. The SI BDV is usually tested by IEC 60060-1 standard. In contrast to AC BDV assessments, impulse BD test is not generally affected by moisture and contamination in dielectric fluid, therefore can be applied to assess the dielectric traits of fluid itself. The summary of research studies on LI BDS in comparison with other transformer oil types is presented in Table 9.

Partial discharge test

Partial discharge (PD) test is generally used rather than AC BD test for non-uniform fields with relatively longer oil gaps. The standard description of PD is an electrical discharge that does not fully bridge the gap between two conducting electrodes. PD happens in various spots and mediums when a small area of insulation in HV environment cannot cope with electrical stress and BD. It does not span the entire gap between insulated electrodes—that's why it's known "partial." It can be triggered by discontinuities or defects in the insulation system, e.g., presence of gas bubbles in fluid insulation. PD might be small; nevertheless, it might originate insulation deterioration over time, which will ultimately lead to breakdown. The voltage level when ionization and PD initiate to happen is called partial inception discharge voltage (PDIV). PD activity can occur at any point in the insulation system, wherever electric field strength exceeds the BDS of that point of dielectric material. PD also plays a critical function in accelerating thermal aging and deterioration of insulating fluid. The effects of PD within transformer can be quite severe, finally leading to complete collapse. The summary of research studies on partial discharge testing in comparison with other transformer oil types is presented in Table 10.

Dielectric dissipation factor (DF)

The DF or tan δ is the extent of dielectric loss occurring in insulating liquid when it is subjected to an AC field. The DF generally surges with a rising presence of contaminants or aging by-products, e.g., moisture, carbon or conducting materials and oxidation by-products. DF gives knowledge on the extent of dielectric losses in transformer oil happening during operation. DF is also called loss factor or tan δ of a transformer oil. As a dielectric material is positioned between a live part and grounded portion of an electrical apparatus, leakage current will flow. The current will lead the voltage by 90° ideally due to dielectric description of the dielectric material. However, no insulating material is perfect dielectric in nature. Therefore, current through insulating material will lead the voltage with an angle a little shorter than 90°. The tangent of the angle by which it is short of 90° is called DF or simply tan δ of transformer oil. The DF is the extent of dielectric loss occurring in an insulating liquid while it is subjected to an AC field. It is generally more with the number of contaminations or aging by-products, e.g., moisture, carbon or extra conducting materials and oxidation products. DF is a good gauge for determining any impurities and estimating dielectric losses in the oil. However, relative permittivity could be used to classify the kind of dielectric insulating liquid. A measurement of DF allows to reveal the state of the insulation. Generally, NEs liquids indicated higher DF than MOs especially at elevated temperatures. Rozga investigated performance of dielectric ester under the influence of concentrated heat flux. The investigation was based on the statistics, e.g. dielectric

Table 8 Summary of research studies on AC BDS of various transformer liquid insulations

Reference (s)	Author (s)	Year	Gap distances	Electrode types	Standard	Oil types studied	findings
Boss and Oommen (1999)	T.V. Oommen et al	1999	2.5 mm 2.0 mm	Disk VDE	ASTM D877 ASTM D1816	Vegetable oil (RDB oil), high-temperature MO	Vegetable oil indicated a. Better BDV b. High biodegradability, c. elevated flash and fire points, d. Good oxidation stability
Abeysundara et al. (2001)	D.C. Abeysundara et al	2001	2.5 mm	Spherical		Coconut oil, MO	AC BDV of NE was 60 kV as compared to 50 kV for MO
McShane (2001)	C. Patrick McShane et al	2001, 2002			D877	MO, SO, HMWH, SE, NE	AC BDV of NE was 12% higher in comparison with other studied liquids
Bertrand and Hoang (2004)	Y. BERTRAND et al	2004		–	IEC 60156	MOs, SOs, SEs, NEs	Vegetable oil indicated a better BDV as compared to other oils
Borsi and Gockenbach (2005)	H. Borsi et al	2005	2.5 mm	Spherical electrode	IEC 60296	Midel 7131, MO	Ester liquid (Midel 7131) and mixtures of Midel and MO manifested better insulating properties as compared to MO
Badent et al. (2002)	R. Badent et al	2002	2 mm	Spherical calotte electrodes	VDE 0370	RAPSOLT, Shell Diala D	AC BDS is as high as for MO
Perrier et al. (2004)	C. Perrie et al	2004	2.50 ± 0.05 mm	Spherical electrodes	IEC 60156	Mineral ester and silicone oils, and mixtures	It was concluded that ester oil has a better BDV performance due to its better water solubility
Tenbohlen et al. (2008)	S. Tenbohlen et al	2008	2.5 mm	Spherical electrodes	IEC156/95, ASTM D1816	Natural ester, silicone easter, MO	AC BDS for homogeneous field manifested that at humidity saturations normal for transformers the NE accomplish superior than MO
Gockenbach and Borsi (2008)	E. Gockenbach et al	2008	2.5 mm	Cylindrical shell around the electrodes	IEC 60156	Natural ester, silicone ester, MO	1. The electrical performance of ester is comparable to MO 2. The dielectric parameters of ester are slightly better compared to MO

Table 8 (continued)

Reference (s)	Author (s)	Year	Gap distances	Electrode types	Standard	Oil types studied	findings
Bashi et al. (2006)	S.M Bashi et al	2006	2.5 mm	Spherical electrode	ASTM D1816	Palm oil, MO	AC BDV of NE comparable to MO
Marulanda et al. (2008)	A. R. Marulanda et al	2008	–	–	–	Vegetable oil, MO	The dielectric BDV are higher than MO; improving with the years the useful life of the dielectric strength of this oil
Martin and Wang (2008)	D. Martin et al	2008	1 mm	Spherically capped electrodes of the VDE specification 0370	ASTM D1816	MO (Nytro 10 GBN), NE (FR3) and the SE (Midel 7131)	1. The AC BD performance of the esters, at low probabilities, wascomparable to mineral oil 2. The lowest BDV of esters was also like that of MO 3. The design of transformer used for MO was feasible for NEs as well
Perrier and Beroual (2009)	C. Perrier et al	2009	2.50 ± 0.05 mm	VDE electrodes	IEC 60156	Three VOs, SE, Silicone oil, MO (naphtenic and paraffinic)	Before aging, NE and SE present BDV close to that of MO while after aging, NE has higher BDV than MO
Dang et al. (2012a)	V.H Dang et al	2011	2.50 ± 0.05 mm	Spherical electrodes	IEC 60156	Naphtenic mineral oils, synthetic ester, vegetable oils	BDV for NE is higher than MO
Liao et al. (2011)	Ruijin Liao et al	2011	2.5 mm	–	IEC 60156	Natural ester, MO	The AC BDS of NE enhanced 43% more than MO during the whole aging process, except for when sampled at 30 days, where the AC BDV of NE is only comparable with the MO aged the same time
Divakaran and Kalaivanan (2012)	D. Divakaran et al	2012	1–4 mm	Plane electrodes	IEC 60156	Coconut oil, MO	The BDV was less than MO
Jeong et al. (2012)	Jeong et al	2012	–	–	IEC 60156	VO, MO	The BDV of VO was 30% enhanced as compared to MO

Table 8 (continued)

Reference (s)	Author (s)	Year	Gap distances	Electrode types	Standard	Oil types studied	findings
Jing et al. (2014)	Yi Jing et al	2012	0.5 mm	–	ASTM D 1816–04	SE (Midel 7131); MO, (Shell Diala D), VO (rapeseed)	Midel 7131 showed the highest ac BDV with standard deviation. Diala D provides a greater BDV in comparison with VO. Rapeseed oil (natural ester) has the lowest AC BDV
Chandrasekar and Montanari (2014)	S. Chandrasekar et al	2014	2.5 mm	–	IEC 60156	MO, palm oil, corn oil	1. The results showed that palm and corn oil have higher BDS than MO 2. The effect of thermal aging on BDS appears much lesser in NE fluids than in MO
Reffas et al. (2016)	A.Reffas et al	2016	2 mm	–	IEC 60156	VO (olive oil), MO	The BDV of olive oil was higher than MO
Rozga (2016a, c)	Pawel Rozga	2016	–	–	–	Synthetic ester, NE, MO	AC BDV of NE was higher than MO and SE
Raof et al. (2016)	N.A Raof	2016	2.5 mm	Mushroom electrode	IEC 60156	Palm-based oil, MO	AC BDV of NE enhanced 2.6% as compared to MO
Sitorus et al. (2016)	Henry B.H. Sitorus et al	2016	2.50 ± 0.05 mm	Spherical electrodes	IEC 60156	Jatropha curcas oil (JMEO), MO	Basing on the BDV results under AC, DC, and lightning impulse voltages, it was concluded that the BDV JMEO and MO are very close
Devi et al. (2016)	K.G Devi	2016	2.5 mm	Plane electrodes	IEC 60156	Coconut oil, MO	The AC BDV for VO at 2 mm gap distance for VO was − 7% lower than MO
Hamid et al. (2016)	M. H. A. Hamid et al	2016	2.5 mm	Bi-spherical electrodes	IEC 60156	Rice bran oil, palm oil, corn oil, sunflower oil and canola oil	NE (canola-based ester oil) has the superior ability to substitute the existing transformer oil because ofits good dielectric features

Table 8 (continued)

Reference (s)	Author (s)	Year	Gap distances	Electrode types	Standard	Oil types studied	findings
Menkiti et al. (2017)	Menkiti et al	2017	–	–	–	Terminalia catappa kernel oil, MO	The AC BDV of VO was 39% lower as compared to MO
Mariprasath et al. (2017)	T. Mariprasath et al	2017	2.5 mm	Hemispherical electrodes	IEC 60156	Karanja oil, MO	The AC BDV of VO was 15% enhanced as compared to MO
Beroual et al. (2017)	A. Beroual et al	2017	2.50 ± 0.05 mm	Sphere-sphere electrode system	IEC 60156	Natural ester, synthetic ester, MO	1. NEs manifested higher BDV than MO 2. NE can be used as a suitable substitute to MO in HV transformer
Yu et al. (2017)	Haichuan Yu et al	2017	1 mm	–	ASTM D6871-2003(2008), ASTM D3487-16	Natural ester, MO	The AC BDV, acidity and dynamic viscosity of MO were inferior to Envirotemp FR3
Reffas et al. (2018a)	A.Reffas et al	2018	2.5 mm ± 0.05 mm	Spherical electrode	IEC 60156	Olive oil, rapeseed oil, naphthenic MO, synthetic esters (e tetra-ester, Methyl Oleate)	1. DBV of olive oil is greater under AC and LI voltages than those of MO. 2. The olive oil may be used as replacement of MO in HV transformers
Kurzweil et al. (2021)	Peter Kurzwei et al	2021	2.5 mm	Spherical	IEC60156	MO, bio-based carbon, synthetic ester, NE	The biodegradable fluid has the highest BDV compared with the others
Atalar et al. (2022)	Fatih Atalar et al	2022	2.5 mm, 2 mm and 1 mm	Disk and VDE type (mushroom)	ASTM D1816-84a, ASTM D877-87	Natural ester, synthetic ester, MO	AC BDV of SE was better than NE and MO
Gutiérrez et al. (2023)	C.M. Gutiérrez et al	2023	2.5 mm	Semi-spherical electrodes s	IEC 60156	MO, unmodified soybean, sunflower, rapeseed esters, altered palm ester and a synthetic ester	Substitute liquids had greater BDV than the MO. Toward the end of the aging, BDV was decreased in all the liquids, due to deterioration. This decline was greater in the NEs than in the conventional MO
Das (2023)	A.K Das	2023	-	Mushroom-shaped electrodes	IEC 60156	RBD coconut oil, SO (MIDEL eN1215), MO	The results suggest that at low probabilities, AC BDV in VO was comparable to commercial MO

Table 8 (continued)

Reference (s)	Author (s)	Year	Gap distances	Electrode types	Standard	Oil types studied	findings
Pompili et al. (2023)	M. Pompili	2023	2.5 mm	Partially spherical shapes	IEC 60156	MO, NE	Average AC BDV of NE was 41 kV as compared to 34 for MO

dissipation factor, gases dissolved and Fourier transform infrared spectroscopy spectrum as well as on the direct examination and registration of the process using digital camera (Rozga 2016b, 2012). The summary of research studies on DF in comparison with other transformer oil types is presented in Table 11.

Dielectric constant

Dielectric constant/permittivity is associated with the competence of any dielectric liquid to transfer an electric field. It could be deemed as a trait vulnerable to polar contaminations; hence, its smaller value may indicate the presence of contaminants, e.g., humidity, particles and variations in oil structure, e.g., oxidation, depreciation or additive consumption. The applied voltages are divided in terms of permittivity values in a complex configuration of liquid/solid (paper) in a transformer. With conventional MO in compound electrical insulation system, electrical stress on oil is higher than solid insulation as the dielectric constant of solid is higher than MO. NEs generally have dielectric constant higher than cellulose insulation (paper/pressboard) which may lead to less stress on the natural ester liquid insulation system as compared to MO insulation system (Martin et al. 2007). The summary of research studies on dielectric constant in comparison with other transformer oil types is presented in Table 12.

Specific resistivity

Resistivity is a gage of the DC resistance between the opposite sides of an oil cube (1 × 1 × 1 cm). A minor fraction of free ions and ion-forming elements results in higher resistivity. This feature is dependent on the presence of oil soluble contaminants and aging derivatives. The specific resistivity of oil has a direct relationship between BDS and dielectric constant and has an inverse connection to the dielectric loss factor. The summary of research studies on specific resistivity in comparison with other transformer oil types is presented in Table 13.

Environmental properties

MOs are not biodegradable fluids, and their emission profile is poor, which suggests they are dangerous to human and marine living (in case of spills). Multiple researchers have made serious efforts to look for alternative fluids which are environmentally friendly and have good fire-associated performance. The environmental attributes generally include constraints, e.g., biodegradability, toxicity and sustainability. Oomen et al. underlined the biodegradability of NE-based insulating liquids for secure transformer insulation (Oommen et al. 1997). McShane (2002) conferred the environmental conduct of ester

Table 9 Summary of research studies on LI BDS of various transformer liquid insulations

Reference (s)	Author (s)	Year	Gap distance	Electrode types	standard	Oil types studied	findings
Binns and Yoon (1982)	D. F Binns et al	1982	0.5–2.5 mm	Spherical electrodes	–	Silicone oil, ester Midel, MO	The result showed that LI BDV of MO was higher than ester and silicone oil
Badent et al. (2002)	R. Badent et al	2002	5–50 mm	Plane-plane and rod-plane	–	RAPSOLT and Shell Diala D	The result indicated that NE (RAPSOLT) impulse strength is comparable to MO
Tenbohlen et al. (2008)	S. Tenbohlen et al	2008	40 mm	point-plate	–	MO (Nynas Nytro 3000 X) and 03 NEs (Envirotemp FR3 liquid, Midel eN, high-oleic sunflower oil)	The results showed that LI under non-uniform field, BDVs of natural esters are higher than MO

Table 9 (continued)

Reference (s)	Author (s)	Year	Gap distance	Electrode types	standard	Oil types studied	findings
Wang et al. (2012)	Z. D Wang et al	2012	0–100 mm	Needle-plane		NE, SE, MO	1. Under LI, the BDVs of the NEs are analogous to that of MO in a quasi-uniform electric field 2. In general, BDVs of NEs are lower than that of MO in a non-uniform electric field, and difference is increased at larger gap distances
Rozga and Stanek (2017)	P. Rozga et al	2017	25 mm Point to sphere	Point to sphere	–	Two types of NEs	Both the liquids present almost similar LI BDV values

Table 9 (continued)

Reference (s)	Author (s)	Year	Gap distance	Electrode types	standard	Oil types studied	findings
Haegele et al. (2018)	Stephanie Haegele et al	2018	10, 15, 25, 40, 50 mm	Various electrode configuration	ASTM D3300	NE, MO	Larger the inhomogeneity, higher the difference between NE and MO with NE demonstrating a decreased mean BD. The greater the inhomogeneity, the greater the impact of speedy streamer events preceding to BD at lower voltages in NEs
Subburaj et al. (2020)	S.K. Subburaj et al	2020	2.5 mm	Gapped semi spherical	–	Olive oil, palm oil, MO	1. The results showed palm oil and olive oil have high BDV than MO 2. Aged VO also presented better BD performance than MO

Table 9 (continued)

Reference (s)	Author (s)	Year	Gap distance	Electrode types	standard	Oil types studied	findings
Li et al. (2021)	Huaqiang Li et al	2021	1 mm to 50 mm	Point-plane	–	: (a) Mineral oil; (b) Synthetic ester; (c) Natural ester; (d) Glycerin trioleate; (e) Ethyl oleate; (f) Ethyl linoleate	1. The positive lightning BDV of the SE is lower than other liquids 2. The negative BDVs of MO are always higher than those of ester liquids, and the differences increase with the extension of gaps distance
Agarwal et al. (2020)	Ritika Agarwal et al	2021	1 mm, 5 mm, 10 mm	Sphere to needle	ASTM D3300	MO, NE	1. It is found that under negative polarity, BDV of NEs is much lower as compared to MO. 2. However, under positive polarity BDV of NEs molecules is slightly higher as compared to MO

Table 9 (continued)

Reference (s)	Author (s)	Year	Gap distance	Electrode types	standard	Oil types studied	findings
Williamson et al. (2020)	C. Williamson et al	2021	–	Needle-sphere	–	NE (Envirotemp FR3), a SE (MIDEL 7131) and a naphthenic MO (Shell Diala S4 ZX)	It was found that the NE outperforms both the SE and MO under positive energization but exhibited the lowest DS when exposed to negative LI
Pompili et al. (2023)	M. Pompili et al	2023	25 mm	Point-sphere	IEC 60897	MO, NE	It was found that LI BDVs of both studied liquids are comparable

Table 10 Summary of research studies on partial discharge of various transformer liquid insulations

Reference (s)	Author (s)	Year	Gap distance	Electrode types	standard	Oil types studied	findings
Gockenbach and Borsi (2008)	E. Gockenbach	2008		needle-sphere and needle-plate	IEC 61294	NE, SE	The NE has the same or a slightly better performance in the PD behavior compared to SE
Wang et al. (2012)	Z.D. WANG et al	2012	–	Needle-sphere	–	SE, MO, NE	At HV, the maximum PD amplitudes of NE increase somewhat more quickly than those of MO, with SE The PD repetition rate was found to be significantly higher in the NE than in the MO, with a higher rate of increase if voltage is further increased
Mohamed et al. (2017)	M. Mohamed et al	2017	25–225 mm	Needle-To-Plane	–	NEs, MO	The NE is indicated good potential for MV transformer insulation with slightly higher PDIV than MO
Kurzweil et al. (2021)	E. Gockenbach	2021	30 mm	Needle-sphere	IEC 60270:2000	MO, SE, NE	PDIV of NE was better than MO but inferior to SE
Pasternak and Rozga (2023)	B. Pasternak et al	2023	–	Point-sphere	–	SE, NE, MO	Alternate fluids were distinguished by marginally smaller PDIV values in comparison with both MO considered
Mahesh Kumar et al. (2021)	K M Mahesh Kumar et al	2021	–	–	IEC TR 61294	NE, SE, MO	It is observed that ester-based oils have proved to be a viable substitute for MO from the point of view of PDIV
Mariprasath and Ravindaran (2022)	T MARIPRASATH et al	2022	–	Needle-plane	–	rice bran oil and sunflower oil, MO	The results show that VO has outstanding withstand strength under thermal stress. Furthermore, VO involves an extensively greater prospective difference for initiating PD on oil samples
Pompili et al. (2023)	M. Pompili et al	2023	25 mm	Needle-plane	IEC 60270, IEC TR 61294	MO, NE	The results showed that as the voltage is increased, the frequency of PD enhances in both dielectric fluids. Moreover, the distribution of PD amplitudes presents similar trend

Table 11 Summary of research studies on DF of various transformer liquid insulations

Reference(s)	Author (s)	Year	Standard	Oil types	findings
Carcedo et al. (2015)	J. Carcedo et al	2015	IEC 60247	Vegetable oils, MOs	The VOs manifested a higher tan delta than for the MO
Mariprasath et al. (2017)	T. Mariprasath et al	2017	IEC 60247	Karanja oil, MO	The dielectric dissipation of Karanja oil is lower than that of MO
Beroual et al. (2017)	Beroual et al	2017	-	Vegetable oil, SO, MO	The dissipation factor was VO is 0.005, whereas it is < 0.006 for SO and < 0.001 for MO
Subburaj et al. (2020)	S.K. Subburaj et al	2020	IEC 60247	Palm oil, olive oil, MO	The result showed that dielectric loss of MO is marginally greater than that of VO
Das (2023)	A.K Das	2023	IEC60247	MO, VO (RDB coconut oil), SO (MIDEL eN1215)	The values of dissipation factor for VO were comparable to that for SO

Table 12 Summary of research studies on dielectric constant of various transformer liquid insulations

Reference(s)	Author (s)	Year	Standard	Oil types	findings
Mariprasath et al. (2017)	T. Mariprasath et al.	2017	IEC 60247	Karanja oil, MO	The permittivity of Karanja oil is greater than that of MO
Beroual et al. (2017)	Beroual et al.	2017	–	Vegetable oil, SO, MO	Dielectric constant of VO is more than MO
Subburaj et al. (2020)	S.K. Subburaj et al.	2020	IEC 60247	Palm oil, olive oil, MO	The VO has greater dielectric constant than MO; meanwhile, VO has polar nature although MO has polar alkane molecules
Das (2023)	A.K Das	2023	IEC 60247	MO, VO (RDB coconut oil), SO (MIDEL eN1215)	The values of relative permittivity of VO were comparable to that for SO

Table 13 Summary of research studies on specific resistivity of various transformer liquid insulations

Reference(s)	Author (s)	Year	Standard	Oil types	findings
Subburaj et al. (2020)	S.K. Subburaj et al	2020	IEC 60247	Palm oil, olive oil, MO	The palm oil has greater specific resistivity than MO and olive oil

liquids and tried to improve the oxidation stability of these liquids to enhance the biological oxygen need. Thomas (2005) and Boss et al. (1999) assessed the ecological conduct of ester liquids in comparison with MOs and concluded that ester fluids to be ecologically friendly. The environmental features of NEs are excellent as they commence biodegradation very briskly and produce nontoxic derivatives. The enormous biodegradability rate of NEs enables a monetary benefit for other capacity undertakings because no detached pollutant capability needed to be set up to dodge environmental contamination in the incidence of leakage.

Pre-breakdown phenomena and breakdown mechanism

The insulating strength of dielectric fluids is mostly illustrated by withstanding voltages prior to usage in HV apparatus. This illustration is categorized based on class of voltage applied for analysis, e.g., AC, DC and impulse waves. Impulse wave testing also works for basic insulation level (BIL) and is generally applied to assess the insulation system of HV transformers. Breakdown mechanism and pre-breakdown phenomenon are critical topics that must be studied to interpret the breakdown process. It is well recognized that breakdown mechanism, pre-breakdown phenomenon and properties of BD incidents are attributed to the chemical structure of dielectric fluid. Therefore, it is highly essential to comprehend the breakdown mechanism and phenomenon of these newly dielectric fluids in comparison with MOs. Nevertheless, multiple research work has attempted to investigate these aspects of ester-based dielectric liquids, there is yet a huge research gap on breakdown mechanism and breakdown phenomenon of these new dielectric liquids. The following segment attempts to summarize research carried out on this phenomenon with ester dielectric fluids.

Natural esters have been introduced extensively in dielectric society in recent years, one of the utmost vital factors in the evaluation of their insulating features has been the studies of pre-breakdown phenomenon happening in esters at different forms of voltage exposures particularly impulse voltages (Badent et al. 1999; Hemmer et al. 2001, 2005; Duy et al. 2007; Liu et al. 2009; Nguyen et al. 2010; Rozga et al. 2013; Liu and Wang 2013; Denat et al. 2015). These assessments have been executed from the very commencement based on assessment with MO, for which numerous information have been gathered for a long time in this field (Forster and Wong 1977; Devins and Rzad 1982; Chadband 1988; Sharbaugh et al. 1978; Beroual and Tobazeon 1985; Tobazcon 1994; Yamashita and Amano 1988; Lewis 1998; Lesaint and Top 2002; Lesaint 2016; Lesaint and Jung 2000). The motivation of using the model of relative evaluation of ester liquids with MO is the fact that pre-BD and BD mechanisms are directly linked to their chemical composition (Liu and Wang 2011; Dang et al. 2012b; Denat et al. 2015; Lesaint 2016; Lesaint and Jung 2000) and esters have significantly different chemical structure as compared to MO (Oommen 2002; Fernández et al. 2013; Rao et al. 2017; Pompili et al. 2008; Tokunaga et al. 2019). Therefore, to study the discharge procedures in esters, identical research techniques may be approved which have previously been used for MO or other hydrocarbon fluids. Pre-BD and BD mechanisms in ester liquids have been investigated likewise as for MOs.

Research on pre-breakdown of natural ester liquids

The process of breakdown and pre-breakdown phenomenon are critical subjects to comprehend the breakdown mechanism. Multiple studies on these subjects have been summarized (Sharbaugh et al. 1978; Beroual et al. 1998; Rao et al. 2020). The pre-BD mechanism and features of BD phenomenon are dependent on the chemical structure of dielectric fluid. Therefore, it is required to understand this breakdown mechanism of NEs in comparison with MOs. Multiple researchers have attempted to study these traits of ester-based dielectric liquids, but there is yet a huge research gap on this pre-BD and BD phenomenon of new dielectric fluids. The following section sums up research conducted on this phenomenon with natural esters.

Normally, slow or fast streamers go along with the breakdown process in insulating fluids. Slow streamers are observed in 1st and 2nd modes, whereas fast streamers are noticed in 3rd and 4th modes. The mode of streamer propagation is dependent on the magnitude of applied voltage and electric stress. The BD in insulating liquids is generally observed with slow (2nd mode) and fast streamers (3rd mode). The 1st mode is challenging to track, and the 4th mode needs great local field stress. Even though numerous streamer features have been mentioned in the literature, streamer acceleration voltage is the utmost considerable constraint related to streamer propagation. Acceleration voltage is the voltage level at which propagation mode changes from 2nd to 3rd mode. A rise in voltage beyond the acceleration voltage adds streamer propagation velocity to several times the existent velocity.

Streamer inception voltage

The applied voltage at which the initial visible start of the streamer appears is known as streamer inception voltage. Multiple researchers studied the streamer initiation conduct of natural esters under various shapes of applied voltages (AC, DC, impulse) and stated streamer initiation in ester liquids as compared to MOs. The summary of research studies on streamer inception voltage in comparison with other transformer oil types is presented in Table 14.

Streamer stopping length

Streamer originates at HV electrode and travels to the grounded electrode in various profiles and through discrete paths. It is to be realized that all the originated streamers will approach the ground electrode. Consequently, the length determined from the extreme ending of the streamer to the tip of the HV needle is known as stopping length. The length is computed from the outcomes of the multi-channel high speed imaging methods. The stopping length of the streamers is examined to be dependent on the chemical structure of the oil, applied field and polarity of the applied voltage (Liu and Wang 2011). The positive streamers are fast and therefore their stopping length seemed greater than the negative streamers with rise in voltage (Dang et al. 2012b). The stopping length and electrode configuration are directly related as the stopping length and velocity of streamer declines with enhancement of the electrode gap (Liu et al. 2016). The stopping length of streamers in ester fluids and MO are evaluated at different electrode configurations for both positive and negative streamers (Dang et al. 2012b). The investigators

Table 14 Summary of research studies on streamer inception voltage of various transformer liquid insulations

Reference(s)	Author (s)	Year	Electrode configuration (Type and gap distance)	Oil types	findings
Duy et al. (2009)	C. T. Duy	2009	2 to 20 cm	rapeseed oil, MO	Rapid positive streamers spread at much lower voltage in VO compared to MO. Sequentially, this induces lower BDVs and shorter time to BD in this liquid
Liu and Wang (2011)	Q. Liu et al	2011	15 mm to 100 mm point-plane	SE (Midel 7131), NE (FR3), MO	streamer inception voltages of NEs are analogous to that of MO, at the same voltage level after inception streamer in NEs propagates abruptly and further, with additional branches, than in MO
Liu and Wang (2013)	Q. Liu et al	2013	Shield to plate 50 mm to 150 mm	synthetic ester, NE and MO	The streamer inception voltages of the NEs are like the MO
Dang et al. (2012b)	V.H. Dang	2012	Point-plane 2 to 40 mm	MO, NE, SE	Findings displayed that the initiation threshold voltages of streamers are near enough in the examined fluids whatever the polarity
Rozga and Stanek (2016)	P. Rozga	2014	Point-plane 15 and 20 mm	NE, SE, MO	The findings indicated that the inception voltages were close to each other for all the three liquids studied
Rozga (2016a, b, c, d)	P. ROZGA et al	2016	Point-plane 15 mm, 20 mm	NE, MO	Inception voltage of NEs is comparable to MO
Reffas et al. (2018b)	A. Reffas et al	2018	37.5 mm point-to-plane point-to-bar	SE, rapeseeds oil (NE) and MO	Inception voltage of NE is comparable to MO

concluded that conductivity and stopping lengths for positive streamers are larger than for negative streamers. The stopping length in NEs were longer than MOs, particularly for negative polarity. The summary of research studies on streamer stopping length in comparison with other transformer oil types is presented in Table 15.

Streamer velocity

Streamer velocity is a critical factor in the process of streamer propagation. Streamer velocity is calculated from the ratio of stopping length and the propagation time. This propagation time can be acquired from the streamer current and charge (Dang et al. 2012b). Streamer velocity could be calculated directly from the inter electrode gap in incident of complete BD. Discharge velocity and discharge spectra for MO and ester-based liquids are investigated. Slow and fast discharges have been described established on inception voltage, applied voltage and that slow discharges are outlined to evolve below acceleration voltages, whereas fast discharges bloom above acceleration voltages (Rozga 2014; Rozga and Tabaka 2015, 2018). The summary of research studies on streamer velocity in comparison with other transformer oil types is presented in Table 16.

Streamer accelerating voltage

The voltage level at which abrupt rise in the streamer propagation velocity is observed is known as streamer accelerating voltage. This abrupt rise in streamer velocity could be identified from instantaneous values of the streamer velocity or from the leakage current assessments. It is reported in various studies that streamer inception voltages of NEs are analogous with MO; nevertheless, streamer propagation is quicker in easter-based fluids.

Even though multiple streamer properties have been illustrated in the literature, streamer acceleration voltage is the most critical factor related to streamer propagation. Acceleration voltage is termed as the voltage at which propagation mode switches from 2nd to 3rd mode. A rise in voltage further than the acceleration voltage raises streamer propagation velocity to several times to the existing velocity. The summary of research studies on streamer accelerating voltage in comparison with other transformer oil types is presented in Table 17.

Table 15 Summary of research studies on streamer stopping length of various transformer liquid insulations

Reference(s)	Author (s)	Year	Electrode configuration (Type and gap distance)	Oil types	Findings
Duy et al. (2009), Duy et al. (2007)	C. T. Duy	2009	2 to 20 cm	rapeseed oil, MO	In NE, the positive streamer propagation develops swiftly from the “2nd mode” to the very fast “4th mode” (velocity up to 200 km/s); however, MO exhibits a higher stability at HV
Nguyen et al. (2010)	Nguyen Ngoc M. et al	2010	5 cm, 10 cm point-plane	NE, SE	The results showed almost no difference between these liquids
Liu and Wang (2011)	Q. Liu et al	2011	15 mm to 100 mm point-plane	SE (Midel 7131), NE(FR3), MO	Negative polarity designates the clear difference between NEs and MO in terms of stopping length; nevertheless, positive polarity displays an enormous difference between NEs and MO of acceleration voltage which specifies the ability to withstand fast streamer events
Dang et al. (2012b)	V.H. Dang	2012	Point-plane 2 to 40 mm	MO, NE, SE	The stopping lengths Lf and conductivity of positive streamers are greater than those of negative streamers. Stopping length is normally longer in VOs than in certain MOs, specifically with negative polarity. This suggests lower BDVs in VOs for medium gaps (20 mm)
Rozga and Stanek (2016)	P. Rozga	2014	point-plane 15 and 20 mm	NE, SE, MO	The results showed in all three fluids the streamers at inception voltages developed as so-called “stopping length” streamers
Sitorus et al. (2015)	H.B.H. Sitorus et al	2015	20, 25 and 30 mm point-plane	Jatropha curcas oil, MO	The stopping length, the correlated current and electrical charge in JMEO and MO are too similar (comparable)
Reffas et al. (2018b)	A. Reffas et al	2018	37.5 mm point-to-plane point-to-bar	Synthetic ester, rapeseeds oil (natural ester) and MO	For a given applied voltage, the stopping length of creeping discharges is shorter in presence of NEs than in MO
Thien et al. (2018)	Y. V. Thien et al	2018	Needle-plane 50 mm gap	VO (Palm Oil), MO	At the identical applied voltage level and polarity, VO has longer streamer stopping lengths and the streamers propagate rapidly than MO
Huang et al. (2018)	Z. Huang et al	2018	Needle-plane	Soybean, camellia, rapeseed-based NEs and MO	The streamer stopping length in NE and MO exhibits similarity under positive polarity Under − ve polarity, the stopping lengths of the NEs under the same voltage are lower than that of MO
Zhou et al. (2018)	J. Zhou et al	2018	Needle plate	Soybean oil, rapeseed oil, MO	If applied voltage is close to the BDV, for both kinds of oil, stopping length is close to 70 mm

Table 16 Summary of research studies on streamer velocity of various transformer liquid insulations

Reference(s)	Author (s)	Year	Electrode configuration (type and gap distance)	Oil types	findings
Liu and Wang (2011)	Q. Liu et al	2011	15–100 mm point-plane	SE (Midel 7131), NE (FR3), MO	The differentiation of negative streamer velocity between esters and MO becomes insignificant Under positive polarity, there is a huge contrast of streamer velocity between esters and MO
Duy et al. (2009)	C.T Duy et al	2009	from 2 to 20 cm point-plane	rapeseed oils, MO	The NEs showing a simpler propagation of streamers, which in turn causes lower BDV in both polarities
Liu et al. (2009)	R. Liu et al	2009	25 mm, 100 mm and 200 mm, needle-plane	MO, VO	Outcomes indicate that the streamer fast event feature in NEs was relatively distinct from that in MO exclusively at positive polarity
Nguyen et al. (2010)	Nguyen Ngoc M. et al	2010	5 cm, 10 cm point-plane	NE, SE	The results showed almost no difference between these liquids
Dang et al. (2012b)	V. H Dang et al	2012	2 to 40 mm Point-plane	Mineral, synthetic and natural ester oils	Streamers velocity reduces when the gap is enhanced, whereas Lf is smaller in MO than in VO or SE
(Rozga and Stanek 2016)	P. Rozga	2014	point-plane 15 and 20 mm	NE, SE, MO	The results showed that average propagation velocities of the streamers developing in NEs were higher than other liquids
(Denat et al. 2015)	A. Denat et al	2015	Up to 35 cm point-sphere and point-plane	Mineral oils and ester	The average streamer velocity in NE is higher than MO for various gap distances
(Sitorus et al. 2015)	H.B.H. Sitorus et al	2015	20, 25 and 30 mm point-plane	Jatropha curcas oil, MO	The propagation velocity of JMEO and MO is too close (similar)
(P Rozga 2016a, b, c, d)	P. Rozga et al	2016	15 mm, 20 mm point-plane	NE (Soyabean oil), MO	The streamer propagation velocity for NE was higher than in MO
(Rozga and Stanek 2017)	P. Rozga et al	2017	25 mm Point to sphere	Two NEs types	Both the liquids present almost similar propagation velocity values
(Thien et al. 2018)	Y. V. Thien et al	2018	Needle-plane 50 mm gap	VO (Palm Oil), MO	The rates of streamer velocity raise of VOs are greater than MO
Huang et al. (2018)	Z. Huang et al	2018	Needle-plane	Soybean, camellia, rapeseed-based NEs, and MO	The positive and negative lightning BDVs of the camellia liquid show trivial larger than that of other classes of NEs for the slower streamer velocity of the camellia liquid
Zhou et al. (2018)	J. Zhou et al	2018	Needle plate	Soybean oil, rapeseed oil, MO	The streamer velocity of MO enhanced slowly after achieving the 50% BDV

Table 17 Summary of research studies on streamer accelerating voltage of various transformer liquid insulations

Reference(s)	Author (s)	Year	Electrode configuration (Type and gap distance)	Oil types	findings
Liu and Wang (2011)	Q. Liu et al	2011	15–100 mm point-plane	SE (Midel 7131), NE(FR3), MO	Negative polarity displays the noticeable variance between esters and MO in terms of stopping length; however, positive polarity indicates a substantial difference between esters and MO of acceleration voltage which specifies the capability to withstand fast streamer events
Duy et al. (2009)	C.T Duy et al	2009	From 2 to 20 cm point-plane	Rapeseed oils	Among the several fluids examined at very HV and considerable distances, MO indicates the extraordinary acceleration voltages
Huang et al. (2018)	Z. Huang et al	2018	Needle-plane	NEs (soybean, camellia, rapeseed-based oil) and MO	Findings exhibit that the BDV and acceleration voltages of the NE are far lesser than MOs
Liu et al. (2009)	R. Liu et al	2009	25 mm, 100 mm and 200 mm, needle-plane	MO, VO	Findings show that the acceleration voltage start point for transition to fast streamer in NEs is prominently lesser than in MO
Zhou et al. (2018)	J. Zhou et al	2018	Needle plate	Soybean oil, rapeseed oil, MO	The accelerating voltage of the NE under positive LI is roughly equal to the BDV. The positive acceleration voltage of MO is two times of the BDV

Streamer shape

The streamers are typically categorized as (1) slow and "bushy" for streamers introduced at negative sharp electrode and/or (2) fast and "filamentary" for streamers produced at the positive sharp electrode. Their velocities range from 10 m/s (subsonic) to 100 km/s (supersonic). Nevertheless, the fact that existence of halogen in the molecular composition of the fluid or the adjunction of trivial sums of electronic scavenger compound or yet the application of very HV might originate negative streamers that are fast and filamentary, suspect this categorization (Beroual and Tobazeon 1986, 1985; Dang et al. 2012b; Beroual 1995). In fact, either slow steamer or fast propagating streamer gives rise to BD in insulating fluids. The propagation of streamer is labeled by four modes of propagation (Rao et al. 2019a, b, c). Slow streamers are observed in 1st and 2nd modes, whereas fast streamers are sighted in 3rd and 4th modes. This mode of propagation generally depends on multiple factors, e.g., nature and magnitude of test voltage, kind of liquid and local electric field stress, etc. It is to be noted that it is hard to study a streamer in 1st mode and investigate streamer in 4th mode due to high electric field stress. It is well understood that out of multiple streamers established due to local electric field, a single streamer gives rise to BD of insulating channel. Therefore, BD is generally observed in 2nd mode or 3rd mode. This switching of streamer from 2nd mode (slow) to 3rd mode (fast) could be noticed by abrupt rise in voltage and leakage current. This is commonly recognized by an instant rise in propagating voltage of streamer to multiple times of the existing streamer instantaneous velocity. Thus, the term "streamer acceleration voltage" is defined as the voltage at which abrupt rise of streamer instantaneous velocity is observed. The recognition of streamer (fast/slow) at a given moment of propagation could also be recognized by the field stress at that particular moment (Lesaint and Massala 1998; Beroual 1993; Denat 2006). The streamers are termed as slow streamers when the electric field is in the range of less than 10 MV/cm (1st/2nd mode). If the electric field stress is in the range of 10–MV/cm to 100 MV/cm, it could be termed as fast streamers (3rd/4th mode).

The rise in propagation velocity results in a change in shape of streamer. The spatial shapes and oscillography of streamers have been studied and examined in accordance with various factors, e.g., propagation velocity, electrode gaps and acceleration voltages (Rozga 2015; Xiang et al. 2018). Multiple studies studied the light emission features and shapes of streamers and concluded that for small electrode gaps, streamer properties, e.g., shape, emission and average propagation velocity are comparable for both MO and ester-based liquids (Stanek and Rozga 2016; Rozga and Stanek 2016).

Multiple researchers concluded that ester-based fluids have inferior characteristics than MO at impeding streamer propagation. Therefore, more research is needed to further study the inception and propagation of streamer in ester-immersed transformers. Numerous studies have shown that esters have small resistance to the propagation of abrupt streamers than MO (Rozga 2016a, b, c, d; Rozga et al. 2018). The fast inception and propagation of streamers in NEs must be addressed while designing natural ester-based transformers. The major factors which affect the development and propagation of streamers include streamer structure, streamer velocity, streamer current, stopping length and light emission. Other parameters which also affect the streamer characteristics are electrode configuration, internal temperature, hydrostatic pressure, chemical structure of the fluid, aging by-products and other additives in the dielectric insulation system (Beroual 2016). Multiple researchers have investigated above-mentioned various critical factors for streamers and concluded that stopping lengths are shorter with NE/pressboard interfaces as compared to MO (Reffas et al. 2016) (Reffas et al. 2018a; Reffas et al. 2018b; Thien et al. 2018; Huang et al. 2018; Zhou et al. 2018). The influence of contaminations on BD phenomenon of insulation system has been reported in (Hao et al. 2019; Thirumurugan et al. 2019) to study the impact of moisture and other impurities during surface discharge activity. It was concluded that ester-based fluids offer better resistance to contaminants than MO. The summary of research studies on the shape of streamer in comparison with other transformer oil types is presented in Table 18.

Table 18 Summary of research studies on shape of streamer of various transformer liquid insulations

References	Electrode configuration	Oil types studied	Shape of streamer
Liu and Wang (2011)	15–100 mm point-plane	Gemini X, Midel 7131 and FR3	1. One or two major branches with numerous minor branches 2. Streamers in NEs have more branches than in MO, specifically for Midel 7131, multiple primary branches appear to spread in various directions
Rozga and Stanek (2016)	Point-plane 15 and 20 mm	MO, SE and NE	Spatial shapes for all studied oil types
Thien et al. (2018)	Needle-plane 50 mm gap	Palm Oil (RBDPO), MO	The + ve streamer forms of RBDPO and MO at various applied impulse voltage levels are for all samples emerge in tree-like shapes. The − ve streamer channels are much thicker and filamentary. The negative streamer forms of RBDPO have more branches; however, MO has either 1 or 2 core branches with numerous small offshoots
Badent et al. (1999), Hemmer et al. (2001)	4– to 50 mm point-plane	Rapeseed oil, MO	Positive main streamer mode for rapeseed oil umbrella-type initially with very filigrane tributaries moving toward the cathode. The morphology of the streamer is close to that noticed in MO insulating. Negative streamers in rapeseed oil indicate roughly the same morphology as streamers in MO
Duy et al. (2007)	Point-plane up to 20 cm	Rapeseed oil	Rapeseed oil has a Branched streamer
Rozga et al. (2013)	Point-plane 5 to 20 mm	Natural and synthetic ester, MO	The obtained results indicated that at the inception voltage both the light courses and shapes of discharge forms are identical in all three liquids, depending on voltage polarity
Rozga (2016a, b, c, d)	15 and 20 mm point-plane e	natural ester and MO	The resemblances between both the fluids were observed not only on the level of their inception voltages and inception electrical field stress nevertheless also in the case of usual streamer features as the spatial shapes of the streamers documented photographically
Reffas et al. (2018a)	Point-plane 20, 25 and 30 mm	MO, SE, NE	The − ve streamers in MO are brighter than those detected in NE and SE. It was observed a distinction in the branching location; in MO, streamer branching position originates at the mid or the end of the streamer; however, in NE & SE it is nearby to the point electrode
Sitorus et al. (2015)	Point-plane 20, 25 and 30 mm	Jatropha curcas oil, MO	The negative streamers in MO are more filamentary and brighter than those in JMEO. The branching location is also distinct. There is not evidently difference between the positive streamer structures in both fluids

Research gap and future research prospects

Most of the research on natural ester liquids is basically dedicated to investigating their breakdown performance, deterioration conduct and compatibility with solid insulation. Moreover, these research studies presented a comparative analysis of natural esters with MOs and recommend the use of NEs as alternate of MOs but their various issues and challenges for NEs research that must be studied. Natural esters have been used in oil-immersed transformers by few utilities around the globe. The knowledge regarding in service information regarding condition monitoring of natural ester-immersed transformers may be beneficial. These research gaps and imminent research prospects should be emphasized to improve insight regarding the applications of NEs in transformers (Rafiq et al. 2016a; 2020a, b, c, d).

Manufacture and application of vegetable oils

Natural ester inherently owns some constituents which tend to decay abruptly after its production so its stability during production and application is huge challenge. Moreover, purity of oil is another challenge. The oil must free from conducting elements to appropriate levels, and commercially available oils not accessible with required purity level (Rafiq et al. 2015c, a, b).

Real-time condition monitoring

Real-time knowledge of insulation performance will be useful in instituting aging markers. This data will aid in interpretation and commencing diagnostic tools for natural ester-filled transformers (Rao et al. 2019a, b, c).

Miscibility of natural esters with MOs and other oils

The addition of MOs and other types of oil in natural esters can enhance their breakdown performance. Thus, this developed blend is better than individual oil insulation. Therefore, more research on the miscibility of natural esters with other oils would provide more understanding their application in transformers (Rao et al. 2019a, b, c). More research on retrofitting of natural ester liquids might be revealed if utilities desire to retro-fill existing units with MOs.

Natural esters compatibility with cellulose insulation

More research is necessary on the compatibility of natural esters with solid insulation of transformers. Real-time condition-monitoring data and retro-filling investigations might result in enhanced use of NE fluids in oil-immersed transformers.

Pre-breakdown phenomenon

Research on the pre-breakdown phenomenon for liquid insulation is one of the largest research challenges. Most investigations on the pre-BD phenomenon have been carried out with point-plane electrode configuration; however, a few studies have been executed with sphere-plane electrodes. Most of these studies directed on the streamer shape and properties. Other functional aspects of streamer development have not been studied till now.

Aging of liquid and cellulose insulation

Multiple studies investigated the effect of humidity and metal particulates on BD phenomenon. Nonetheless, cellulose diffused fragments and other rotting pieces also cause serious effects in real-time environment. Multiple researchers investigated the influence of electrode geometry (shape, gap and tip radius), whereas research is need to study the aging of liquid/cellulose insulation system on breakdown phenomenon (Dang et al. 2012a, b, c; Li et al. 2014).

Use in on-load tap changers (OLTC)

The rate of collapse in tap changers is greater than collapses in transformers. The application of natural esters in OLTC will be a huge task. More specifically, the depreciation profile of natural esters in OLTCs needs to be investigated. Degradation of oil is accelerated due to high sparks frequency in tap changers.

Additives and chemical scavengers

NEs have low LI resistance; hence, effort has been made to improve their LI resistance by using some additives. Detailed research is required to investigate congruity of natural esters in working environment. Therefore, there is a huge research gap regarding the use of additives and chemical scavengers to enhance the conduct of natural esters (Thomas 2005).

Oxidation and viscosity

High viscosity and low resistance to oxidation are major factors which hinder the application of natural esters. These factors should also be further studied to enable natural esters applications in transformers (Rao et al. 2019a, b, c).

End of life criteria analyses

A lifetime principle for different dielectric liquids is an additional concern for the industrial segment. The deprivation of NEs shows a deficiency of colloidal particulates at low and moderate aging (Rao et al. 2019a, b, c), though soluble particles are predicted with aging of NEs. There is still a huge scope of research on additives and adsorbents which are consistent with NEs.

Application of nanotechnology to natural esters

The application of nanotechnology to natural esters to develop nanofluids is another new research subject. Multiple studies have investigated various electrical properties including AC, LI BDS of transformer oil-based nanofluids (Wang et al. 2016; Rafiq et al. 2020a, b, c, d; Rafiq et al. 2019; Rafiq et al. 2015a, b, c; Hu et al. 2014) (Lv et al. 2017). A huge amount of research has been conducted with the aim to enhance the chemical, physical and electrical properties of NEs. However, more research work is required with a focus on the aging profile of developed nanofluids and their compatibility with other transformer components (Rafiq et al. 2015a, 2016a; b, c, b, c).

Reliability of future insulation system

The rise in global green energy demand is resulting in bulk power integration into the electrical grid via distributed production. Electricity from distributed generation is engaged in nonlinear abrupt switching encounters that influence grid limits. Thus, the consistency of potential insulation systems should be enhanced to cope with repeated switching transients.

Price and other associated concerns

Research work is needed to discover techniques to reduce the development cost and identify markets to balance price and accessibility. Environmental advantages and benefits offered by this naturally renewable and ecologically friendly (NEs) liquids over traditional liquids required to be recognized, marketed and advocated.

Improvement of gelling properties

Visible examination of gelling is observed due to thermal aging of natural esters which leads to enhancement in viscosity and affects the flow behavior of liquid insulation (Gautam et al. 2023). Therefore, NEs are not appropriate for breathing units because deficiencies in the sealing system may lead to NEs in direct contact with atmospheric air and result in development of sol and gel in the bulk of the liquid insulation. The existence of the sol greatly affects the viscosity of the liquid insulation and promotes speedy acceleration of the oxidation process (Rao et al. 2022). Therefore, it is highly required to improve the gelling properties of natural esters for applications in HV equipment.

Future research directions

The application of NEs as transformer oil is good to meet environmental needs and for sustainability. Nevertheless, there are multiple issues and challenges attached with NEs, such as pour point, viscosity, oxidative stability, low resistance to ionization and high dielectric loss. These challenges have thwarted their practical applications in transformers. The primary complications linked with the application of NEs as transformer oil are listed as follows.

1. The pour point of NEs is one of the intriguing features that is hindering their application as transformer oil mainly in extremely cold areas. This is owing to the easy crystallization of the oil at low temperatures, which may cause clogging of transformer cooling system. The addition of pour point depressants and modification of pour point through chemical processes can be useful to address this issue (Sani et al. 2018).
2. Transformers produce huge amounts of heat from their core and winding during their operation; consequently, the oil used for cooling must possess a low viscosity for better cooling. The viscosity of NEs is generally high and hence they do not achieve a better cooling in transformers. Therefore, it is required to search for ways to reduce the viscosity of NEs for better cooling of transformers (Aransiola et al. 2012).
3. Low ionization of natural esters (which could be attributed to weak intermolecular bonds presented between the molecules) has been one of the serious topics that entails appropriate consideration while considering the application of NEs as insulating liquids in transformers (Rao et al. 2022).
4. Poor oxidation stability of NEs is another critical practical issue which may lead to their reduced applications in transformers. When oil is oxidized, its acidity and viscosity of liquid rises, making viscosity and acidity as obvious dynamics that may be employed for monitoring oxidation progress in NEs. The stability improvement of NEs to oxidation can be tackled in multiple ways such as addition of antioxidants and modification of chemical structure, etc. (Ab Ghani et al. 2018).

Conclusion

The NEs are being viewed as next-generation dielectric fluids owing to their environmental, health benefits and fire safety properties as compared to MO. Researchers in various countries conducted a huge research work utilizing natural esters as transformer oil alternatives. The application of natural ester as transformer oil may perform a critical task in aiding the dielectric society to decrease the environmental effect of MOs. The evolution of natural ester liquid realizes modern needs for an ecologically friendly transformer fluid.

In notion of environmental risks, fire safety, health vulnerability, call for footprint decline, insulating liquids based on NEs are the next era insulating fluids that will substitute MOs. NEs score over MOs on ecological concerns with ample biodegradability, nontoxicity and are a viable, ecological and sustainable origin with carbon–neutral character. Moreover, environmental favorability, NEs are insulating fluids that have qualities critical for HV equipment. Natural esters demonstrate as fire safe with greater fire point ("K" category fluid). Moderate oxidation stability of natural esters assists enhanced attention and airtight composition of the container. NEs also exhibit stray gassing trends and produce ethane and hydrogen—ensuing misconception in DGS evaluation. The serious problem of the space constraints of HV equipment (e.g., transformers) may be reduced by the application of high-temperature natural esters dielectric fluids.

In this review, developments in research and the state of the art of fundamental attributes that should be focused regarding the potential application of natural easter liquids are depicted, followed by potential research. Moreover, an analysis of the pre-breakdown phenomenon, the application of NEs in transformers is reported. Future challenges associated with alternate liquid insulation are illustrated. This review shall be beneficial for utilities, scholars and experts concerned in alternate insulating liquids for potential usage HV transformers. More exploitation of these fluids for applications in transformers requires additional investigations and tests.

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Conflict of interest The authors declare that they have no conflict of interest.

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