

Review

Comparative evaluation of alternative fluids for power transformers

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ABSTRACT

The demands on the power supply are increasing continuously, and it seems that this trend will not change in the near future. Power transformers are used in power systems where there is a transition between voltage levels. For this reason, transformers are one of the most strategic components for electric power generation, transmission and distribution. Many users prefer oil-filled transformers to the dry-type because dielectric oils cool and insulate. In this type of transformer, the combination of a solid (cellulose) and a liquid insulation (naphthenic mineral oil) is the most frequently used insulating system. Although mineral oil has been widely used, it does not meet health and current environmental laws because it is not biodegradable. In addition, mineral oil presents high fire risk, which becomes a serious problem for safety in electrical facilities. All of these drawbacks have encouraged the search for alternative fluids such as organic esters.

This work compares the main properties of alternative liquids to show their possibilities for naphthenic oil replacement. The development of dielectric fluids based on vegetable oils is also described. The advantages of these liquids over mineral oil are discussed.

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1. Introduction

Due to the higher electrical power dependency of our society, the demand for a reliable power supply is increasing [1]. Power systems usually consist of a huge number of generation locations, distribution points, and interconnections within the system or with nearby systems. Power transformers must be used at each of the points where there is a transition between voltage levels [2]. For this reason, transformers are one of the most strategic components for electric power generation, transmission and distribution [3,4]. They are expected to function reliably and efficiently for many years.

A transformer can be defined as an electromagnetic device composed of two or more windings (coils) coupled by a mutual magnetic field [5]. Transformers can be classified applying different criteria [6]:

1. Distribution and power: distribution transformers (50–2500 kVA) and power transformers (above 2500 kVA).
2. Insulation: dry-type transformers (open-wound, cast coil, vacuum pressure impregnation and encapsulated and vacuum pressure encapsulated); liquid-insulated-dielectric coolant; combination of liquid-, vapour- and gas-filled.
3. Substation or unit substation: primary substation transformer (secondary windings rated 1000 V) or secondary substation transformer (secondary windings rated <1000 V).

One of the main requirements in designing transformer windings is to provide a means of dissipating the heat generated during operation due to resistive losses [7]. The rejection of heat is critical because excessive temperatures can damage insulation, precipitating failures with high costs. The cooling capability determines the amount of power that can be reliably handled by a transformer [3]. Many users prefer liquid-insulated-dielectric coolant transformers (oil-filled transformers) to the dry-type because, unlike solids, liquids cool as well as insulate [4,8,9]. In fluid filled transformers, the insulation system must provide adequate dielectric strength for the operating and test voltage stresses, adequate cooling channels to allow the fluid to dissipate the heat generated in the windings and sufficient mechanical strength for the windings to withstand service conditions [10,11]. In oil-filled transformers, the combination of a solid (cellulose insulation) and a liquid insulation (naphthenic mineral oil) is the most frequently used insulating system in high voltage transformers [12–14] due to its outstanding thermal and dielectric properties [15]. The insulation system of oil-filled transformers is built up in a composite structure consisting of oil-impregnated pressboard layers and oil channels in between these layers [16–20].

Although mineral oil has predominantly been used as the insulation and cooling liquid in the transformer industry for more than 100 years [21,22], it has low flash and fire points and a low dielectric breakdown voltage. The most serious of its shortcomings is the inability to meet health laws and new environmental laws because this type of oil is not biodegradable. Additionally, the naphthenic crude oil reserves from which mineral oil is obtained are limited [23–25]. These disadvantages led the search for new fluids.

In the early 1930s, insulating fluids based on polychlorinated biphenyl (PCB) were introduced due to their low flammability and good dielectric properties. Afterwards, it was confirmed that the combustion products of PCB under certain conditions were toxic. For this reason, in the 80s, the industry was forced to search for possible alternatives [18,26–28]. It is generally agreed that any new insulating liquid has to meet a number of operational requirements such as: good dielectric and thermal properties, low viscosity, chemical and thermal stability, low flammability, compatibility

with other transformer materials, miscibility with other liquids, environmental acceptability and low cost [21,29].

Organic esters and silicon liquid possess similar electric properties compared to mineral oil [25,30]. The recent focus on health, safety and the preservation of the environment has promoted the use of environmentally friendly and biodegradable liquids to avoid the effects of mineral oils [31–33].

Although the electrical power transmission and distribution industry has showed its interest in these alternative liquids as alternatives to mineral oil, it is necessary to demonstrate that they offer suitable electrical performance and that they are safe and economic. The aim of this work is to analyse the main properties of alternative liquids to show their possibilities to replace mineral oil.

2. Types of insulating fluids

This section describes the main types of dielectric liquids that are used in oil-filled transformers as coolants.

2.1. Mineral transformer oil

Mineral oil is made of fossil fuel (crude oil) and consists of hydrocarbon compounds of different bonds [34,35]. It is obtained by refining a fraction of the hydrocarbons collected during the distillation of a petroleum crude stock. The boiling range of the collected fraction and the type and degree of the refining process are selected such that the resulting oil reaches the requirements specified for use in transformers [17]. There are different oils (paraffinic, naphthenic, aromatic, etc.), which contain different ratios of components [36,37].

2.2. High molecular weight hydrocarbons (HMWH)

These coolants are classified by the National Electric Code as “less flammable” if they have a fire point above 300 °C [2,7]. These coolants can be natural or synthetic. The natural ones are derived from higher boiling fractions of petroleum than the fractions used for mineral oil. These fluids are comparable in performance to mineral oil except for their higher temperature endurance, their higher viscosity and their pour point. The synthetic ones are produced by the polymerisation of olefins, and they are known as polyalphaolefins (PAOs). Due to the higher viscosity of these fluids, transformers with convection cooling must be designed with wider cooling ducts to compensate for the lower mobility of the fluid [38].

2.3. Silicones

Silicone fluid is the generic name for a series of inert and thermally stable insulating liquids with electrical properties similar to mineral oil [28,39]. These liquids are a family of synthetic liquids, chemically known as polydimethylsiloxane [7]. They have a molecular structure in which the groups identified as methyl groups may represent any organic group. The organic groups can be all the same or different. These groups define the molecular weight of the silicone fluid, which in turn determines its viscosity [8].

2.4. Ester-based fluid

Other alternatives to mineral oils are ester liquids, which are compounds synthesised from organic acids and alcohols. They are available as natural products or chemically synthesised from organic precursors [40–42].

2.4.1. Synthetic esters

Synthetic ester dielectric fluids, most commonly polyol (pentaerythritol) esters [41], have suitable dielectric properties and are significantly more biodegradable than mineral oil or HMWH. They have excellent thermal stability and good low-temperature properties. There are seven main types of synthetic esters: diester, phthalate, trimellitate, pyromellitate, dimer acid ester, polyols, and polyoleates.

2.4.2. Natural esters

Natural ester fluids appear as saturated and single, double and triple unsaturated fatty acids. Saturated fatty acids are chemically stable but of high viscosity. Triple unsaturated fatty acids have a low viscosity, but they are very unstable in oxidation. Fluids with a high percentage of single unsaturated fatty acids have proven as useful [43].

Seed-based esters, including liquid fats and oils, are derived from glycerol and are known as triglycerides. The fatty acid segments are composed of straight chains, which is the natural result of the biosynthesis of fats, where molecules are built up two carbons at a time. The natural esters tested for potential transformer application are fatty acid ester triglycerides. The fatty acid components are linear chains 14–22 carbons long containing zero to three double bonds. Based on data obtained from laboratory and field trials, a practical, edible-oil-based dielectric coolant using food-grade additives can be successfully incorporated into transformer insulation systems with minimal modifications [41].

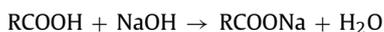
3. Development of dielectric fluids based on vegetable oils

The commercial oils based on vegetable oils are the result of a huge research effort that was started in the mid 1990s to develop a fully biodegradable insulating fluid.

Different candidates that have been evaluated as possible insulating fluids (Table 1) contain a high percentage of unsaturated fatty acids (Table 2), resulting in a lower viscosity and better low-temperature properties. Others have a higher percentage of saturated acids, which are known to improve oxidative stability. An optimal balance has to be selected between the two types of fatty acids contents in vegetable oils [44].

3.1. Refinement of crude vegetable oils

The starting point in the production of a vegetable oil based dielectric fluid is the vegetable seeds. Generally, crude vegetable oils, extracted from oil seeds, have a dark colour and contain solid constituents such as proteins and fibres. These oils are treated to obtain a RBD (refined, bleached and deodorised) oil, which is the starting material used to develop a candidate fluid. The procedure to refine the vegetable oil consists of different steps: alkaline refinement, bleaching and deodorisation [46]. Alkaline refinement is the first step to eliminate free fatty acids in vegetable oil. The neutralisation equation can be expressed as



Bleaching is the second step to eliminate colouring materials. In this step, clay filter presses that further purify the oil are usually used. Finally, deodorisation, which is a high-temperature, high-vacuum steam-distillation process to remove volatile and odoriferous materials, is performed. Additionally, a winterisation process may also be used to remove easily frozen saturated fats [47].

The RBD oil varies in purity with conductivities ranging from 5 to 50 pS/m. For transformer use, it is desirable to have a conductivity of 1 pS/m or below [3].

3.2. Vegetable oils candidates

The first works used RBD oil based on high oleic oil with over 80% oleic content as a starting material to obtain an insulating fluid. The chemical, physical and electrical properties of the RBD base oil were found to meet most of the desired properties except for the dissipation factor, the acidity and the oxidation stability. Two modifications to the RBD oil were applied to improve the desired properties: further purification and the addition of oxidation inhibitors. The RBD was reprocessed with special high adsorbent neutral clay until the electrical conductivity was below 1 pS/m. This additional purification step modified some properties (Table 3). However, this purified high oleic oil was not sufficiently stable for oxidation stability compared with mineral oil in the presence of copper. For this reason, this oil was stabilised through the choice of an inhibitor system. These additives caused a modest increase in the dissipation factor and the conductivity [24,47–50]. The result of all these works was the development of BIOTEMP [51]. Later, gene manipulation techniques were used, and partial hydrogenation was proposed as an added step that may be used to minimise the very unstable tri-unsaturated bonds [26]. Later, BIOTEMP fluid was used in some distribution transformers in critical areas to demonstrate its suitability [52].

Abeyundara et al. studied coconut oil as an insulation fluid in transformers [18]. They also concluded that it is necessary to use RBD oil to obtain a dielectric fluid whose properties will be similar to that of mineral oils (Table 1).

As shown in Table 1, other vegetable oils have been studied. One example is rapeseed oil. Two general classes of rapeseed oils are available: refined rapeseed oil with major use in nutrition and rape-methyl-ester (RME), which is employed in some places as a substitute for fuel. At the beginning, rapeseed oil for nutrition with high purity was employed by researchers. It was demonstrated that rapeseed oils were quite good insulators and may be used as insulating material in high-voltage components [53]. However, this oil was unstable under atmospheric conditions due to oxidation and hydrolysis. For this reason, oxidation inhibitors and metal passivators were added to the basic rapeseed oil; as a result, an oil of high oxidation stability called RAPSOL-T was obtained [54].

This new oil was used to compare the suitability of other marketable bio-oils of different viscosity classes and two oils especially developed as transformer liquids (Table 4). Furthermore, rapemethylester (RME) was examined as well [55].

Other authors such as Hammer et al. [56] and Li et al. [20,46,57,58] have also evaluated the basic dielectric properties of original and refined rapeseed oil (RBD) and compared them with mineral oil. The experimental results demonstrated that this vegetable oil could be used as dielectric fluid. Later, Li and co-workers utilised the RBD rapeseed oil to prepare a nano-modified insulating rapeseed oil [59]. This nano-modified insulating oil was prepared by the homogeneous precipitation deposition of ferroferric oxide nano-particles of Fe_3O_4 , which were modified to improve their lipophilic and hydrophobic properties. The experimental results showed that nano-particles with a proper content in oil significantly improve some electric properties such as the breakdown voltages and the volume resistivity, of the RBD rapeseed oil.

Tran et al. used a modified vegetable oil (RS50) based on an oleic rapeseed oil. They measured some dielectric properties such as the permittivity, the dissipation factor over a wide frequency range (10^{-2} – 10^6 Hz) as a function of temperature (-20°C to 120°C) and the water content (below and above saturation). Their results conclude that RS50 oil and pure rapeseed oil possess similar electric properties, and they also have lower oxidative stability compared to mineral oils. This disadvantage could be overcome by using additives [60].

Table 1
Properties of vegetables oils.

Property		Sunflower oil	Coconut oil	Canola oil	Palm oil		Rapeseed oil			Soybean oil	Olive oil
					RBD palm oil	Crude palm oil	Crude rapeseed oil	Refined rapeseed oil	Modified oleic-rapeseed-oil (RS50)		
Density (kg/dm ³)	at 15 °C				0.90	0.87					
ASTM D1298	at 20 °C	0.919	0.917	0.920			0.9	0.9		0.923	
Pour point (°C)		–12 to –25	20	–12			–17	–18		–21	
ISO 3016											
Flash point (°C)		<330	225	321	>220	195	320	325	>170	326	
ASTM D92											
Fire point (°C)		<360		341	>220	206				362	
ASTM D92											
Moisture content (ppm)		<80		110						<80	
ASTM 1533											
Kinematic viscosity (cSt)	at 0 °C	300			<500						
ASTM D445	at 20 °C						72.8				
	at 25 °C				300						33
	at 40 °C	41.4–45	29	92	48–50		44.2	43.0	17	33.8	
	at 90 °C										2.20
	at 100 °C				12–15						
	at 20 °C	10			<0.2	<0.17					
Thermal conductivity (W/mK)											
ASTM D2717											
Gassing tendency		–52.7		22						–80.5	
ASTM D2300											
Acidity (mg KOH/g)		0.02		0.05			0.6	0.03		0.02	
ASTM D974											
Breakdown voltage (kV)		38–45	60	45	75	23	24.3	73		51	
ASTM D1816											
Dissipation factor (%)	at 25 °C	0.0093		0.09			2	0.07	0.001	0.061	
ASTM D924	at 90 °C						17.3	0.75	0.0003		
	at 100 °C	0.590		0.30					0.00025	1.85	
Dielectric constant (at 25 °C)		3.1		2.86			2.93	2.93		3.1	3.06
ASTM D924											

Table 5
Properties for castor, sunflower, and rapeseed oil and some of their derived esters.

	Castor oil	Methylc	Iso-propylc	X-olc esters	Sunflower oil	Methylc	Iso-propylc	Rapeseed oil	Methylc	Iso-propylc	X-olc esters
Breakdown voltage (kV) IEC 60156	86.7 ± 3.1	74.1 ± 5.9	96.0 ± 5.2	70.0 ± 13.6	58.4 ± 5.1	79.6 ± 8.2	82.9 ± 6.9	97.1 ± 3.7	67.4 ± 7.8	85.0 ± 9.8	89.5 ± 4.9
Pour point (°C) ISO 3016	-27	-22	-35	< -38	-15	-8	-22	-23	-16	-24	< -38
Viscosity (cSt) at 40 °C ISO 3104	261.5	14.4	16.0	11.0	41.2	11.1	12.0	41.1	7.2	5.2	8.1

Al-Ammar. The results showed that canola oil exhibits a much better breakdown voltage values than mineral oil. However, olive oil exhibits very poor dielectric values [64].

4. Basic physical and chemical properties of insulating fluids

Although the mineral oil offer is higher than those of dielectric fluids (silicones, synthetic and natural esters, etc.), in recent years several companies have developed new transformer oils to increase demand of safer and more environmentally friendly products [65]. There are different examples of commercial alternative dielectric fluids (Tables 6–8).

The main functions of dielectric fluids are to ensure the electrical insulation in a transformer and to ensure the heat transfer. Additionally, insulating oil must have a good ageing stability. Electrical insulation is controlled by the paper/oil structure. Oil impregnates the cellulose (paper, pressboard) and drives away the air, which presents a lower dielectric strength than the oil. The efficiency of oil as an insulator is usually defined by the breakdown voltage (BVD). Heat transfer is performed by thermal conductivity and convection. The convection represents the properties that lead to heat transfer through fluid displacement (viscosity, specific heat, thermal expansion coefficient), whereas the conduction occurs within the fluid. It has been shown that the kinematic viscosity is the most influential parameter for the heat transfer. The ageing stability is mainly influenced by oxygen. The temperature acts as a catalyst as well as some metals such as copper. The ageing stability of the oil could be more critical if the transformer is free breathing. The study of the oxidation stability is performed through the measure of the acidity and $\tan \delta$ once ageing has been carried out [65].

4.1. Fire safety

The growing demands for improved fire safety, source material availability and environmental sustainability have encouraged the research and development of alternative fluids. Many authors have compared the main properties of these new fluids with mineral oil [21,26,38,40,42,44,45,51,59,65,73,82–89] to evaluate their suitability. Table 9 gathers the results obtained by these authors. Silicone fluid and both natural and synthetic esters offer a high reduction in fire risk due to their flash and fire points. They possess higher flash and fire points than mineral oil, and they are classified as K class fluids according to the standard IEC 61100. The main advantages of using this type of fluid are less cost for the installation and maintenance safety equipment, no fire risk in event of major electrical fault, low density and non-toxic smoke.

4.2. Biodegradability

Natural and synthetic esters are classified as biodegradable [78,79], whereas mineral oils and silicone oils are more resistant to biodegradation. The formulation of natural esters has essentially no human toxicity, and their biodegradation rate is higher than that of mineral oil. However, silicone oils do not biodegrade quickly when tested by standard methods [90].

4.3. Viscosity

Laboratory results have also showed that, at the normal operating temperature of a power transformer, except for the low viscosity silicone fluid, the alternative fluids are more viscous than mineral oil. The difference between the viscosities of the ester liquid and mineral oil is relatively important at low temperature, although

Table 6
Properties of some commercial silicone oils.

Property		561 Silicone oil [66]	A]621 Silicone oil [67]	Bluesil FLD 604V50 [68]	KF-96-20 [69]	Powersil fluid TR50 [70]
Density (kg/dm ³)	at 20 °C	0.96				0.96
ISO 3675	at 25 °C		0.96	0.96	0.95	
Pour point (°C)		<−50		−50	≤−60	<−50
ISO 3016						
Flash point (°C)		>300	>300	280	≥260	>240
ISO 2719						
Fire point (°C)		>350	370			>340
ISO 2592						
Water content (ppm)		<50			<50	
IEC 60814						
Kinematic viscosity (cSt)	at −30 °C				66.4	
ISO 3104	at −20 °C			140		
	at 0 °C	86		85	32.8	
	at 20 °C	54				40
	at 25 °C	50	50	50	20	
	at 40 °C	39				
	at 100 °C	15		16	15.9	
Thermal conductivity (W/mK)	at 25 °C			0.15	0.15	
ASTM D2717	at 50 °C	0.151	0.151			
Specific heat (kJ/kgK)	at 20 °C	1.51	1.51	1.525	1.6	
ASTM D2766						
Expansion coefficient (1/°C)		0.00104	0.001055	0.00104	0.00104	
ASTM D1903						
Neutralising value (mg KOH/g)		<0.01				<0.01
IEC 60836						
Breakdown voltage (kV)		50	50		≥50	>40
IEC 60156						
Dissipation factor (%)	at 25 °C		0.0001	0.00003		
IEC 60247	at 75 °C			0.00005		
	at 90 °C	<0.001				<0.001
	at 100 °C			0.00003		
Dielectric constant	at 25 °C	2.7	2.7	2.7	2.7	2.50–2.60
IEC 60247	at 75 °C			2.6		
	at 100 °C			2.5		

it is less important when the operating temperature is up to 80 °C. The viscosity of a fluid plays a key part in determining the cooling capability of the fluid because this property represents the resistance to the flow. For this reason, a high viscosity may slow the flow of fluid in the winding cooling ducts and increase the operating temperature of a transformer, which is not necessarily a critical issue, but should be considered in the design of power transformers [12,91]. In addition, a high viscosity must also be considered during the liquid impregnation of the cellulose solid in the transformer manufacture process. The more viscous a fluid is, the slower flow speed inside the capillaries will be. Consequently, an oil with low viscosity is preferred during the impregnation procedure. Nevertheless, Dai et al. found that effective impregnation of cellulose insulation by ester oils can be achieved within the same time period as mineral oil by increasing the temperature of the impregnation [84,92].

4.4. Breakdown voltage

The breakdown voltage (BDV) of an insulating system is one of the essential parameters for the design of power transformers. It depends on the physicochemical properties of the oil and impurities that can be present as well as the arrangement of the electrodes. Because the breakdown is a random phenomenon, it is necessary to analyse the reproducibility of experimental measurements in a sufficient number of tests. Thus, using statistical techniques, it is possible to determine the mean or lowest BDV value from the dispersion of the BDV data [12,42,87,93]. The results have shown that natural and synthetic esters present a BDV relatively close to mineral oil.

4.5. Moisture

A huge difference between ester oils and mineral oils is water solubility. Ester oils can absorb many times more moisture than mineral oil at different temperatures before saturation because moisture molecules are easily bonded to the hydrophilic groups of vegetable insulating oil molecules. This phenomenon is not found in mineral insulating oils [65,94–97]. The solubility of water in all of these fluids increases with temperature (Fig. 1). The most polar oils absorb more water across the temperature range [1]. This better solubility decreases the influence of the humidity on the insulation strength and dries the paper, which could increase

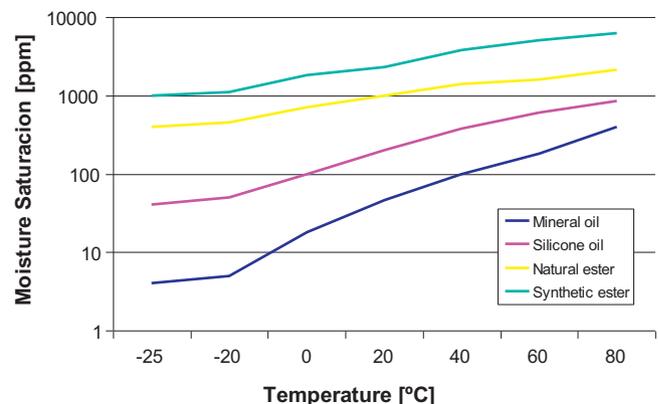


Fig. 1. Variation of the moisture saturation with temperature.

Table 7
Properties of some commercial synthetic esters oils.

Property		MIDEL 7131 [71,72]	NYCODIEL 1244 [73,74]	BecFluid 9902 [75]	ECO-FR PDS [76]	Naturelle Transformer Oil S4 [77]	Envirotemp 200 [78]
Density (kg/dm ³)	at 20 °C	0.97	0.983	0.97		0.983	≤1.0
ISO 12185/ISO 3675							
Pour point (°C)		−60	−45	≤−50	−65	−45	≤45
ISO 3016							
Biodegradability OECD 301 B		>89	84	>80	<90		
Flash point (°C)		275	260	265	310	275	≥250
ISO 2719							
Fire point (°C)		322	310	315		>310	≥300
ISO 2592							
Water content (ppm)			40				
IEC 60814							
Kinematic viscosity (cSt)	at −20 °C		645–650			660	≤3000
ISO 3104	at 0 °C	240					
	at 20 °C	70	50	61			
	at 40 °C	28	21.4–22			21.8	≤35
	at 100 °C	5.25	4.6	5	33		
Thermal conductivity (W/m K)	at 20 °C	0.144	0.14	0.139			
ASTM D2717	at 24 °C		0.135–0.149				
	at 92 °C		0.132–0.146				
Specific heat (kJ/kg K)	at 20 °C	1.88	1.73	1.82			
ASTM D2766	at 90 °C		1.91				
Expansion coefficient (/°C)			0.0007	0.00076			
ASTM D1903							
Acidity (mg KOH/g)		<0.03	0.02	<0.03		0.15	≤0.03
ISO 6618							
Breakdown voltage (kV)		>75	>70	80	55	>60	≥45
IEC 60156							
Dissipation factor (%)	at 20 °C	0.001					
IEC 60247	at 90 °C	<0.03	0.02	0.005		0.02	≥0.03
	at 100 °C				0.1		
Dielectric constant (at 20 °C)		3.2–3.3	3.1	3.2			
IEC 60247							

Table 8
Properties of some commercial natural esters oils.

Property		BIOTEMP [79]	Envirotemp FR3 [78]	Ambiant insulating fluid [80]	Ambiant prime insulating fluid [80]	NeuGen 1540 [81]
Density (kg/dm ³)	at 20 °C	0.91	0.92–0.923			
ASTM D1298						
Pour point (°C)		−15 to −25	−21	−18	−18	−18
ASTM D97						
Biodegradability CEC L-33-A-93		97				≥95
Flash point (°C)		330	330			≥225.1
ASTM D92						
Fire point (°C)		360	360	340	336	
ASTM D92						
Water content (ppm)		<80				≤50
IEC 60814						
Kinematic viscosity (cSt)	at 0 °C	300	207			
ASTM D445	at 20 °C	115	78			
	at 40 °C	45	36	36	38	≤14.4
	at 100 °C	10	8	8.0	8.3	
Thermal conductivity (W/m K)	at 20 °C	0.17	0.167			
ASTM D2717						
Specific heat (kJ/kg K)	at 20 °C		1.850–1.883			
ASTM D2766						
Expansion coefficient (/°C)		0.000688				
ASTM D1903						
Acidity (mg KOH/g)		<0.03	0.022	0.05	0.05	
ASTM D974						
Breakdown voltage (kV)		45		55	51	≥86
IEC 60156						
Dissipation factor (%)	at 20 °C			0.13	0.40	
IEC 60247	at 25 °C					≤0.00379
	at 90 °C	0.007	0.005			
Dielectric constant (at 20 °C)		3.2	3.2			
IEC 60247						

Table 9
Comparison of transformer oils.

Property		Mineral oil	HMWH	Silicone	Synthetic esters	Natural esters
Density (kg/dm ³)	at 20 °C	0.83–0.89		0.96–1.10	0.90–1.0	0.87–0.92
ASTM D1298	at 23 °C	0.85				
	at 90 °C	0.81				
Pour point (°C)		–30 to –63	–20 to –24	–50 to –60	–40 to –60	–10 to –33
ASTM D97						
Biodegradability 21 – day CEC – L – 33		<30%	20%	0%	80%	97–99%
Water solubility (ppm)	at 20 °C	45		200	2700	
ASTM D1533						
	at 100 °C	650		1100	7200	
Flash point (°C)		110–175	275–285	300 to 310	250–310	310–343
ASTM D92						
Fire point (°C)		110–185	300–312	330–350	300–322	300–369
ASTM D92						
Kinematic viscosity (cSt)	at 0 °C	<76	2200–2500	81–92	26–240	77–500
ASTM D445	at 20 °C	16			63–70	
	at 25 °C		300	50		55–75
	at 40 °C	3.0–16.0	110–130	35–40	14–29	16–50
	at 90 °C	2.3		16	7–8	10–15
	at 100 °C	2.0–3.0	11.5–14	15–17	4.0–6.0	4–15
Thermal conductivity (W/m K)	at 20 °C	0.135	0.13	0.151	0.165	0.17
ASTM D2717	at 90 °C	0.125			0.155	
Specific heat (kJ/kg K)	at 20 °C	1.85		1.55	1.81	
ASTM D2766	at 25 °C	1.63–2.0	1.88–2.04	1.50–1.52	1.80–2.30	1.50–2.38
Expansion coefficient (1/°C)		7×10^{-4} – 9×10^{-4}	7.3×10^{-4}	10.4×10^{-4}	6.5×10^{-4} to 10×10^{-4}	5.5×10^{-4} – 7×10^{-4}
ASTM D1903						
Oxidation inhibitor (%)		≤ 0.30				0.15
ASTM D2668						
Gassing tendency (μl/min)		–10 to +24	–10 to +30	+10	+19 to +30	–22 to –80.5
ASTM D2300						
Biochemical oxygen demand (ppm)		6	6	0	24	250
5-Day SM5210B						
Trout fingerling toxicity mortality		n.a.	n.a.	n.a.	n.a.	0
COECD203						
Acidity (mg KOH/g)		0.01	0.01		0.06–0.2	
ASTM D974						
Breakdown voltage (kV)	at 20 °C	45–85	40–52	35–60	43–70	49–97
ASTM D1816	at 50 °C				42–45	44–58
	at 90 °C				52–58	51–64
	at 110 °C				60–63	45–65
Dissipation factor (%)	at 25 °C	0.005–0.05	0.010–0.05	0.010	0.0006–0.001	0.001–0.003
ASTM D924	at 90 °C	$<10 \times 10^{-4}$		1.6×10^{-4}	10^{-4} to 0.03	0.005–0.009
	at 100 °C	0.001–0.3	0.3	4×10^{-4}		
Dielectric constant	at 20 °C	2.1–2.5	2.2	2.6–2.9	3.0–3.5	2.9–3.3
IEC 60247	at 90 °C				2.8–3.0	2.8
Resistivity		10^{13}	10^{14} – 10^{15}	10^{14}	10^{13}	10^{13} – 10^{14}
ASTM D1169						

the life of a transformer, as its life is controlled by the state of the paper. At elevated temperatures, ester fluids can undergo hydrolysis, consuming available water from the paper, thereby improving the paper ageing characteristics. Moreover, the esterification of the reactive OH sites in cellulose with bulky ester groups stabilises the molecule and extends the thermal life of the solid insulation [95]. However, due to this higher solubility, ester oils recapture moisture rapidly, and special care has to be taken during handling compared to mineral oil [65]. Fig. 1 shows the variation of the moisture saturation with temperature.

4.6. Pour point

Although natural esters have a relatively high pour point, but not much higher than the HMWH, which have a very good service record in distribution transformers installed in cold and hot climates, it was demonstrated by Rapp et al. that freezing the natural ester fluids had no effect on their physical, chemical or electrical properties. Their tests also showed that a distribution transformer can be energised at solid phase temperatures without adverse effects [98]. Synthetic esters have a pour point close to that of conventional mineral oil [40].

4.7. Oxidation stability

Furthermore, because natural ester oils are more biodegradable than mineral ones, they tend to have a lower oxidation stability. Oxidation stability studies have been conducted by various authors, who first aged the oil and later measured acidity and $\tan \delta$ because they constitute the most suitable properties to evaluate the oxidation [65]. The results have shown that the relative stabilities of dielectric fluids to oxidation are: silicone oil > synthetic ester > mineral oil > natural ester. In natural esters, the greater number of carbon–carbon double bonds that the molecules contain makes the oil more susceptible to oxidation. The oxidation stability of dielectric fluids for transformers is a critical issue because the oxidation of dielectric oils generates the formation of by-products such as acids and sludge, which may cause problems in a transformer by reducing the dielectric properties of the insulation.

5. Miscibility of alternative fluids

The miscibility of alternative fluids at ambient temperature (Fig. 2) has been used by some authors to improve the properties of mineral oil by mixing. Although silicone oil is miscible with

Table 10
Some properties of the mixed insulating liquids investigated.

Property		Mineral oil	Mineral oil + 10% synthetic ester	Mineral oil + 20% synthetic ester	Mineral oil + 50% synthetic ester	Synthetic ester
Density (kg/dm ³)	at 23 °C	0.856	0.881	0.890	0.918	0.960
ISO 3675	at 90 °C	0.810	0.841	0.851	0.876	0.915
Water solubility (ppm)	at 20 °C	45	100	310	830	2700
IEC 60814	at 100 °C	650	940	1600	2900	7200
Kinematic viscosity (cSt)	at 20 °C	16	17.4	19.44	28.65	63
ISO 3104	at 90 °C	2.3	3.45	3.76	4.80	7.70
Breakdown voltage (kV)		>55	>55	>55	>55	>55
IEC 60156						
Dielectric constant (at 25 °C)		2.2	>2.2	>2.3	>2.6	3.3
IEC 60247						
Dissipation factor (at 90 °C)		<10 × 10 ⁻⁴	≥0.001	≥0.002	≥0.002	10 ⁻⁴
IEC 60247						

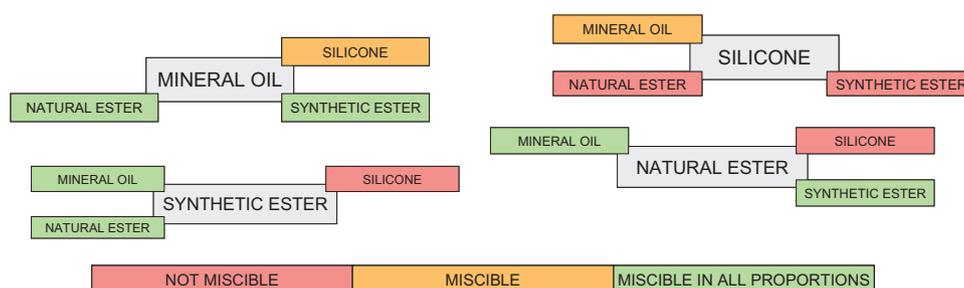


Fig. 2. Miscibility of alternative fluids at ambient temperature.

mineral oil, it can cause excessive foaming in mineral insulating oil even in small quantities. Additionally, silicone oil is not miscible with ester fluids. However, natural and synthetic esters are miscible with mineral oil in all proportions.

Gockenbach et al. studied the properties of mixtures of a synthetic ester liquid (Midel 7131) and a mineral oil (Shell Diala D) [13,21,99]. Their work demonstrated that some electrical and physical properties of the mixed liquids (Table 10) were not inferior to those of mineral oil, particularly for mixtures with less than 20% ester content. For the mixture with 50% of ester liquid, the density and the kinematic viscosity exceeded the limiting values suggested by the standards. Although the density is normally not very significant in determining the quality of oil, it may be pertinent in determining oil suitability in cold climates. Moreover, adding ester liquid to mineral oil helps to decrease the gassing tendency under local thermal stresses.

Perrier et al. considered mineral, silicone and ester oils as well as two types of mixtures based on mineral oil [100,101]. These mixtures consisted in adding silicone oil or ester oil to mineral oil. They studied different properties such as the viscosity, the breakdown voltage, the acidity, and $\tan \delta$. The experimental results showed that mineral oil is the most efficient to evacuate heat, ester oil enables the transformer to have a better breakdown voltage and silicone oil ages slowly. The mineral/20% ester oils mixture appeared to be the optimum from technical and economical viewpoints. These authors also highlighted that: (i) chemical interactions or parameters such as the water content influence the mixture properties and (ii) each fluid has one advantage with regard to the others.

Suwarno and Darma reported experimental results on the dielectric properties of a mixture between conventional mineral oil (Shell Diala B) and methyl ester from palm oil. The content of ester in the mixture ranged from 0 to 100%. They concluded that the composition of 50% ester content was a good mixture to be used as biodegradable insulating liquid [102].

The miscibility of alternative fluids is also crucial when retrofilling is considered. There are several reasons to conduct retrofilling

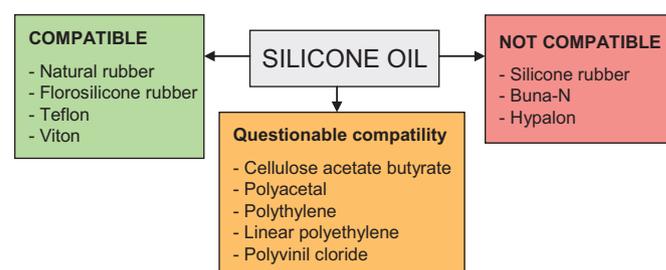


Fig. 3. Compatibility of some materials with silicone oil.

with another fluid: alternative fluids have higher fire safety, biodegradability, moisture tolerance, solid insulation longevity, etc., than mineral oil [21]. If both fluids, the old oil (mineral) and the new oil (silicone, synthetic or natural ester), are miscible, the procedure to remove the old one is more effective. However, the retrofilling procedure can be performed with immiscible fluids, but it requires more care. Additionally, it is required to check the compatibility of the materials before retrofilling. Generally, the materials that are used in mineral oil filled transformers are compatible with alternative fluids. Nevertheless, there are some materials that are not compatible with new dielectric liquids or whose compatibility is questionable (Fig. 3) [66–81].

The physical, chemical and dielectric properties of the insulating fluids should be maintained constant to obtain the longest possible service life and provide the maximum protection for the transformer [103]. For this reason, it is critical to study the behaviour of insulating fluids during transformer performance.

6. Conclusions

This work reviewed the state of the art of alternative fluids used in power transformers. The main alternative oils found were silicone and natural and synthetic esters. There are many authors who

have compared the main physical, chemical and dielectric properties of dielectric oils as well as their behaviour when these fluids have been aged. All of these papers were analysed, and the main conclusions were summarised.

New environmental laws have encouraged the search for vegetable oils that can be used as dielectric fluids in power transformers. Currently, the vegetable oils that have shown the best properties to produce a new insulating fluid are sunflower, soybean, rapeseed and canola oil. The analysis of commercial oils concludes that silicone fluid and both natural and synthetic esters offer a high reduction in fire risk due to their flash and fire points. Second, natural and synthetic esters are classified as biodegradable, whereas mineral and silicone oils are more resistant to biodegradation. Moreover, all alternative fluids are more viscous than mineral oil, which is critical to determine the cooling capability of the fluids. Additionally, it has been observed that natural and synthetic esters present a BDV close to mineral oil. These alternative fluids can absorb many times more moisture than mineral oil. The results on oxidation stability have shown that silicone and synthetic ester are more stable than mineral oil and natural ester. Therefore, most of the performance characteristics of ester fluids are far superior to those of conventional mineral oil, including fire safety, electrical and thermal properties, and a significant reduction in the ageing rate of the insulation paper.

The miscibility of different fluids was studied. It has been shown that some electrical and physical properties of the mixed liquids were not inferior to those of mineral oil, particularly for mixtures with less than 20% ester content. Furthermore, adding ester liquid to mineral oil helps decrease the gassing tendency under local thermal stresses. Some experiences with mixtures between mineral oil and methyl ester from palm oil showed that the biodegradability could be improved.

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