Electrical insulating liquid: A review

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Insulating liquid plays an important role for the life span of the transformer. Petroleum-based mineral oil has become dominant insulating liquid of transformer for more than a century for its excellent dielectric and cooling properties. However, the usage of petroleum-based mineral oil, derived from a nonrenewable energy source, has affected the environment for its nonbiodegradability property. Therefore, researchers direct their attention to renewable and biodegradable alternatives. Palm fatty acid ester, coconut oil, sunflower oil, etc. are considered as alternatives to replace mineral oil as transformer insulation liquid. This paper gives an extensive review of different liquid insulating materials used in a transformer. Characterization of different liquids as an insulating material has been discussed. An attempt has been made to classify different insulating liquids-based on different properties.

Keywords: Transformer oil; liquid insulation; insulating materials; vegetable oils.

1. Introduction

Transformers are key components of electrical power system network. It plays a vital role in every field of power system network like electrical power generation, transmission, and distribution.¹ The majority of transformers depends on liquid dielectrics as an insulating material.² The classification of insulating liquids are given in Table 1. It prevents internal short circuit, protects the transformer from chemical attack, prevents sludge formation and acts as a cooling agent to remove heat when the transformer is being energized.^{3,4} The mineral oil obtained by fractional distillation and subsequent treatment of crude oil has been used as the liquid insulation for more than 75 years.^{5,6} It is also used in different electrical equipment other than a transformer, which includes different types of high voltage capacitors,⁷ switches, circuit breakers, tap changers and bushings etc.⁸ The purpose of this study is to provide information about different properties of various types of environment-friendly insulating oils which shows potential as regards application in the transformer. This study encouraged researchers to direct their focus onto renewable and biodegradable insulating materials. It reviews the present status of vegetable oils used as insulating and cooling medium in transformer, including their characterization, production, and processing. It shows the main advantages and disadvantages of vegetable oils in comparison with mineral oil giving an outline of the recent research carried out.

1.1. History of transformer insulating liquid

In 1892, "General Electric" started the use of first petroleum-based oils as an insulating liquid in the transformer. Commercial production of paraffinic-based mineral oil was started in 1899. Paraffinic-based mineral oil contained large quantity wax resulting undesirable high pour point. It also produced a large amount of insoluble sludge in subzero climate condition which lowered the viscosity and thus reduces heat transfer capacity. Later on paraffinic mineral oil was replaced by naphthenic oils which kept mineral oil as fluid at very low temperature but had the disadvantage of high flammability. Polychlorinated biphenyl (PCB) was first made in 1930,¹⁰ which overcame the flammability of naphthenic oils. But in early 1970, it was determined that PCB were no longer environmentally acceptable and hence new uses and production of PCBs have been banned. With the termination of the PCBs, the power industries turned to other liquid insulation like synthetic esters, vegetable oil, silicon fluid, etc.¹¹ Mineral oil remained the major source among these all.^{12,13}

1.2. Mineral oil as transformer insulating liquid

The chemical structure of transformer oil is very complex, which is composed of both hydrocarbons and non-hydrocarbons.¹⁴ Nonhydrocarbon presents in small amount in transformer oil whereas hydrocarbon constitutes the main part containing only carbon and hydrogen. The chemical

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Table 1. Classification of insulating liquids.

Mineral insulating oil	Paraffinic oils	Nonring long-chained structure
	Naphthenic oils	Saturated ring structure
	Aromatic oils	Nonsaturated ring structure
Synthetic insulating oil	Polyalphaolefins	Manufactured by polymerization of hydrocarbon molecules
	Polyglycols	Produced by oxidation of ethylene and propylene
	Synthetic ester oils	Produced by reaction of acids and alcohols with water
Vegetable insulating oil	Soybean oil	Vegetable oils are nontoxic, biodegradable, low inflammable, have a higher breakdown voltage, high flash point, high acidity number, high viscosity and pour point
	Coconut oil	
	Cottonseed oil	
	Rapeseed oils	

structure of different hydrocarbons present in transformer oil is shown in Fig. 1. Good quality transformer oil contains optimum amount chemical compound. The aromatic compound presence in transformer oil increases the stability of the oil in service while too much of it can reduce the impulse strength or dielectric strength of oil and increase the solvency property of the oil for many of the solid particles immersed in it. Again, presence of sulfur compounds in high concentration causes corrosion of copper in contact with insulating oil. Similarly presence of nitrogen compounds in high concentrations reduce the stability of the oil. The basic properties of transformer oil which are desirable for serving the purpose as dielectric medium and coolant are a high impulse strength, high electric strength, and high volume resistivity, high thermal conductivity, high specific heat, high flash point, low viscosity, low volatility, and low dielectric dissipation factor. Apart from these, good transformer oil should have high resistance to chemical deterioration, nonflammable, cheap and easily available.¹⁵

1.3. Alternative to mineral insulating oil

In recent years, many researchers have been carried out to find out the suitable alternate of transformer oil.^{16–18} Many synthetic, as well as natural fluids have been tested and used as an alternate to the transformer oil.^{19,20} The chemical structure of synthetic ester and the natural ester is shown in Fig. 2. Transformer oil has many disadvantages like presence of polynuclear aromatic hydrocarbons which may readily be released into the environment due to the explosion of a transformer, poor biodegradability and future scarcity. Attention has been paid to vegetable oils like oil from soya beans, sunflower, etc.^{21,22} and synthetic esters as a liquid insulating medium. It has been found in the literature that vegetable oils and synthetic esters have drawn the most attention among all other alternatives of transformer oil. It has properties of low flammability, negligible environmental impact, and high moisture tolerance, nontoxic to aquatic life, high flash point, lower volatility and lower pour point.^{23,24}

Aging of vegetable insulating liquids in presence of air leads to oxidation resulting an increase of viscosity. Therefore, it is important to take care during filling the insulating liquid in transformers to exclude oxygen. It shows less thermal aging of insulating paper in it over the temperature range of 70°C to 190°C compare to the mineral oil. Again, CO and CO₂ concentration are less in aged vegetable oil compared to the aged mineral oil. However, the concentration of water in aged vegetable oil is more when compared to aged mineral oil. Comparison of aging effect on mineral oil and vegetable oil is shown in Table 2.

1.4. Performance analysis of different insulating liquids

1.4.1. Fire and flash point

Thermal characteristics of both aged and virgin samples of mineral and vegetable oils have been studied in the paper.²⁵ It concluded that vegetable oil has better thermal behavior than mineral oil. Palm and coconut oils have safe flash and fire point than mineral oil.

Fig. 1. Chemical structure of different hydrocarbon of mineral oils.

Fig. 2. Chemical structure of synthetic ester and natural ester.

1.4.2. Arc-quenching property

The arc-quenching behavior of vegetable oil is high compared to that of mineral oil. It has been found from Ref. 25 that production of acetylene and hydrogen under arcing

condition for mineral oil is much more compared to the vegetable oil. But the production of CO and CO₂, due to the breaking of carbonyl group-COO, is much more for vegetable oil in comparison to mineral oil.

1.4.3. Dielectric breakdown strength

The dielectric strength, which depends on the moisture in ppm, is better for vegetable oil compared to mineral oil. The effect of moisture on dielectric behavior of ester oil is less compared to that of mineral oil.²⁶ Coconut and palm oils have the better dielectric strength than compared with mineral oil.

1.4.4. Oxidation stability

Reference 27 explains the experimental study about oxidation stability and found that there was a little change in breakdown

Table 2. Aging properties of insulating liquids.⁹

Property	Units	Standards	Mineral oil	Vegetable oil
Viscosity, 40°C	mm ² /s	ISO 3104, ASTM D 445	7.6	39.2
Density, 20°C	kg/dm ³	ISO 12185, ISO 3675, ASTM D 1298	0.877	0.9128
Breakdown voltage (2.5 mm)	kV	IEC 60156	40–60	81
Acidity	mgKOH/g	IEC 62021, ASTM D 974	0.01	0.05
Tan delta (90°C and 50 Hz)	—	IEC 60247	0.001	0.0134
Flash point	°C	ISO 2719, ASTM D 92	144	332
Moisture content	mg/kg	IEC 60814	< 20	100

Table 3. Deterioration of liquid insulation.

Categories	Reasons	Elements	Results
Physical contamination	Solid impurities	Paper Pressboard Wood Varnish Cotton tap	Absorb moisture Electrical breakdown Formation of copper soaps
	Foreign matters	Dust Metallic particles Fibrous matter	Lowering of electric strength Chemical decomposition of oil Formation of carbon particles
Contamination by gases	Dissolved gases in the oil from atmosphere	Breather inhaling	Lowering the electric strength of the oil due to the formation of the following gases:
	Thermal decomposition of oil	Decomposition due to arcing Electrolysis Vaporization of the oil Chemical reaction among different particles	Methane, Ethane, Ethylene, Acetylene, Propylene, Butane, Carbon monoxide, Hydrogen, Carbon Dioxide
Chemical decomposition	Oxidation	Air	Corrosion
	Electrical stress	Water	Impairment of heat transfer
	Thermal stresses	Solid particles	Deterioration of electrical properties
			Dielectric losses Arcing

voltage and an acid value of vegetable oil which concluded that vegetable oil has superior oxidation stability compared to mineral oil.

2. Test of Insulating Liquid

While transformer in service, insulating oil is subjected to thermal, electrical and mechanical stresses. On the other hand, contaminations caused due to chemical reactions between windings and other solid insulation, which is catalyzed by high operating temperature. As a result, it loses its original properties, causing it ineffective for its main purpose after many years. Different reasons responsible for the deterioration of liquid insulation is given in Table 3 and different tests which are considered to ascertain the quality of insulating oil are listed in tabular form in Table 4.

3. Dissolve Gas Analysis

The analysis of different gases in insulating transformer oil to quantify and identify the dissolved combustible gases is called dissolved gas analysis (DGA). It is used as a specialized diagnostic test for the transformer internal health condition monitoring.^{29,30} Out of nearly 3000 hydrocarbon compounds of transformer insulating oil, only as many as seven gases are usually considered for diagnostic purposes. There are different methods used for predicting the health condition of transformer.³¹ Some of these methods are Roger's Ratio method, Duval Triangle method, IEC Ratio method, Key gas method and combustible gas method.^{32,33} The temperature range at which these individual gases are produced, causes of evolution, their solubility in transformer insulating oil and concentration are given in Table 5.

Table 4. Test of insulating liquid.

Categories	Parameters	Indication/quality	Apparatus/methods
Physical Test	Appearance	Clear, transparent oil: good oil Cloudy or foggy appearance: indicates moisture presence Greenish oil: indicates presence of copper salts Acrid smell: indicates presence of acid	With naked eye
	Density	Generally varies between 0.80 to 0.89 Lower density indicates lower viscosity	Density Hydrometer
	Viscosity	High viscosity: indicates low heat removal	Viscometer
	Pour point	High pour point: indicates better-insulating oil	Cloud pour point apparatus
	Flash point	High flash point: indicates better insulating oil	Pensky–Martens closed cap apparatus
	Interfacial tension	Lower value of IFT: indicates better insulating oil	Tensiometer, Ring method, IFT apparatus
Chemical Test	Neutralization number	Low neutralization number: indicates minimum electrical conduction, minimum metal corrosion, maximum life of insulation	Potassium hydroxide required in gram to neutralize the acid
	Water content	High water value: indicates low dielectric strength, high chemical deterioration of insulating paper	Water content test apparatus, Karl Fisher titration method
	Sediment and sludge	High sediment/sludge: indicates low electrical property	With a naked eye
	Corrosive sulfur	More sulfur: more corrosion of metal parts	Degree of corrosion by copper in contact with oil under measurement
	Oxidation stability	Low oxidation value: indicates low acid and sludge formation, minimum electrical conduction, and metal corrosion, high heat transfer	Oxidation stability test vessel, oxidation stability apparatus
	Inhibitor content	Inhibited oils deteriorate more slowly than uninhibited oils	Di-tertiary butyl para-Cresol
Electrical Test	SK value	Volume of concentrated sulphuric acid on adding to test sample	Bis: 335-1993 test method
	Electric strength: Breakdown voltage (BDV) test	Higher the BDV value: better the ability to withstand electric stress	Spherical and semi hemispherical brass electrodes test arrangement
	Dielectric dissipation factor (tan delta)	Lower dissipation factor: indicates better insulating oil	Measurement of phase difference between applied voltage and resulting current
Optical Test	Resistivity	Higher resistivity: indicates better insulating oil	Automatic resistivity test set
	Oil level measurement	Oil level proportional to output voltage, higher the output voltage higher the oil level	Continuous and discrete optical sensor-based instrumentation system
	Temperature measurement	Change of temperature proportional to output voltage	Optical sensor-based instrumentation system
	Moisture measurement	Amount of moisture in oil proportional to output voltage	Optical sensor-based instrumentation system

Table 5. Dissolve gas analysis.

Gases	Evolution temperature	Nature of faults	Solubility coefficient	Concentration (ppm)		
				Less than four years	Between 4 to 10 years	More than 10 years
H ₂	≥ 150°C	Partial discharge, arcing in oil	7	50–70	100–150	200–300
CH ₄	150°C to 300°C	Partial discharge in oil, overheating of oil	30	30–50	100–150	800–1000
C ₂ H ₆	250°C to 350°C	Overheating of oil	280	100–150	150–200	200–400
C ₂ H ₄	350°C to 700°C	Overheating of oil	280	20–30	30–50	150–200
C ₂ H ₂	≥ 700°C	Arcing in oil, overheating of oil	400	100–150	200–300	300–400
CO	≥ 300°C	Cellulose overheating	9	200–300	400–500	600–700
CO ₂	≥ 300°C	Cellulose overheating	120	3000–3500	4000–5000	9000–12000

4. Properties of Alternative Transformer Insulating Liquid

It has been found from the literature that most of the physical properties such as moisture content, flash point, dielectric strength, etc. of vegetable insulating oils are within the recommended level. Researchers are trying to bring the viscosity of coconut oil to recommended level by doing some chemical modification. Again, the pour point of coconut oil could be reduced to a considerable level by adding styrenated phenol to it. Besides the coconut oil, sunflower and rapeseed have excellent fire resistance and biodegradability properties.¹⁴ Comparison of typical values³⁴ of different insulating properties has been given in Table 6. A large number of research works have been done by the researchers across the globe to find out an environment-friendly substitute of transformer mineral oil. Some findings of these research works are analyzed here. References 35–37 explained the performance of vegetable oil like coconut oil as an alternative to mineral oil in the transformer and compares the thermal aging of insulating paper in mineral oil with that of paper in vegetable oil over the specific temperature range. Yang Xu *et al.*³⁸ investigated oxidation stability of vegetable transformer oil under accelerated thermal aging by using pressure differential scanning calorimetry (PDSC) method and draws

the conclusion that acidity is not suitable but viscosity is responsive for vegetable oils. Imad-U-Khan *et al.* and Muhamad *et al.*^{39,40} adopt a new ratio criteria of dissolved gas analysis for fault detection and diagnosis and found that less amount of gases are produced in ester-based insulating liquid compared to mineral oil. References 41, 42 and 43 studied the breakdown characteristics of coconut oils with mineral insulating oil. The results indicated that coconut oil has higher breakdown value than mineral oil. Ramli *et al.* and Arief *et al.*^{44,45} studied about the partial discharge characteristics of palm fatty acid ester (PFAE) and draws the conclusion that PFAE has good potential to be used as cooling and insulating liquid in power transformer. Hosier *et al.*⁴⁶ investigated biodegradable olive oil, rapeseed oil, crone and sunflower oil using ultraviolet/visible, infrared spectrometers and found that olive oil offered excellent resistance to aging, rapeseed oil offered intermediate properties whereas corn and sunflower oil oxidized appreciably after aging. Nanayakkara *et al.*⁴⁷ presented variations of capacitance and dielectric losses of coconut oil and mineral oil impregnated pressboard samples during oven heating using frequency domain dielectric spectroscopy (FDS) and draws the conclusion that losses were relatively higher for coconut oil impregnated pressboard samples in comparison to mineral oil.

Table 6. Comparison of electrical insulating liquids-typical values.²⁸

Properties	Mineral oils	Silicone oils	Synthetic esters	Vegetable oils	Test method
Dielectric breakdown, kV	30–85	35–60	45–70	82–97	IEC60156
Relative permittivity at 25°C	2.1–2.5	2.6–2.9	3.0–3.5	3.1–3.3	IEC60247
Viscosity at 0°C, mm ² s ⁻¹	<76	81–92	26–50	143–77	ISO3104
Viscosity at 40°C, mm ² s ⁻¹	3–16	35–40	14–29	16–37	ISO3104
Viscosity at 100°C, mm ² s ⁻¹	2–2.5	15–17	4–6	4–8	ISO3104
Pour point, 0°C	–30 to –60	–50 to –60	–40 to –50	–19 to –33	ISO3016
Flash point, 0°C	100–170	300–310	250–270	315–328	ISO2592(1)
Fire point, 0°C	180–185	340–350	300–310	350–360	ISO2592(1)
Density at 20°C, kg dm ³	0.83–0.89	0.96–1.10	0.90–1.00	0.87–0.92	ISO3675
Specific heat, J g ⁻¹ K ⁻¹	1.6–2.0	1.5	1.8–2.3	1.5–2.1	ASTME1269
Thermal conductivity, Wm ⁻¹ K ⁻¹	0.11–0.16	0.15	0.15	0.16–0.17	(DCS)

Table 7. Properties of new insulating oil filled in new power transformer as per IS 1866:2000.

Properties	Voltage level	Voltage level	Voltage level
	> 72.5 kV	72.5 kV to 170 kV	> 170 kV
Appearance	Clear, sediment and suspended matter free	Clear, sediment and suspended matter free	Clear, sediment and suspended matter free
Density at 29°C, gm/cm ³ , Max	0.89	0.89	0.89
Viscosity at 27°C, cSt, Max	27	27	27
Flash point, °C, Min	140	140	140
Pour point, °C, Max	−6	−6	−6
Neutralization value, mg KOH/g, Max	0.03	0.03	0.03
Water content, ppm, Max	20	15	10
Interfacial tension, Mn/m, Min	35	35	35
DDF (tan δ) at 90°C, 40–60 Hz, Max	0.015	0.015	0.010
Resistivity at 90°C × 10 ¹² ohm – cm, Min	6	6	6
Breakdown Voltage, kV (rms), Min	40	50	60
Oxidation stability of uninhibited oil:			
Neutralization value, mgKOH/g, Max	0.4	0.4	0.4
Sludge, Max	0.1	0.1	0.1

Table 8. Important work recently published in IEEE transaction.

Sl.No.	Author/Year	Findings	Involved instrumentation system/ Technology	Comment
1	B. S. H. M. S. Y. Matharage/2013	Coconut oil can be a good choice as an alternative to the conventional mineral oil for power transformers	Frequency dielectric spectroscopy measurement and using dissolved gas analysis method	This paper presents the performance of coconut oil as an alternative of transformer oil
2	Maria Augusta G. Martins/2010	The use of the vegetable oil as an insulating liquid is a very promising option.	Compare the vegetable oil-based dielectric fluid Biotemp, and the Kraft paper.	This paper compares the thermal aging of insulating paper in mineral oil with that of paper in vegetable oil over the specific temperature range
3	S. Okabe/2013	Due to the aging, for example, of about 30 years, properties of both insulating oil and solid insulation were degraded as a whole	Based on volume resistivity, dielectric loss, Interfacial, acid value	In this paper, insulation degradation of shell-type and core-type transformer has been studied by aging
4	H. Borsi/2005	Use of ester liquid midel 7131 reduces the risk of environmental pollution, increases the lifetime of the component and reduces the fire risk.	Comparative study using ester liquid midel 7131	Presents a comparison of the performance of natural and synthetic ester as an alternative to mineral oil
5	Yang Xu/2014	Acidity is not suitable but viscosity is responsive for vegetable oils.	Investigated by using Pressure Differential Scanning Calorimetry (PDSC) method	This paper focuses on oxidation stability assessment of a vegetable transformer oil under accelerated thermal aging
6	Imad-U-Khan/2007	Less amount of gases produces in ester-based insulating liquid	Dissolve gas analysis method on ester-based transformer fluids	Modified or new ratio criteria has to adapt for fault detection and diagnosis
7	N. A. Muhamad/2008	Validate the result based on existing DGA fault interpretation methods	Experimental tests performed on laboratory models	This paper explains about the investigation of hydrocarbon gas products generated when arcing happened
8	S. Ranawana/2008	Breakdown value is considerably higher than that of new mineral oil	Measurements were carried out in frequency domain at different temperatures	Stability of coconut oil as an insulating liquid has been studied
9	S. S. Sinan/2015	Palm oil and coconut oil have fairly similar AC breakdown strength and withstand voltages	Comparative study of palm oil and coconut oil with mineral oils	The breakdown voltage of palm oil and coconut oil are investigated

Table 8. (Continued)

Sl.No.	Author/Year	Findings	Involved instrumentation system/ Technology	Comment
10	A. A. H. Zaidi/2015	Virgin coconut oil has the highest breakdown voltage, lowest moisture content and also lowest viscosity	Comparative study of palm oil, coconut oil, and virgin coconut oil with mineral oils	In this paper, palm oil, coconut oil and virgin coconut oil are tested in a single-phase step down transformer and induction motor as a load
11	Y. Z. Arief/2014	Both palm fatty acid ester and FR3 oils have a lower value of the dielectric dissipation factor and higher value of capacitance	Analyzed using computational simulation to investigate the dielectric characteristic	A comparative study on the effect of electrical aging on electrical properties of palm fatty acid ester and FR3 has been discussed
12	M. R. Ramli/2014	Palm fatty acid ester (PFAE) has a good potential to be used as a power transformer oil	Comparative study of PFAE with mineral oils	Partial discharge characteristics of palm fatty acid ester has been studied
13	I. L. Hosier/2011	Olive oil offered excellent resistance to aging, rapeseed oil offered intermediate properties whereas corn and sunflower oil oxidized appreciably after aging	Used ultraviolet/visible, infrared and dielectric spectroscopies	Aging of biodegradable oils and assessment of their suitability for high voltage applications has been studied
14	N. W. N. J. Nanayakkara/2013	Losses were relatively higher for coconut oil impregnated pressboard samples in comparison to mineral oil.	The dielectric properties were obtained by FDS measurements	This paper presents variations of capacitance and dielectric losses of coconut oil and mineral oil impregnated pressboard samples during oven heating

5. Properties of New Insulating Oil Filled in New Power Transformer as per IS 1866:2000

Properties of unused new insulating oil filled in new power transformer differ from that of new insulating oil. The new insulating oil when filled in power transformer comes in contact with different construction materials and other solid insulating materials and gets contaminated and changes its properties. These changes of properties depend upon the types of materials used for construction and ratios of solid to liquid insulation, and should be kept within acceptable limits adapting proper processing techniques and proper selection of materials. Power transformers need testing of liquid insulation before energizing the transformer. Indian standard recommended limits are given in Table 7. Some papers published in IEEE transaction is listed in Table 8.

6. Conclusion

The nonrenewable mineral oil used in power transformer is nonbiodegradable and it can be potentially hazardous to the environment. Researchers are looking for the alternatives which are derived from renewable and environmentally friendly sources. This review paper explains about the physical, chemical and electrical characteristics and the various deterioration reasons of the liquid insulation used in the transformer. As per literature survey, research in recent years on alternate insulating oil clearly draws the following points:

- (1) Virgin Coconut oil can be a good choice as an alternative to the conventional mineral oil for power transformers. It

has the highest breakdown voltage, lowest viscosity and lowest moisture content compare to palm oil and other renewable insulating oil.

- (2) Vegetable oil which can be used as one of the alternatives to replace mineral oils in transformers is suitable to be used in sealed transformers.
- (3) The rate of production of dissolved gases in esters during thermal and electrical faults is less in comparison with petroleum-based mineral oil. Esters are predominantly stable under particular temperature range thermal faults.
- (4) Acetylene is mainly responsible for electrical fault for low energy discharges and hydrogen is the key fault indicating gas for partial discharges.
- (5) Partial discharge magnitudes of palm fatty acid ester (PFAE) are slightly lower than those of petroleum-based mineral oil during the aging time. Therefore, palm fatty acid ester has a good potential to be used as power transformer oil in electrical power system application.

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