Vegetable oil as insulating fluid for transformers

by Mike Rycroft, features editor, EE Publishers

Oil constitutes a major component of power transformers. Conventionally, mineral or synthetic oils have been used. In an attempt to overcome some of the drawbacks with mineral oils, vegetable oil has been considered as an alternative. Used in the industry for several decades it has proved to be a viable alternative to mineral oil and has several advantages over mineral oil.

Mineral oil is the most commonly used insulating liquid for transformer applications, and an extensive database of knowledge has been accumulated over the years. Increased environmental, safety, performance and economic have led to the consideration of other oils for use as transformer insulating fluids. Vegetable oils or esters have been used as dielectric liquids since the invention of oil-filled transformers in the late 1880s. The earliest natural esters were found to be incompatible with free breathing equipment, because of their oxidation characteristics, and were gradually replaced by mineral oils [1].

Environmental requirements have caused the electrical power transmission and distribution industry to look for viable alternatives to mineral oil. To be acceptable, any environmentally acceptable alternative must be safe, economical, and offer a high standard of electrical performance over a long working life. Recently there has been a resurgence of the use of natural ester dielectrics because of their obvious "green" credentials [1].

Natural ester fluids [1,2,3,4]

Natural esters are produced from vegetable oils, which are manufactured from plant crops. They offer the advantage of a high fire-point as well as good biodegradability, but all types of natural esters suffer from not being as oxidation stable as other types of insulating liquids. Although natural ester fluids can be produced from a wide variety of crop oils, natural esters for electrical applications are most commonly produced from soya, rapeseed and sunflower oil. This is due to factors such as availability, cost and performance characteristics.

Properties

The properties of commercially available esters vary with the product and typical representative values of the most important properties for the use of vegetable oils as transformer oil described in the following sections.

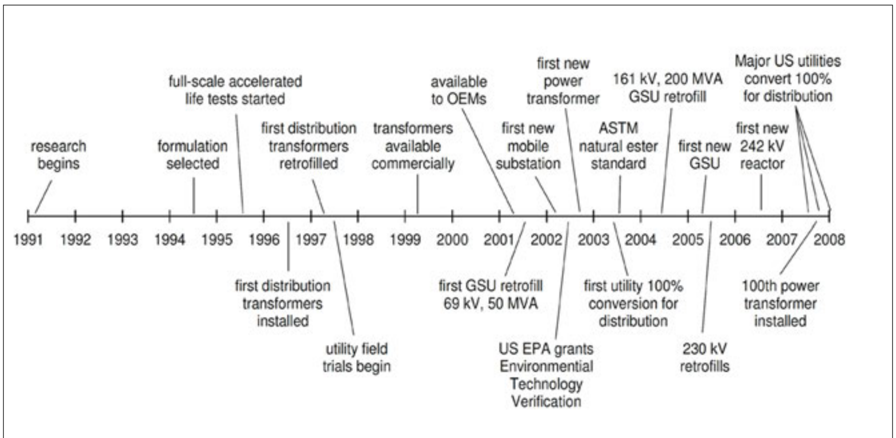

Fig. 1: Development of natural esters as transformer insulating fluid [1].

Test	Mineral oil	Synthetic ester	Natural ester	Silicone oil	Low viscosity silicone oil
IEC 60156 2,5 mm	70 kV	>75 kV	>75 kV	50 kV	70 kV
ASTM 1816	-	-	37 kV	-	-
ASTM	60 kV	-	76 kV	-	-
ASTM	55 kV	43 kV	46 kV	43 kV	-

Table 1: Typical values of breakdown voltage for various insulating fluids [1].

Electrical properties

All transformer oils need to meet AC withstand voltage, lightning impulse, and switching impulse standards. Many tests have been carried out to compare breakdown voltages and discharge characteristics of natural esters and mineral oils from various suppliers [6].

AC breakdown voltage

The most common requirement that an insulating fluid must meet is the AC breakdown voltage, which is defined as the value of an applied AC voltage at which disruptive discharge begins. A variety of standard test methods are used where a small volume of oil is subjected to an almost homogenous electric field between two electrodes immersed in the insulation fluid. The voltage is increased at a controlled rate until breakdown occurs. The standard international test is that described in IEC 60165, which uses an electrode separation of 2,5 mm and a voltage increase rate of 2000 V/s. Table 1 shows a selection of results obtained from different products compared to mineral oil. Typically the breakdown voltage which is quoted is the mean of a number of tests; in the case of IEC 60156 the mean of six breakdowns on the same oil sample is taken.

The test results indicate that natural esters have similar insulating properties to mineral oil.

The AC breakdown voltage is extremely sensitive to the impurities existing in a transformer fluid, such as the presence of excessive moisture, particulates, and air or gas bubbles. Consequently the measured AC breakdown voltage of an insulating fluid mostly represents the oil quality rather than oil characteristic itself.

Breakdown voltage moisture tolerance

Moisture can have two main forms of existence in insulating liquids: dissolved or free water. Polar fluids tend to form hydrogen bonds with water molecules so that water can dissolve easily. This is why polar fluids have significantly more water tolerance. On the other hand, non-polar mineral oil and slightly polar silicone oil is particularly sensitive to the absolute moisture content. Fig. 2 shows the breakdown voltage at

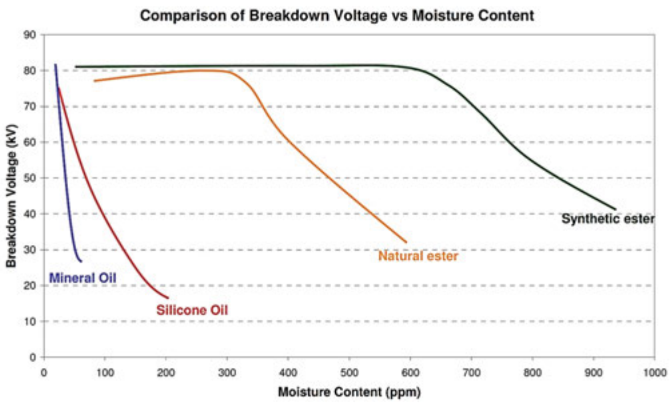

Fig. 2 :Breakdown voltage of impregnated cellulose [1].

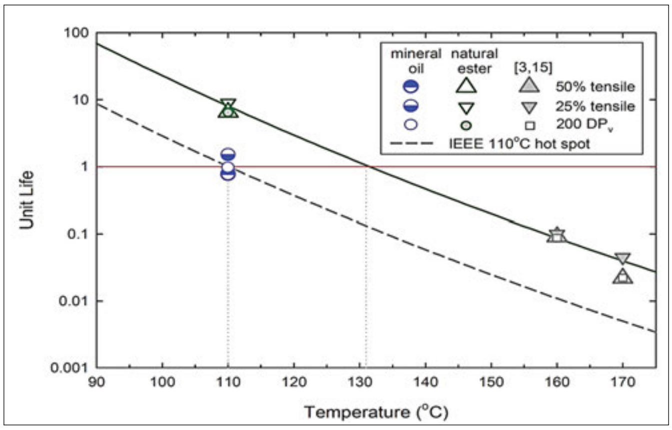

Fig. 3: Comparison of unit life of transformer for oil and natural ester [5].

Fluid type	Flash point °C	Fire point °C	Class
Mineral oil	160 – 170	170 – 180	O
Silicone fluid	>300	>350	K3
Low visocosity silicone fluid	268	312	K3
Natural ester	>300	>350	K2
Synthetic ester	>250	>300	K3

Table 2: Fire and flash points for various insulating fluids [1].

Class	Fire point	Class	Net calorific value
O	≤300°C	1	≥42 MJ/kg
K	>300°C	2	≤42 MJ/kg and ≥32 MJ/kg
L	No measurable fire point	3	<32 MJ/kg

Table 3: Fire classification of insulating fluids according to IEC 61100.

ambient temperature of synthetic ester, natural ester, silicone and mineral oil with increasing moisture levels. It clearly illustrates that even small amounts of water in mineral oil cause a rapid deterioration in breakdown voltage. In contrast, both types of esters maintain high breakdown voltages even with significantly larger amounts of dissolved moisture.

Viscosity

Viscosity of the insulating fluid affects the ability to transfer heat by conduction. Conduction cooling is the main heat removal mechanism in transformers and thus higher viscosity would be expected to result in higher hot spot temperatures within the transformer. Tests have shown that the use of vegetable oils in transformers does result in increased temperatures of between 1 and 3°C.

Pour point

The pour point is the temperature at which transformer oil will just flow under the prescribed conditions. Pour point is a useful measure of how transformer oils will perform under low temperatures, especially when it is required to cold start a transformer under very low temperature conditions. Natural esters have a higher pour point than mineral oil, typically in the range -15 to -25°C [6], but tests have shown successful cold start down to -30°C.

Flammability – flame point and flashpoint

The flammability of transformer oil is major safety concern. There are many cases of transformer explosions resulting in external fires which are difficult to extinguish, and which spread to surrounding areas as the oil leaks out. The flame-point, or fire-point, is defined as the temperature at which the fluid surface emits enough vapour to sustain a fire for five seconds in the presence of a flame, and the flash point as the temperature at which the fluid surface emits enough vapour to ignite in the presence of a flame. Comparative values for different insulating fluids are shown in Table 2. It can be seen that for natural esters both values are above 300 °C compared to the 160 to 170°C range for mineral oils.

Fire safety is a key concern of today's users of insulating liquids, especially when considering their use in areas such as in subway tunnels or aboard ships. Equally this applies where they will be used in populated areas such as near offices, shops and in the workplace.

Insurance companies are increasingly aware of the fire potential of transformer fluids, and are encouraging end-users to specify fire safe fluids, especially in areas where a fire originating from flammable transformer oil causes

- Risk to human life
- Evacuation of surrounding area
- Down-time costs
- Transformer replacement time and cost
- Costly insurance claims

The classification of insulating liquids is based upon fire-point and net calorific value according to the standard IEC 61100.

Vegetable oils are classed as low flammability fluids and fall in class K by the IEC standards. This results in less less stringent requirements for installation, and units can be installed indoors. Some of the fluids will self extinguish in a case of spillage.

Operating temperature

The operating temperature of the transformer affects the lifetime of the paper insulation, which degrades at rates depending on both the temperature and insulating fluid. Tests have shown that it is possible to operate a transformer at higher temperatures using natural esters than with mineral oil (Table 3). This gives an increase in temperature of 20°C in one case. Temperature is measured not as the average but as a "hot spot" temperature in the transformer windings. Higher operating temperature means increased loading of the transformer, an important consideration when looking at existing plant.

Degradability and stability

Natural esters are degradable and this is both an advantage and a disadvantage, as while oil spills benefit from degradability, oil must be prevented from degrading inside the transformer oils degrade in the presence of oxygen. The oxidation stability of vegetable oils for transformers is a key concern to end users.

Natural esters are the most susceptible to oxidation of alternative insulating fluids. In

	Ester linkages	Approx water saturation at 23°C (ppm)
Mineral oil	0	55
Silicone oil	0	220
Natural ester	3	1100
Synthetic ester	4	2600

Table 4: Water solubility of transformer fluids.

simple terms natural esters are susceptible to oxidation because of their chemical structure. To ensure and maintain optimum performance of natural esters, exposure to oxygen and moisture must be minimised. Thus hermetic sealing against ambient air is the best way to benefit from the characteristics investigated before [10].

Water absorption

Table 4 shows the water solubility of transformer fluids at room temperature, i.e. the total amount of moisture content which the fluid can hold without free water being deposited.

The solubility of water in all these fluids increases with temperature. The more polar esters are able to absorb more water across the temperature range.

Natural ester oils can increase the thermal stability of paper, as they remove moisture from solid insulation more effectively than mineral oil, thus allowing either higher hot spot temperatures, or increased component life. Test results show that for synthetic ester at 60°C, water content in fluid of 200 ppm would equate to a water content in the cellulose of 1,1%. At the same temperature, mineral oil with a water content of 20 ppm would lead to a water content in the cellulose of 2,6%. It is important to note that the moisture equilibrium curves are most meaningful at higher temperatures, >60°C. At lower temperatures the rate of moisture transfer between the cellulose and fluid is significantly slower and so equilibrium is rarely reached.

Environmental safety

Environmental safety is determined with two basic criteria: biodegradability and low toxicity. In general fluids which possess a rapid biodegradation rate and can demonstrate low toxicity are classified as being "environmentally friendly". These factors are important when considering the use of fluids in environmentally sensitive areas, such as water courses, to avoid contamination.

The term "biodegradability" reflects the extent which the fluid is metabolised by naturally occurring microbes in soil or water courses, in the event of a spillage or leak. Clearly it is an advantage if spilt fluids can quickly disappear naturally without the need to instigate expensive clean up measures. To be classified as readily biodegradable a substance must satisfy both of the following criteria [6]:

- 60% biodegradation must occur within 10 days of exceeding 10% degradation
- At least 60% degradation must occur by day 28 of the test

The OECD 301 series of tests for ready biodegradability has six main test methods covering all types of materials, solids and liquids, water soluble and non-water soluble. Natural esters are officially classified as being "readily biodegradable".

Corrosive sulphur

It is generally accepted that the presence of corrosive sulphur compounds and the problems they cause in transformers is inherently an issue for mineral oil. Corrosive sulphur is not an issue for fluids other than mineral oil. Synthetically made fluids such as synthetic esters and silicone fluids do not contain sulphur as they are manufactured from sulphur-free raw materials. Natural esters are produced from the seeds of crops and also do not contain corrosive sulphur. Hence these fluids will not cause corrosive sulphur problems in transformers or other equipment. Any slight trace quantities of sulphur that may be detected by sensitive analytical techniques will be chemically different from the types of sulphur compounds which react with metals. The manufacturers of vegetable oils should be able to provide evidence that their fluids are non corrosive.

Retrofilling transformers where corrosive sulphur compounds have been detected in mineral oil, but before the transformer has shown signs of copper corrosion is likely to prevent further damage. However, it should however be stressed that alternative fluids will not correct the effect of corrosion that has already occurred, nor are they able to restore transformers that have failed due to corrosive sulphur problems [1].

Advantages of use

Higher loading of existing transformers

Higher maximum operating temperature means that a transformer can be loaded at higher rating than it would be with mineral oil, while maintain its expected life. Figures in the region of 20% are quoted [5]. This means that existing transformers retro-filled with vegetable oil could be run at higher load factors, with possible extension of life, and new transformers can be designed for smaller volumes of insulating fluid. Increasing the load factor is an important factor means that upgrading or increasing capacity of existing plant can be delayed, at a much lower cost than replacement.

Reduced spread of spillage

Higher viscosity means reduced spread under spillage conditions, with obvious advantages for fire control and environmental issues

Fire safety

Vegetable oils have much higher flash and fire points than mineral oil. Replacing mineral oil will greatly enhance fire safety, especially in populated or sensitive areas. The cost of retrofilling for fire safety reasons is often less than the cost of installing or upgrading fire safety systems for insurance purposes.

Retrofilling

The term retrofilling refers to the process of removing the insulating liquid of an existing working transformer and replacing it with a new liquid. Usually the fluid being replaced is mineral oil in distribution class transformers. Retro-filling of power transformers requires qualified engineering assessment as there would probably need to be design considerations to accommodate the differences between mineral oil and vegetable oil. Retro-filling is not possible with transformers fitted with breathers.

When changing fluids it is necessary to check whether the new fluid is compatible with the other materials in the transformer e.g. gaskets, seals, paints, etc. This should be done by consulting the fluid manufacturer or by using appropriate data sheets. The actual procedure to be followed must be done in accordance with the recommendations of the transformer manufacturer and fluid supplier. The procedure needs to be carried out by a qualified engineer.

Case studies and applications

Vegetable-oil natural esters have been used extensively in distribution transformers, and there are currently over 300 000 distribution transformers using vegetable oil in service. In addition there are in the region of 200 power transformers up to 200 MVA and 242 kV being energised and operating globally [1].

420 kV vegetable oil filled transformer

Siemens has produced the world's first large-scale transformer that uses vegetable oil. In the future, the device will link the 380 kV ultra-high voltage level with the 110 kV grid in the Bruchsal-Kändelweg substation plant near Karlsruhe, Germany. Transformers are usually cooled and insulated with mineral or silicone oil. By comparison, vegetable oils are environmentally friendlier and less flammable. Until now, Siemens has used vegetable oil insulation in power transformers with voltages of up to 123 kV. The new transformer is designed for 420 kV. This marks the first time that vegetable oil is used with this voltage category instead of mineral oil for insulation and cooling.

The new power transformer is the world's first transformer at the 420 kV extra-high voltage level for which no water hazard classification must be issued. As a result, this transformer can be installed and operated in water conservation areas or in zones subject to stringent environmental protection restrictions.

Rapeseed, soy or sunflower oils, on the other hand, are biodegradable and have a much higher flashpoint. A vegetable oil transformer can therefore be operated without additional protective equipment such as collecting tanks, even in zones with strict environmental requirements. With their comparatively better fire safety class, vegetable oil transformers can even be used in densely populated residential areas.

The properties of this vegetable oil are not only beneficial to the environment, but also offer the customer cost advantages over transformers cooled with conventional mineral oil. The bio-degradability of the insulating oil means that additional collecting vessels and separation systems are no longer required at the installation location, resulting in cost savings for these items. The lower flammability of this insulating oil also provides the transformer with a higher fire protection classification. This means that the fire protection system can be optimised accordingly and that the transformer can also be operated favourably in densely populated residential areas.

The new transformer weighs just under 340 t and contains 100 t of insulating oil. The oil comes exclusively from renewable vegetable resources. As a result, the device is the world's first power transformer on the 420 kV ultra-high voltage level that does not require proof of its water hazard classification [11].

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