Insulating fluids for power transformers

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Introduction

The insulating fluid is one of the essential components to ensure proper operation of the transformers. It must ensure a good insulation of various parts of the equipment while ensuring its cooling. It is needless to say that the insulation and cooling must be provided during the entire life of the transformer, despite the aging of the fluid which can be more or less severe depending on the operating conditions of the transformer (temperature, humidity, oxidation by contact with the ambient air, etc.).

In recent years, other important requirements have been identified, namely: environmental protection, safety of people, fire safety, etc. Naturally, the economic aspect remains an essential parameter and that is the reason why the insulating fluids for transformers must be subjected to maintenance actions to ensure a sufficient lifetime.

Since several years, developments are in progress in order to permit a replacement of mineral oils. A CIGRE survey performed worldwide in 2000 showed that the replacement of mineral oil was of great importance and should be considered as a high priority by a majority of transformer users.

Recently, the availability of synthetic ester as well as natural ester fluid, or so-called 'vegetable ester fluid' can be seen as a solution to solve this problem. The use of vegetable fluids took place mainly in the USA for distribution transformers. In Europe, synthetic esters are used since almost 20 years in area with a need to protect water and more recently also in the domain of fire protection issues. Synthetic esters are also widely used since years for their ability to operate at higher temperatures while providing enhanced safety. There are also few cases where vegetable fluid is used in large transformers, but this remains marginal in comparison with the volume of mineral oil used in the world. Finally, it can be said that a huge amount of ester fluid is used to fill liquid-immersed distribution transformers.

Fluid type and history

Mineral oils are standardized according to IEC 60296 [1][1]. This standard has been modified recently to consider the problem of corrosive oils. It is important to note that the physical properties of the oils according to this standard apply only to the new oils before topping up of transformers. After filling, the required properties are defined in the standard IEC 60422 [2].

Mineral oils are divided into two types, namely: naphthenic and paraffinic[2]. But it shall be known that all mineral oils contain a certain percentage of paraffin's and naphthenic molecules. Depending on the concentration of these basic elements, the oil will be declared as naphthenic or paraffinic types. It is very important to note that paraffinic oils offer a poor flow at low temperature (generally below -25 °C) requiring a pour point depressant additive to improve the oil flow up to -45 / -60 °C. In case of

[1] IEEE D3487-09 – 'Standard Specification for Mineral Insulating Oil Used in Electrical Apparatus' and local standards are covering the same domains

[2] New developed iso-paraffin based transformer fluids offer improved performance characteristics such as low temperature properties (pour point -60 °C) and biodegradability compared with common naphthenic oils

topping up or refilling, it is important to note that according to IEC 60422 chap 6.12 [2], naphthenic and paraffinic oils shall be mixed with cautions. Compatibility tests are recommended when the mixing rate is above 5 %.

The industry of insulating oils has developed processes to provide oils able to absorb the gases produced in service (such oils are named 'gas absorbing'). These oils have a better behavior in presence of impulse stresses, such as lightning, and have been adopted by certain national standards. The other oils are classified under the name of 'gas evolving'. Analysis of dissolved gas to check the operating conditions of transformers seems not to be deeply influenced by the use of one or other of these types of insulating oils.

To provide a superior oxidative withstand (reduced ageing), it is usual to add an inhibitor type DPBC[3] at a rate of 0.3 to 0.4%. This inhibitor against aging is consumed in service and requires continuous monitoring throughout the life of the transformer. This inhibitor can also be added later, for example during an oil treatment, especially in case of regeneration treatments with fuller earth[4] which have the particularity to remove all inhibitors (natural, DPBC) contained in oil.

The life expectancy of the oils can be easily extended by the use of such inhibitors. According IEC 60296, a test duration of 500 h is requested for inhibited oils and 164 h for non-inhibited oils. Therefore, when choosing an oil, it is very important to refer to the data-sheets of the various products where the results of the ageing test are reported. Aging is characterized by an increase in acidity and power factor (tan delta), changes in color (darkening) and formation of sludge. It is useful to say that, in practice, the breakdown voltage of an insulating oil is practically not significantly influenced by his ageing.

Since 2008, IEC 62535 [3] has imposed changes in the manufacture of mineral oils. This standard was developed to identify the risks of failures of power transformers due to corrosive sulfur. CIGRE SC A2 made a significant development work in that domain as shown in a CIGRE Technical Brochure [4]. The inhibited oils, already containing additives against oxidation, were less affected by this standard. In contrary, for non-inhibited oils, the changes in the process of raffination do not allow practically the production of oils with sufficient performance for applications in high loaded transformers.

The development of synthetic insulating fluids has started more than 50 years ago with the use of polychlorinated (PCB) fluids. Further developments were done in the field of silicone fluids according to IEC 60836 [5] and synthetic ester according to IEC 61099 [6].

In some parts of the world, such ester fluids replaced silicone fluids in reason of their excellent fire performances and their good biodegradability in water.

Since approximately 15 years, natural ester fluids (or vegetable fluid) have been developed in the USA. Standards within IEC [7] and IEEE [8] are available. Currently there is a great development in this area with various formulations (type of base oil, addition of additives, biodegradability, fire safety objectives, etc.).

Physical properties, aging, biodegradability

[3] DBPC – 2,6-di-tert-butyl-para-cresol
[4] See also IEC 60422 – chap 12.3 'Reclaiming'

Table 1 (enclosure A) shows the main properties of various fluids used in all types of transformers as: biodegradability, ageing performance, fire behavior. CIGRE published interesting reports about the new insulating fluids [9] [10].

In table 1, the oxidation of the fluids is measured through the RBOT test at elevated temperature in the presence of pressurized oxygen and catalysts. High oxidation may conduct to a gel formation.

Figure 1 shows the good biodegradability of ester based insulating fluids.

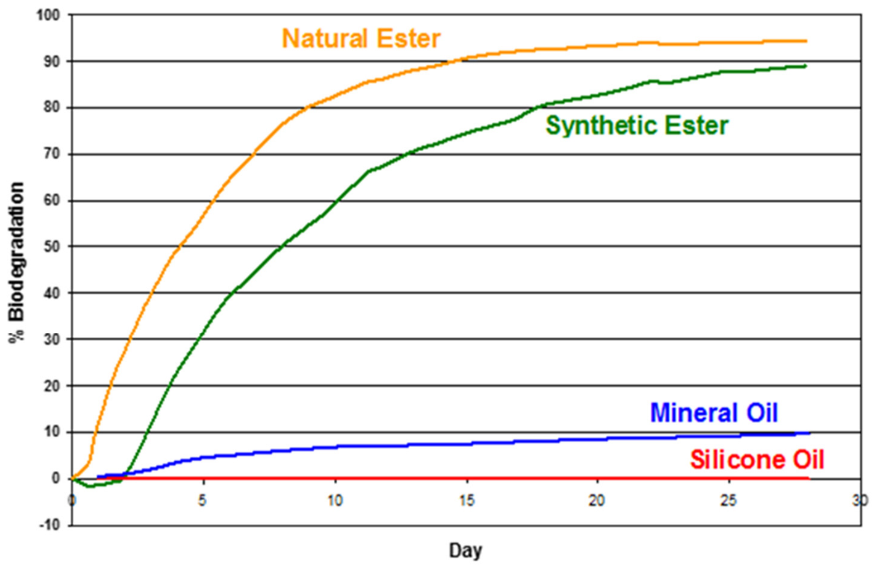

Fig. 1 : Biodegradability of various insulating fluids

In contact with humidity, all these fluids have a similar breakdown voltage when expressed in function of the relative humidity (see Fig. 2)[5].

[5] Typical water content is quite different between mineral oil (20 - 30 ppm) and ester fluids (> 200 ppm)

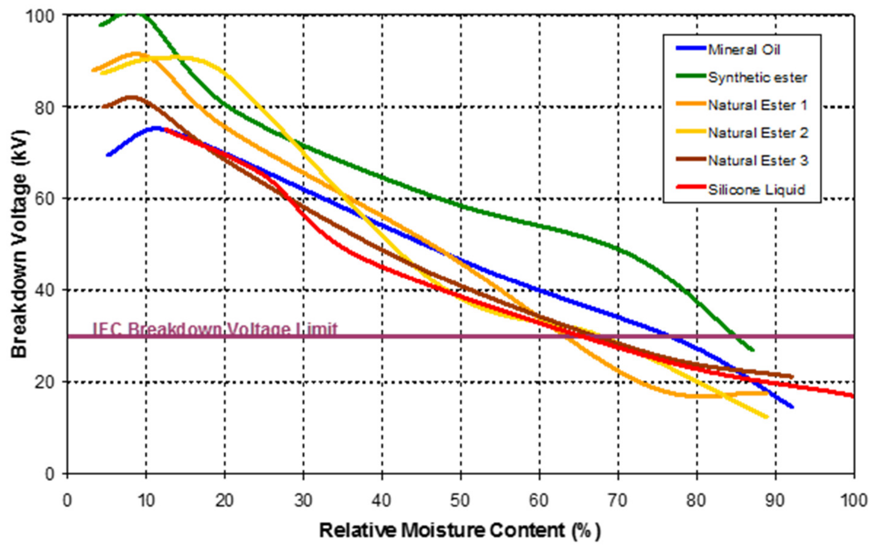

Fig. 2: Breakdown voltage related to relative humidity

Fire Safety

As mentioned in the introduction, insulating fluids are seen as a fire hazard. IEC 61039 [11] has established a classification based on fire point, net caloric value, biodegradability and others (see table 2 and 3).

Tab. 2: Fire classification acc. IEC 61039

Class	Fire point	Class	Net calorific value
O	≤ 300°C	1	≥ 42 MJ/kg
K	> 300°C	2	≤ 42 MJ/kg et ≥ 32 MJ/kg
L	Not measurable	3	< 32 MJ/kg

Tab. 3: Performance of various fluids regarding fire risk

Fluid Type	Flash Point °C	Fire point °C	Class
Mineral Oil	160 -170	170 -180	O1
Natural Ester	>300	>350	K2
Synthetic Ester	>250	>300	K3
Silicone Fluid	>300	>350	K3

Replacement of a mineral oil by an ester, miscibility of fluid

In USA, vegetable fluids are used to replace (refilling) mineral oils in the domain of distribution transformers (< 60 kV). In general, and if the fire point must be located above 300 °C, it is needed to avoid a large contamination with a mineral oil (max 3-5%). All of these fluids are miscible. However a mixture of fluid will result that the best fluid will eventually see its properties slightly degraded.

Natural or synthetic ester fluid for large transformers

Some large transformers were filled in several countries by different manufacturers. Siemens (former ELIN) has filled few transformers 240 kV, 130 MVA with Midel 7131 for the European utility Vattenfal in 2004. ABB has filled a few units 130 kV, 25 MVA with BIOTEMP for users in Brazil in 2007 (Fig. 3) [12] and in Egypt in 2010. Alstom (former AREVA) has filled several transformers 130 kV, 90 MVA and reactors with a voltage up to 220 kV with FR3. Recently, Siemens published a report about the use the natural oil FR3 in a large transformers rated 420 kV. The use of an ester fluid to fill transformers with an operating voltage > 123 kV needs some cautions as the resistance to impulse voltages for large distances is significantly different than for mineral oil. In the case of a natural fluid, it is necessary to have a separation (hermetic in conservator, hermetic tank, etc.) between fluid and atmosphere in order to avoid rapid oxidation of the fluid. In addition, consider that below a fluid temperature of -10 ° C, the viscosity of the fluid will be too high for a normal use of the tap changer. A specific procedure for switching-on at low temperature must be observed.

Courtesy ABB

Fig. 3: 25 MVA, 138 kV filled with natural ester Biotemp

Synthetic esters can be considered for applications where insulating materials classified in a temperature class higher than class A is required. The resistance to the heat for natural ester can be improved by using inhibitor against oxidation like in the domain of the mineral oils (enclosure A, Table 1).

Periodic inspections

As for mineral oils, periodic controls are recommended. In the case of a synthetic ester, IEC 61203 gives guidance. For natural ester, an IEC standard is available only for new fluid. IEEE has standards for new and used fluid. These standards are being revised to align with the work done within IEC. Rules for DGA interpretation of ester fluids have been proposed by Duval and CIGRE [13].

Aging of impregnated cellulose-based insulation with esters

Cellulose-based insulation impregnated with ester fluids shows a clear reduction (factor 1.5-2) of the aging rate compared to similar insulation impregnated with mineral oil [14] [15]. This is due to the fact that ester fluid have a higher capability to absorb moisture thus reducing the moisture in equilibrium in the solid insulation. This allows an overload capacity with a temperature increase of 6 - 10 ° C compared to a mineral oil at a given ageing rate.

Conclusions

Since 2008, IEC Standard 62535 has imposed important changes in the manufacture of mineral oils. The inhibited oils, already containing additives against oxidation, were little affected by this standard. On the other hand, for non-inhibited oils, changes are important as there are practically no more such oils on the markets with sufficient performances to be used in power transformer applications.

Development of insulating fluids of ester type allows an alternative to the use of mineral oils. In the domain of distribution transformers, the experience shows that the performances of vegetable fluids are sufficient. For power transformers, the experience with both types of ester is still limited, but is nevertheless positive so far. The good fire behavior and the positive environmental performances have been recognized. The recent standardization of natural ester in IEC will probably accelerate the implementation of such fluids.

Economically, mineral oils are less expensive as all ester fluids, but the costs for elimination as wastes, the better fire safety and the better biodegradability of the ester fluids may influence positively the decision to use synthetic or natural esters in the future.

References

[1] IEC 60296 ed4.0 -2012 - Fluids for electrotechnical applications – Unused mineral insulating oils for transformers and switchgear

[2] IEC 60422 ed4.0 -2013 - Mineral insulating oils in electrical equipment - Supervision and maintenance guidance

[3] IEC 62535 ed1.0 -2008 - Insulating liquids - Test method for detection of potentially corrosive sulphur in used and unused insulating oil

[4] CIGRE Brochure N° 378, April 2009 – Copper sulphide in transformer insulation

[5] IEC 60836 ed2.0 -2005 - Specifications for unused silicone insulating liquids for electrotechnical purposes

[6] IEC 61099 ed 2.0 -2010 - Insulating liquids - Specifications for unused synthetic organic esters for electrical purposes

[7] IEC 62770 ed1.0 - 2013 - Fluids for electrotechnical applications - Unused natural esters for transformers and similar electrical equipment

[8] IEEE Guide C57.147 – 2008 - IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers

[9] CIGRE Brochure N° 436, October 2010 – Experiences in service with new insulating liquids

[10] CIGRE Brochure N° 445, February 2011 - Guide for Transformer Maintenance

[11] IEC 61039 ed2.0 – 2008 - Classification of insulating liquids

[12] New Insulating fluids for transformers based on biodegradable high oleic vegetable oil, P. Boss et al., Matpost Conf. 2007, Lyon/France

[13] CIGRE Brochure N° 443, December 2010 – DGA in non-mineral oils and tap-changers and improved DGA diagnosis criteria

[14] Natural ester dielectric fluid development, C.P. Mc Shane et al. IEEE/PES Conf. , Dallas / USA, 2006

[15] Thermal evaluation of cellulosic board in natural ester fluid for hybrid insulation systems, R. Asano et al., 78th Annual Doble Conf., Boston / USA, 2011

Enclosure A

Tab. 1: Typical properties of various insulating fluids

	Units	Mineral Oil 10GBN (unhibited)	Mineral Oil Luminol TRi (inhibited)	Synthetic Ester Midel 7131	Natural Ester Biotemp	Natural Ester FR3
Kinematic Viscosity at 40 °C	mm^2/s	9	9.2	30	42	33
Kinematic Viscosity at 100 °C	mm^2/s	2.5	2.8	5.25	9	8
Density at 20 °C	kg/l	0.88	0.835[6]	0.97	0.91	0.92
Pour point	°C	-25 / -50	-60	-50	-20	-20
Specific heat at 25 °C	J/kg K	1860	-	1880	1963	1880
Thermal conductivity at 25 °C	W/m K	0.126	-	0.144	0.170	0.170
Expansion coefficient	1/°C	0.00075	-	0.00075	0.00068	0.00074
Breakdown voltage [7]	kV	> 70	> 65[8]	> 75	>75	> 75
Rel. permittivity at 20 °C [9]	-	2.2	-	3.2	3.2	3.2
Power factor at 50 Hz, 90 °C [10]	-	< 0.001	0.001[11]	< 0.006	< 0.020	< 0.020
RBOT Aging Test [12]	minutes	300	600	420	197	17
Biodegradability at 28 days [13]	%	< 10	-	89	95	95

[6] At 15 °C
[7] IEC 60156 – sphere electrode – 2,5 mm gap
[8] ASTM D1816 - 60 Hz - VDE electrode – 2 mm gap
[9] IEC 60247
[10] IEC 60247
[11] ASTM D924 – 60 Hz - 100 °C
[12] Rotating bomb test acc. ASTM D2112
[13] OECD 301-1992 D or F