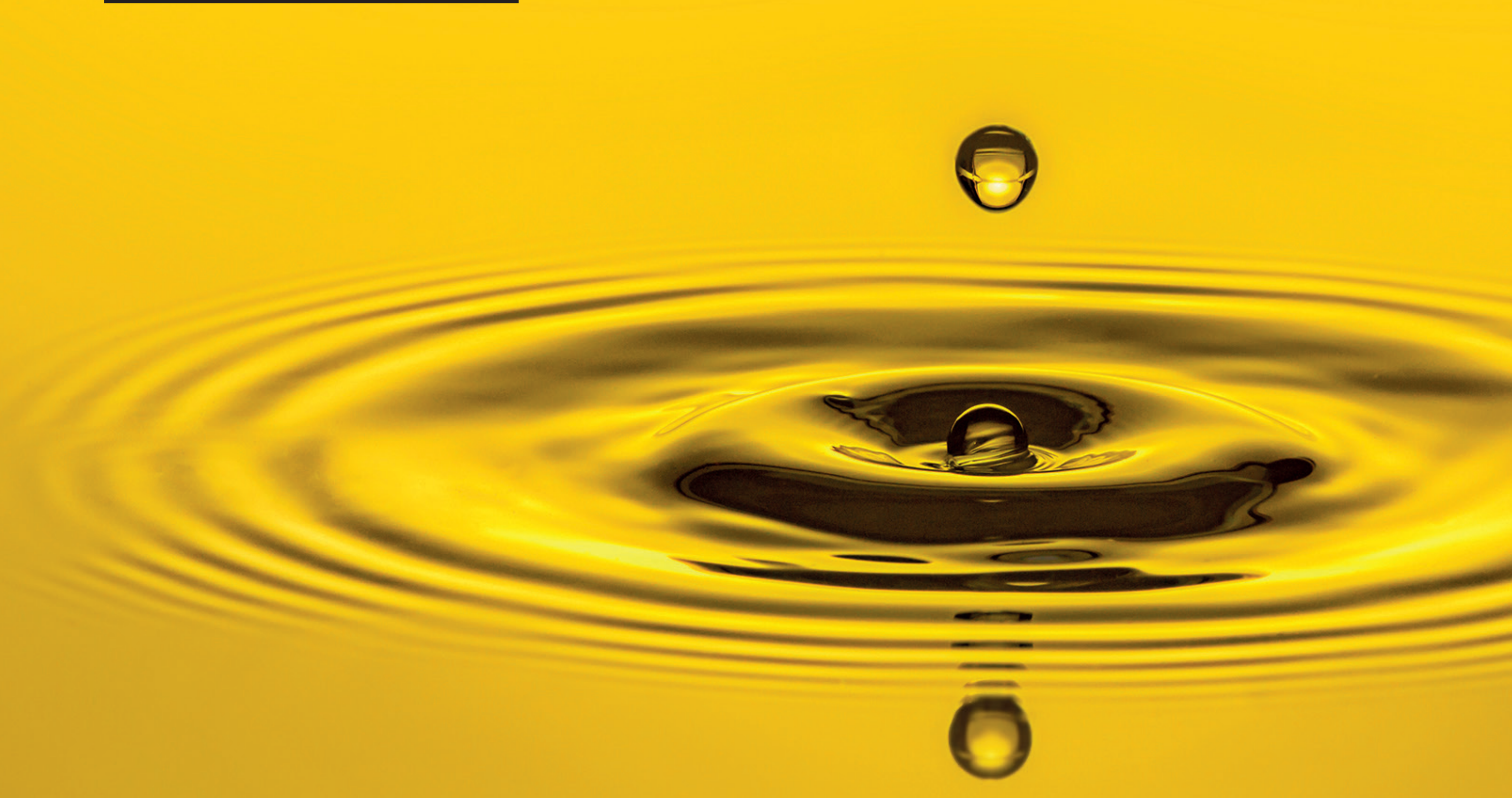


Tap-changer know-how

Insulating liquids – Part II: Non-mineral insulating liquids

1. General

In the previous edition of Transformers Magazine, the typical properties of mineral insulating oils were illustrated. In this issue, the column will discuss alternative insulating liquids and their potential for being used with tap-changers.

A short update on the Recycled mineral oils chapter (see *Insulating liquids – Part I*, section 2.4., Transformers Magazine, Vol 3, Issue 2, April 2016) seems to be adequate here. The IEC Standard Management Board has given instruction that recycled mineral oils shall be integrated into IEC 60296 (which, up to now, was dedicated exclusively to unused mineral oils). To execute this, IEC Working Group TC10/MT38 has been established, which shall immediately revise IEC 60296 and give proper advice on how to recognize and classify recycled mineral oils based on their performance only and not on their provenance. 28 participants have been nominated for the working group by the IEC National Committees, producers of recycled oils among them.

Over the past 20 years, extensive research on various alternative liquids has been performed with the objective of qualifying selected tap-changer models to be used with these liquids. The liquids and eligible tap-changer models have been chosen according to their market share. Really laborious is the evaluation of the arc-quenching behavior, which includes the determination of arcing times at high and low oil temperatures, and the amount and composition of deterioration products, such as carbon (soot), acids and gases. Gases can be toxic, and acids can attack solid insulating materials [1]. For this reason, research work has been focused on vacuum type on-load tap-changer (OLTC) models, so that the alternative liquid can be used both inside the transformer tank and tap-changer oil compartment. Non-vacuum type models (oil switching OLTCs) should only be used with alternative liquids in the transformer tank / tap selector compartment, while the diverter switch compartment is filled with mineral oil. De-energized tap-changers (DETCs) may also be used with alternative liquids.

2. Non-mineral insulating liquids

Certain non-mineral liquids have been identified as suitable substitutes for mineral insulating oil, providing benefits for special applications. High-temperature or downtown substation transformers need liquids with low flammability (high flash point); transformers in environmentally sensitive areas should be filled with fully biodegradable liquids, and for applications like traction transformers the liquid should be chemically inert.

Eligible liquids show significant differences to mineral insulating oils concerning their composition, properties and performance; therefore, they don't comply with the mineral oil standards discussed in *Insulating liquids - Part I*. If such liquids shall be used in tap-changers, each liquid has to be tested and evaluated properly.

One apparent difference, for example, is the higher viscosity of some alternative liquids (see Fig. 1). Viscosity affects the timing of the tap-changer switching operation at (very) low oil temperatures, and

Over the past 15 years, extensive research on various alternative liquids has been performed with the objective of qualifying selected tap-changer models to be used with these liquids

influences the oil flow which determines the cooling of transformer windings, terminals, contacts and transition resistors. Furthermore, liquid viscosity also influences the arc-quenching behavior. Even for vacuum type OLTCs, low-energy arcs or sparks are produced at the change-over selector which reverses the regulating winding or switches the coarse tap winding in and out. Capacitive currents of up to 500 mA have to be broken, and recovery voltages up to 40 kV on the opening contacts must be controlled. For liquids showing a higher viscosity than mineral oil, the switching capacity of the change-over selector is reduced, because arcing-times are longer than in mineral oil. This is probably due to the effect that cold liquid is not delivered fast enough into the hot arcing path to cool and quench the switching arc within the admissible time frame.

2.1. Ester liquids

Ester liquids can be divided in two families: synthetic and natural esters. Synthetic esters (e.g. *MIDEL 7131*, M&I, U.K.) have been invented in the late '70s as an environmental friendly alternative to the non-flammable, but highly questionable polychlorinated biphenyls (PCBs). Synthetically composed from alcohols and saturated fatty acids, all molecules are nearly same size, which gives them well-defined properties. They show good oxidation stability, but are rather expensive.

Natural esters, however, are produced from seed oils, such as soya (e.g. *ENVIROTEMP FR3* by Cargill, U.S.), rapeseed (e.g. *SunOhm Eco* by Kanden Eng., Japan, or *MIDEL eN* by M&I, U.K.), sunflower (*BIOTEMP* by ABB, withdrawn from market) and others. They are a blend of unsaturated and saturated fatty acids in order to achieve a sensible balance between oxidation stability and low-temperature behavior. One exotic variant of natural esters is palm oil (e.g. *Pastell Neo*, Japan): despite exclusive use of saturated

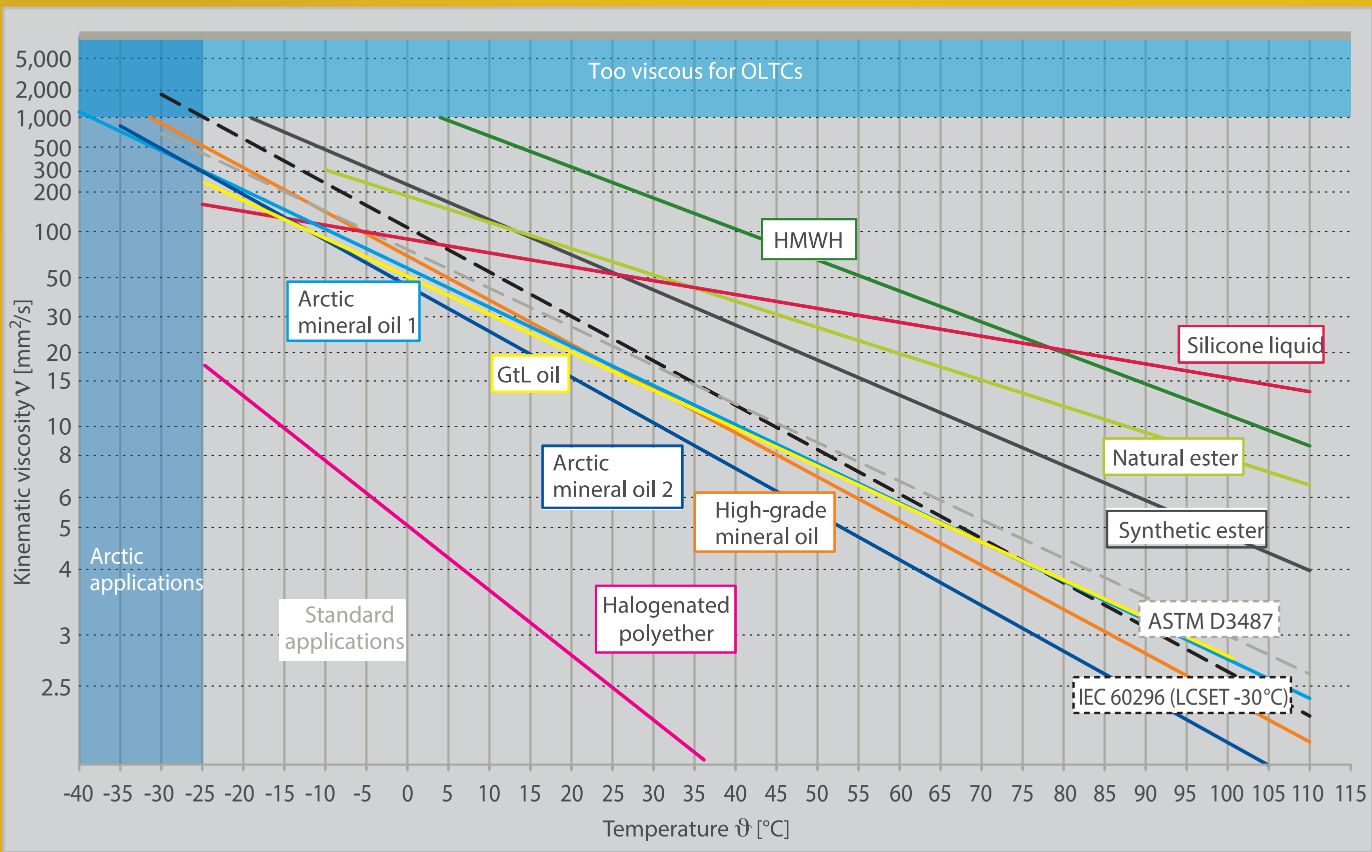


Figure 1. Viscosity of different insulating liquids on a ln(ln(ν)) scale, and temperature limits

High-temperature or downtown substation transformers need liquids with low flammability; transformers in environmentally sensitive areas should be filled with fully biodegradable liquids, etc.

fatty acids, it has a low pour point of less than -30 °C, good oxidation stability, but a flash point only slightly higher than mineral oil. This palm oil cannot be regarded as a less-flammable liquid. *MIDEL eN* also shows a pour point lower than -30 °C but is less-flammable at the same time. Here, pour-point depressant additives help to improve the liquid flow at low oil temperatures.

The higher the percentage of unsaturated fatty acids, the more the liquid tends to polymerize under permanent air exposure, leading to an increase in viscosity and finally to a jelly-like appearance. As this is not acceptable, it is highly recommended to use natural esters only in sealed applications. Free-breathing application with natural esters may work for distribution transformers with limited breathing (there is some long-term experience in the U.S.), but not for highly optimized power transformers and OLTCs.

Both synthetic and natural ester liquids are biodegradable, show very low oral and aquatic toxicity, and are classified as "not water endangering". This allows usage in installations in sensitive environments such as water catchment areas, off-shore wind parks or downtown substations. For the latter, a low fire hazard is essential. Ester liquids show a much lower fire hazard than mineral oils, not only through the significantly higher flash point, but also through the lower calorific value (Table 1). This means that the energy produced in a fire is significantly lower than for mineral oils. By using a K-class less-flammable liquid, clearances and fire protection measures can be reduced for both indoor and outdoor transformers [2].

Ester liquids can hold huge amounts of moisture, compared to mineral oil. While a typical mineral oil gets saturated with 50-60 ppm water at 20 °C, natural ester can hold up to 1000 ppm and synthetic ester approximately 2200 ppm of water at 20 °C [3], [4]. This hygroscopic behavior provokes two effects:

- the water content in the cellulose insulation of the transformer is lower than with mineral oil; and
- the dielectric strength of the liquid stays high even with hundreds of ppm of water (high moisture tolerance).

The reason why ester liquids can hold so much water is simply due to their polar structure: water (which is also polar) can easily attach to the acid groups of the ester molecules via hydrogen bonds; see Fig. 2.

The permittivity of ester liquids is roughly 1.5 times higher than that of mineral oils. This leads to more uniform field distributions in combination with solid insulation materials. On first glance, this seems to be an advantage, but it also means that the absolute field strength inside the solids is higher than with mineral oils. Therefore, inadequate impregnation or little cavities inside the solids have a more distinct detrimental impact on the dielectric strength of the solid insulating material.

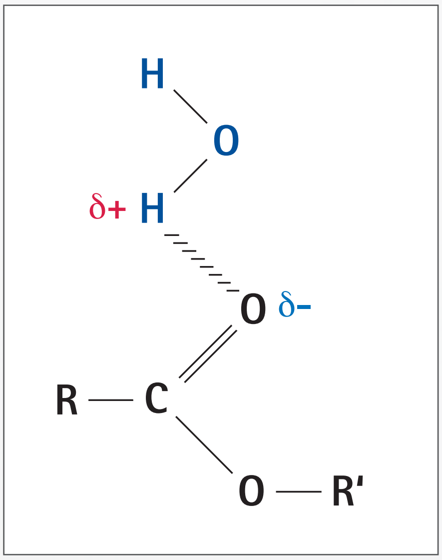


Figure 2. Polar molecules and hydrogen bonds are responsible for high water absorption capability of ester liquids

Another difference in electrical properties of ester liquids is their different streamer propagation behavior, which is visible on inhomogeneous electrode configurations and long insulating distances. Numerous investigations (e.g. [5], [6]) have revealed that fast streamers in ester liquids develop at lower voltages and have a longer stopping length than in mineral oil. This means that, for tap selectors showing moderately inhomogeneous fields and insulating distances of typically 5-10 cm, lower withstand voltages are achieved. This is true for lightning impulse (LI) as well as for operating frequency (AC) voltage waveforms, and has been verified by numerous full-size tests on different tap selector arrangements. As a consequence, a bigger tap selector size may be appropriate or, as a workaround, varistors can be added along the regulating winding to limit the AC and LI voltages which are applied during

Table 1. Classification of insulating liquids acc. to IEC61039 (Extract)

Fire point (ISO 2592)	
Class O	≤ 300 °C
Class K	> 300 °C
Class L	Not quantifiable
Synthetic ester Natural ester	Class K

Calorific value (ASTM D240)	
Category 1	≥ 42 MJ/kg
Category 2	< 42 MJ/kg and ≥ 32 MJ/kg
Category 3	< 32 MJ/kg
Synthetic ester	Category 3
Natural ester	Category 2

> **Both synthetic and natural ester liquids are biodegradable, show very low oral and aquatic toxicity, and are classified as “not water endangering”**

transformer testing or which can occur as overvoltages in service.

On the other hand, homogeneous field configurations do not show this phenomenon, probably because the starting point of a streamer discharge which leads to a flashover is not properly defined – it is statistically distributed. So, for typical phase-to-phase or phase-to-ground insulation arrangements with optimized homogeneous field geometry, the full withstand voltages as for mineral oil can be applied.

It is highly likely that the streamer breakdown behavior also depends on the absolute level of the applied voltage. It has been found that OLTCs for distribution transformers do not require the said reduction of withstand voltages in ester liquids. With the grade of field inhomogeneity being comparable to bigger-sized tap selectors, the comparatively low LI and AC test voltage levels applied for U_m 36 kV or lower are probably not high enough to reveal the differences between ester liquids and mineral oil. Further investigation on this seems to be necessary.

For short distances (like in the IEC 60156 or ASTM D877 / D1816 standards – Determination of the breakdown voltage at power frequency), the differences in stopping length are not influential because the insulating distance is just too short. This is why ester liquids achieve the same (or higher) breakdown voltages (BDV) than mineral oil. *So, by considering the BDV only, one cannot judge the dielectric quality of an ester liquid*. Because every brand behaves differently, it would be good if one had an easy method to quantify the streamer breakdown behavior of an unknown ester liquid in comparison to mineral oil under realistic dielectric field conditions, without the need of running full-size tests on tap-changers.

The lubricating behavior has been evaluated as well, as it is an extremely important parameter for tap-changers. Ester liquids show a comparable (or slightly better) lubricating behavior than mineral oil, and so ensure low mechanical wear and the same mechanical endurance as for mineral oils for all mechanically operating parts.

All ester liquids contain acids, which may attack solid non-metal materials, such as nitrile rubber gaskets, plastics or paints. Natural esters are more gentle to these materials than synthetic esters. It has been observed that nitrile rubber gaskets get brittle in synthetic ester but swell in natural ester, with the grade of degeneration depending on the individual rubber composition. Sophisticated thermoplasts or thermoset materials, as commonly used in modern tap-changers, may lose some percentage of their mechanical strength when stored in ester liquids. This must be considered in the design process.

On the other hand, at least natural esters show an excellent compatibility with cellulose (Kraft paper): cellulose ageing is 2.5 times slower than in mineral oil; it seems as if the ester “protects” the cellulose from ageing [7].

2.2. Silicones

Silicone liquids consist of chains of silicone oxide, which have been saturated by methyl groups (siloxane). A huge range of products with different viscosities is available; for electrical purposes, viscosities of 20 mm^2/s and 50 mm^2/s (at 25 °C) are used. Silicone liquids are usually used in small high-temperature transformers (e.g. traction transformers) or voltage transformers, but very seldom in power transformers. They have an extreme longevity, behave inert, but are not easily biodegradable.

Already at moderate field stress, as it can occur on tap-changer electrode configurations, silicone liquids produce clusters (tufts) of semi-solid silicone oxide (Fig. 3).

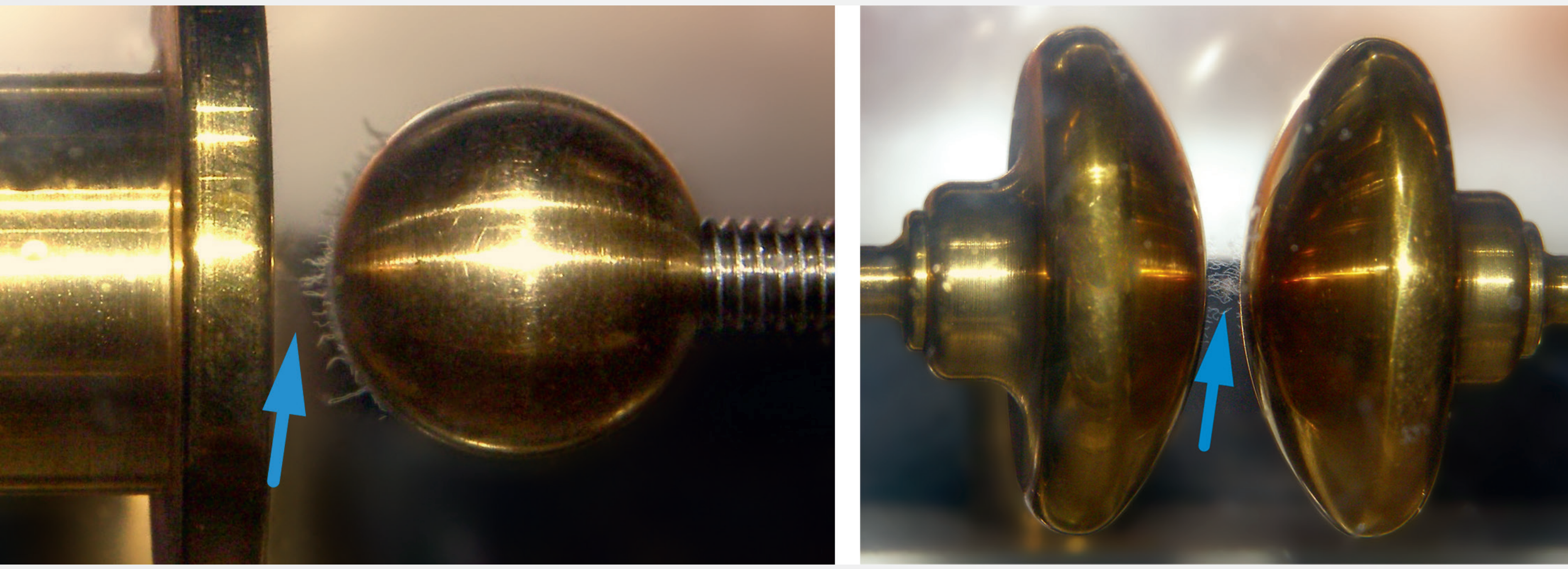


Figure 3. Semi-solid tufts of silicone oxide; left: after 3 weeks at 20 °C, 2 kV/mm; right: after 6 hrs at 50 °C, 5 kV/mm

Drawbacks of silicone liquids in combination with tap-changers is the affinity to build up jelly bridges between electrodes and their insufficient lubrication behavior

In moving oil, these tufts may be washed off the electrode, dissolve completely in the liquid or attach again to other uncoated electrodes as a thread, with unknown long-term effect on the dielectric strength of the insulating gap. This affinity to build up jelly bridges between electrodes is also the reason why the BDV of silicone liquids is noticeably lower than that of mineral oils or ester liquids. It also hampers their use with higher system voltages (e.g. U_m >72.5 kV).

Another drawback of silicone liquids in combination with tap-changers is their insufficient lubrication behavior. Tests have revealed that the mechanical wear on sliding friction arrangements, which are common for tap-changers, is multiple times higher than in mineral oil. This leads to a significantly reduced lifetime of mechanically operated parts. It may be acceptable for DETCs which are seldom operated, but not for OLTCs. To overcome this deficit, a trial has been set up in which 10 % *MIDEL 7131* was added to *KF-96AE*, a 20 mm²/s silicone liquid from ShinEtsu Chemicals (Japan). This in fact improved the lubricating capability significantly, but resulted in unwanted side effects: the switching arcs of the change-over selector (low energy arcs) caused some deterioration of both ester and silicone liquid, which ended in an awkward mixture of black soot deposits (produced by *MIDEL 7131*) and said jelly threads of silicone oxides. This mixture was highly conductive and caused unpredictable dielectric breakdowns. So, the message is clear: *The mixing of a silicone liquid with an ester liquid is definitely not recommendable if there is arcing!*

Overall, silicone liquids offer only a very limited applicability for on-load tap-changers. They may be used with DETCs if field strength is kept low so that a formation of semi-solid tufts can be avoided and if the DETC is not operated excessively. Up to 50,000 operations over the whole lifetime of the transformer is acceptable. This is also true for the change-over selector of the VACUTAP® VV, which can be operated in silicone liquid without restrictions. This has been verified by tests. Wherever possible, bare electrodes (e.g. terminals, shielding rings) should be coated or paper-wrapped to minimize the detrimental effect of said tufts. In any case, the OLTC oil compartment has to be filled with another approved liquid (mineral oil, ester liquid or HMWH).

2.3. High molecular weight hydrocarbons

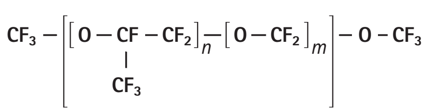
High Molecular Weight Hydrocarbons (HMWHs, also called LFH, less-flammable hydrocarbons) were invented in the 1970s as the first substitute to PCBs. The major brand was *R-TEMP Fluid* (by Cooper Industries, USA), which was manufactured until 2005. Former Cooper scientist David Sundin (DSI) issued an improved LFH called *BETA-Fluid*, which is still available and is mainly used for distribution transformers in the U.S. In Korea, a local comparable product called *MICTRANS-G* has been used for less-flammable regulated power transformers in underground downtown substations.

HMWHs are refined from paraffinic petroleum resources. Their long saturated hydrocarbon chains care for low flammability, but are also responsible for a much higher viscosity, which limits their use in cold environments. Principally, these

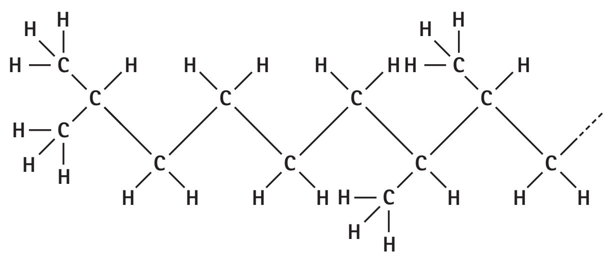
Table 2. Possible combinations of MR tap-changers with alternative liquids

OLTC type	HMWH	Synthetic ester	Natural ester	Silicone oil
VACUTAP® VV	✓	✓	✓	✓ 2) Approved non-silicone liquid in OLTC oil compartment.
VACUTAP® VM (except VM 300)	–	✓	✓	–
VACUTAP® VRC/VRE VACUTAP® VRD/VRF 1)	✓	✓	✓	–
VACUTAP RMV-II	✓	✓	✓	–
VACUTAP® iTAP, ECOTAP®	–	✓	✓	–
OILTAP® M/RM Mineral oil inside OLTC oil compartment	✓	✓	✓	–
OILTAP® V Mineral oil inside OLTC oil compartment	✓	✓	✓	✓ 2)
DEETAP® DU	✓ 2)	✓ 2)	✓ 2)	✓ 2)

✓: Approved – : Not approved 1) On request 2) Special case; please consult MR for individual approval



Halogenated polyether (perfluorinated polyether)



HMWH (high molecular weight hydrocarbon) liquids work well in all types of tap-changers, because their properties (except viscosity) are similar to "classic" mineral insulating oils. The high viscosity causes longer arcing times which lead to significantly reduced switching capacities of the change-over selector. Because ester liquids can fully replace HMWHs, an oncoming fading out of such liquids can be predicted.

Extensive tests on different tap-changer types and model setups have been performed with various HMWHs, natural and synthetic esters and silicone oils, resulting in possible combinations of MR tap-changers with alternative liquids

2.4. Halogenated polyether

Halogenated polyethers (e.g. *GALDEN*, by Solvay, France) are a liquid family mainly used as a cooling agent for heat-exchangers. They are non-flammable, but can be deteriorated by pyrolytic processes, such as arcing. This causes Per-Fluoroiso-Butylene (PFIB) and COF_2, which is further deteriorated to, a very aggressive, hydrofluoric acid (HF).

One variant of *GALDEN*, *HT200*, has been investigated for potential use in transformers and OLTCs. In a project for Italy, initial tests with an OILTAP® M have been performed during 1995-1998. The goal was to develop regulated power transformers, sized 25-40 MVA, for U_m 170 kV, with *GALDEN* filling. The excellent cooling properties and the high liquid density of *HT200* should allow for a very compact transformer design. A service duty test was performed which, after 18,000 operations, revealed inadmissibly prolonged arcing times of the switching contacts. The liquid was analyzed and showed the toxic deterioration products mentioned above. A visible indication for HF was the dull surface of the diverter switch oil compartment (made of glass-reinforced plastic, GRP). Additional 160,000 mechanical operations on a tap selector caused unremarkable mechanical wear and so proved a sufficient lubricating capability.

Even if this project has never been realized, one can state that halogenated polyether can principally be used with vacuum-type OLTCs.

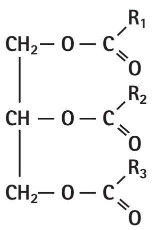
3. Approvals for tap-changers with alternative liquids

Extensive tests on different tap-changer types as well as on model setups have been performed with various HMWHs, natural and synthetic esters and silicone liquids to determine the limits for use. Complete tap-changers have been worn out in mechanical endurance tests performing up to 1.5 million operations and they were destroyed in high-voltage tests to determine the true withstand voltages of all insulating distances in HMWHs, natural and synthetic esters. Diverter switches have been stressed in the cold-climate chamber to find the lowest operating temperature with permissible timing, and all non-metal materials used in the respective tap-changer types were "cooked" for 180 days in 70-115 °C hot alternative liquids to ensure material compatibility. Several publications have been issued which give details on the test methods used and illustrate the behavior of tap-changers in these liquids [8], [9], [10].

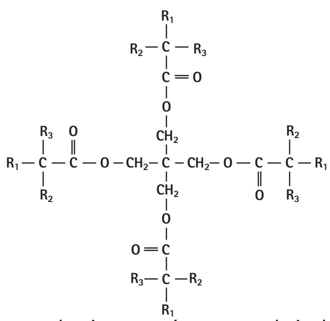
As a summary, Table 2 gives an overview on possible combinations of MR tap-changers with alternative liquids. From the test results, admissible operating conditions have been derived; see Table 3.

Table 3. Parameters and limit values for tap-changers in alternative liquids

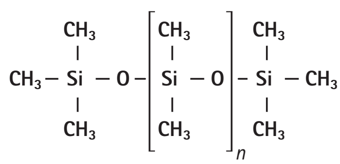
Percentage levels of mineral oil values			HMWH	Synthetic ester	Natural ester	Mineral oil
Withstand voltage (test voltage)	Phase to ground, Phase to phase	1.2/50 µs (LI) [%]	100	100	100	100
		50/60 Hz (AC) [%]	100	100	100	100
	Tap range, Tap to tap	1.2/50 µs (LI) [%]	70	70–100	63–100	100
		50/60 Hz (AC) [%]	84	80–100	74–100	100
Recovery voltage	Change-over selector		60	60	72	100
Temperature range		[°C]	+5 … +115°C	-18 … +115°C	-10 … +115°C	-25 … +115°C
Gasket materials			Standard	VITON	VITON	Standard
Hermetical sealing required			No	No	Yes	No
Pressure range for sealed systems		[bar] absolute	0.7–1.8			



Natural ester (triglyceride fatty acid ester)



Synthetic ester (pentaerythritol organic acid ester)



Silicone oil (polydimethylsiloxane)

It is possible to “upgrade” a mineral oil filled regulated power transformer with oil-switching type OLTC to a modern, less-flammable and environmentally friendly transformer with vacuum type OLTC

Please note that the voltage values for withstand voltage and recovery voltage of the change-over selector are expressed as percentage levels of the standard values for mineral oil, the values varying with the OLTC type.

4. Retrofitting

It is possible to “upgrade” a mineral oil filled regulated power transformer with oil-switching type OLTC to a modern, less-flammable and environmentally friendly transformer with vacuum type OLTC. Some considerations are necessary to ensure a safe and reliable operation with the new liquid (and tap-changer). First, it must be determined if the combination of the tap-changer and desired liquid according to Table 2 is approved. In case of an OILTAP® M, the diverter switch can easily be replaced by a VACUTAP® VM model. Then, the following parameters have to be checked:

- Required withstand voltages for all relevant insulation distances
- Required recovery voltage on change-over selector
- Required operating temperature range
- Material compatibility
- Breathing conditions

The tap-changer manufacturer will also check the application for possible geometric incompatibilities (e.g. insulating distances to tank walls etc.).

If one or more limit values defined in Table 3 are violated, adequate measures must be taken:

- If the required withstand voltages do exceed the permissible values which have been defined for the chosen ester liquid, the risk of a flashover must be estimated and, if not tolerable, adequate measures must be taken (like surge arresters or varistors). In rare cases, a substitution of the tap-changer with a bigger size can be appropriate.
- Tie-in measures may need adjustment.
- A temperature lockout must be installed to prevent the tap-changer from switching at liquid temperatures beyond the permissible temperature range.
- Unsuitable gaskets should be exchanged to avoid leakage in the long-term.
- If natural ester liquids are used, sealing measures like rubber bags or nitrogen-filled expansion tanks have to be applied to prevent the natural ester from persistent contact with oxygen from the ambient air.
- If sealing measures are applied, an adequate protection concept for the tap-changer has to be adopted, because the standard oil flow relay may not work properly in combination with sealed expansion tanks.

When retrofilling a mineral oil-filled transformer with an ester liquid, it has to be considered that the residual mineral oil remaining in the cellulose will reduce the flash point and fire point of the liquid mixture. To maintain a fire point of more than 300 °C, it is recommended to keep the mineral oil contamination below 3-5 % [11].

5. Outlook

Producing oil from natural gas is one way to face the fading resources for high-quality crudes which are necessary to produce a good transformer oil. But this process needs a lot of energy. Much less energy is needed to generate synthetic esters, and they are fully biodegradable. Natural esters are presently the only insulating liquids which are really CO_2 neutral. Their development continues, improving oxidation stability and pour point. Dupont has recently issued a new sustainable ester-based fluid which perfectly fits to the NOMEX™ solid insulation product line, paving the way for high-temperature applications.

It looks as if natural ester liquids show the best compromise between usability, price and environmental friendliness of all alternative liquids which are commercially available. But they stay in competition with arable crop which is needed for food production. As in many other areas, finding a balance between different interests is a question of social, environmental and economical responsibility. Breeding of oil seeds with higher output continues and can slow down the increment of arable crop needed for industrial vegetable oil products.

In this context, however, attempting the use of palm oil as insulating liquid appears questionable from the technical perspective and from the perspective of the accelerated tropical rain forest conversion into palm oil plantations.

A promising alternative can be oil from algae. Current projects investigate the cultivation of super-efficient microalgae to produce feedstock from which fuels and maybe

Author

Dipl.-Ing. (TU) **Rainer Frotscher** was born in Bremen, Germany on March 4, 1960. He received his Master’s Degree in Electrical Engineering from the Technical University of Munich where he wrote his thesis in high-voltage engineering.

Dipl.-Ing. Frotscher works for Maschinenfabrik Reinhausen (MR) in Regensburg, Germany as an expert for special tap-changer applications.

He has been working on various projects concerning the technology of on-load tap-changers. His area of expertise is the applicability of alternative liquids and DGA on tap-changers. As a member of CIGRE and DKE, he has authored multiple publications and he contributes to several working groups in CIGRE, IEEE and DKE.

Phone : +49 (0) 941/4090-4136
Fax : +49 (0) 941/4090-4005
Email : r.frotscher@reinhausen.com
Address : Maschinenfabrik Reinhausen GmbH
Falkensteinstraße 8, 93059 Regensburg, Germany

A promising alternative can be also oil from algae, because super-efficient microalgae might be cultivated to produce feedstock from which fuels and maybe also an electrical insulating liquid can be refined

also an electrical insulating liquid can be refined. Algae consume carbon dioxide from the atmosphere and so help solving another apparent problem of mankind. But the biggest benefit is that algae can be grown anywhere, in direct vicinity of the markets where the oil is needed. Not endangering sensitive environments, short routes of transportation - wouldn't that be great?

Bibliography

[1] W. Breuer, G. Hegemann, *Behavior of On-Load Tap-Changers in MIDEL 7131 – A PCB-Alternative for Transformers*, CIGRE-Symposium 05-1987, Vienna, Austria

[2] M. Lashbook, M. Kuhn, *The use of ester transformer fluids for increased fire safety and reduced costs*, paper A2-210, CIGRE 2012, Paris, France

[3] M&I Materials, Technical Data Sheets on MIDEL 7131, http://static.mimaterials.com/midel/documents/technical/MIDEL_7131_Technical_Information_Pack_A4.pdf

[4] Cargill, Reference Data R2020 on ENVIROTEMP FR3, http://www.cargill.com/wcm/groups/public/@ccom/documents/document/na3076889.pdf

[5] C. T. Duy, O. Lesaint, A. Denat, and N. Bonifaci, *Streamer propagation and breakdown in natural ester at high voltage*, IEEE Transactions on Dielectrics and Electrical Insulation, vol. 16, pp. 1582-1594, 2009.

[6] P. Jarman, G. Wilson, P. Dyer, F. Perrot, Q. Liu, Z.D. Wang et.al., *Electrical Performance of Ester Insulating Liquids for Power Transformers*, CIGRE SC A2 & D1 Joint Colloquium 2011, Paper PS2-O-5, Kyoto, Japan

[7] P.McShane, K. Rapp, J. Corkran et.al., *Aging of paper Insulation in Natural Ester Dielectric Fluid*, IEEE Transmission and Distribution Conference, Atlanta, USA, Nov 2001

[8] R. Frotscher, *On-Load Tap-Changers with Vacuum Switching technology for increased fire safety, reliability and environmental performance*, Advanced Research Workshop on Transformers, Santiago de Compostela, Spain, 2010

[9] R. Frotscher, D. Vukovic, J. Harthun, M. Schäfer et.al., *Behaviour of Ester Liquids under Dielectric and Thermal Stress – From Laboratory Testing to Practical Use*, paper D1-105, CIGRE 2012, Paris, France

[10] R. Frotscher, *Alternative Liquids for Tap-changers*, Technical Publication F0310300, Maschinenfabrik Reinhausen GmbH, Regensburg, Germany, 2014,

http://www.reinhausen.com/en/XparoDownload.ashx?raid=86521

[11] Cargill: *Recommended Procedures for Retrofilling Oil-Filled Transformers*, Section S900-20-2 Reference Document, 2006