Natural/Synthetic Esters Usage from an OLTC Perspective

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Regulated power transformers are equipped with on-load or de-energized tap-changers to adjust the transformer output voltage in accordance with the needs of the power supply network. The switching operations of conventional non-vacuum type on-load tap-changers partially deteriorate the oil and generate free gases. Modern on-load tap-changers with vacuum switching technology avoid such oil deterioration by encapsulating the switching arcs inside vacuum interrupters.
Today the majority of power transformers are filled with mineral oil. The flammability and limited biodegradability of mineral oil presents a significant environmental risk. Stringent fire safety and environmental laws developed by government authorities and pushed by new installations of transformers for solar and wind farms in places where usually no network exists has led to the investigation of alternative of insulating liquids. The search has resulted in the development of natural and synthetic ester liquids, that exhibit a high flashpoint and exceptional environmental performance.
The combination of vacuum type tap-changers and ester liquids offers numerous functional benefits including lifetime maintenance-free operation as well as reduced installation and maintenance costs realized through simplified installations, e.g. combined oil households of transformer and tap-changer. However, some specific factors have to be considered to ensure reliable on-load tap changer operation over the long-term.
After giving a general overview on the requirements on a suitable liquid to be used with tap-changers, the specific properties of natural and synthetic esters are highlighted. The results of extensive tests with different tap-changer models operating in selected natural and synthetic ester liquids are described. They give a comprehensive overview and reveal the peculiarities that should be considered when furnishing tap-changers for ester liquids. Guidelines have been defined which enable a straight-forward order processing of tap-changer applications with ester liquids. These guidelines are integrated in international application guides and standards. The guidelines have been applied successfully in commissioning over more than 600 ester filled tap-changer installations worldwide. Almost all projects using esters as insulation liquid are for new transformers, however an option also exists to retro-fill existing in-service transformers. This paper provides an overview of considerations; environmental, safety, cost and operational, that must be taken into account when developing an on-load tap changer ester strategy.

1 Introduction

Insulating liquids used in transformers have to perform a multiple role as an electrical insulating and heat transfer agent. They must have adequate dielectric strength to withstand the electrical stresses imposed in service as well as a favourable combination of thermal conductivity, specific heat and viscosity to ensure sufficient heat transfer for the particular equipment. Furthermore, they must be compatible with all insulating materials used in the transformer and cannot deteriorate in a manner that adversely affects other materials in the system. The most common insulating liquid that fulfils all these requirements is mineral insulating oil. Mineral insulation oil is produced from crude oils by complex refining processes. Unused mineral oils suitable for use in transformers and switchgears follow the specifications given in IEC 60296, ASTM D3487 or similar standards. These liquids have a proven operational track record that spans one hundred years, but their flammability and limited biodegradability represents a significant environmental risk. Mineral oils can only be used in applications where a high degree of fire or environmental safety is not required.

Power transformers contain up to 120,000 litres of liquids. As natural crude oil sources slowly run dry, methods are being developed to use reclaimed or recycled mineral oils of various origin. Natural gas for the composition of insulating liquids which show comparable parameters as unused mineral insulating oils. Recycled mineral oils for electrical purposes are generally cheaper than conventional insulating oil and can be used for applications with moderate demands on purity and stability. For these liquids, dedicated standards have been set up by ASTM and IEEE. In IEC, recycled mineral oils will be integrated in the next edition of IEC60296. On the other hand, liquids produced from natural gas ("GtL oil" – Gas-to-Liquid process) exhibit a very high purity, essentially no sulphur, an exceptional resistance to degradation and a moderately increased flashpoint[1], but the complex manufacturing process makes them somewhat more expensive than conventional mineral oils. For these liquids, the above-mentioned standards for unused mineral oils are applied, as there is no separate standard for such oils.
The rising consumption of power in metropolitan areas has necessitated the installation of power transformers in densely populated urbane precincts. The use of transformers in such environments requires adherence to stringent safety standards that require the use of less or non-flammable liquids to minimize the hazard of fire and explosion damage in the event of electrical faults within the equipment. The expansion of water-catchment and suburban areas has led to location of an increasing number of substations in environmentally sensitive areas. As these areas are often flood zones, liquid collecting measures in the transformer foundation are generally useless. For such installations, environmentally friendly liquids have to be used. Natural and synthetic esters, which have been designed for electrical purposes, perfectly meet these demands. They show a fire point above 300°C (K-Class liquids), are fully biodegradable and show good performance in high-voltage equipment. However, some properties of these liquids are different to mineral insulating oils and require deeper investigation.

2 Applicability of Ester Liquids for On-Load-Tap-Changers

2.1 General Requirements

Regulated power transformers are equipped with on-load tap-changers (OLTCs) or de-energized tap-changers (DETCs) to adjust the voltage levels and power flow in networks and industrial applications. Conventional tap-changers use arc-switching contacts under liquid to make and break the load-current. The high arcing stress which occurs during the normal operation of the tap-changer leads to severe deterioration of the liquid and formation of free gases, acids, soot and cracking products. In combination with ester liquids, it has been found that the arcing times are prolonged and volatile toxic by-products can be generated[2]. Therefore, ester liquids are not recommended to be used with this type of tap-changers.
Tap-changers with vacuum switching technology (vacuum type OLTCs) encapsulate the switching arcs within sealed vacuum interrupters. With this, the surrounding liquid keeps its original properties over a long period, which enables maintenance intervals between 300'000 and 600'000 switching operations and so requires less replacement and disposal. The insulating liquid remains stable and is comparable to the conditions inside the transformer. No free gases are generated by vacuum-type

OLTCs during normal service. This offers additional benefits like Dissolved Gas Analysis (DGA), combined households of transformer and tap-changer liquid and sealed applications with no contact of the liquid to ambient air. The latter is compulsory for using natural ester liquids, as they oxidize quickly. Nevertheless, a sufficient liquid quality must be ensured over the whole lifetime of the equipment in the same way as it is usually applied for the transformer. Regular measurement of the dielectric strength according to IEC60156, ASTM D-1816 or ASTM D-877 is sufficient. Vacuum type OLTCs are and DETCs are principally suitable for use with ester liquids. Table 1 shows possible combinations.

Table 1 Applicability of Natural and Synthetic Esters in Tap-Changer Oil Compartments

	Natural Ester		Synthetic Ester	
	Free-breathing	Sealed	Free-breathing	Sealed
Non-vacuum type OLTCs	No	No	No	No
Vacuum type OLTCs	No	Yes	Yes	Yes
DETCs	No	Yes	Yes	Yes

2.2 Tap-Changers and Their Requirements on a Suitable Liquid

2.2.1 Electrical Requirements

Tap-changers show many different electrode configurations with insulating distances which have been accurately optimized for mineral oil. The electrical field can be homogenous or moderately inhomogeneous, due to specific functional requirements of contacts, shielding rings and mechanical parts. Uncoated metallic surfaces have to be accepted.

Many different insulation materials support the metallic parts and they are chosen according to their electrical and mechanical function. They all contribute to the complexity of the resulting electrical fields. Ester liquids show a 1.5 times higher permittivity than mineral oil and so will lead to different field distributions and field strengths which may be lower or higher than for the original mineral oil design[3].

2.2.2 Mechanical Requirements

The complete tap-changer mechanism is working under liquid. All mechanically operated parts have to be sufficiently lubricated to reach the desired lifetime and ensure a safe operation between service intervals. Insufficient lubrication causes excessive mechanical wear which can lead to premature failing of the tap-changer mechanism. Lubrication also affects the switching sequence of the spring-driven diverter switch. Once released, the diverter switch has to perform the load transfer from one tap to the next tap without external drive so a proper timing of all contact movements has to be ensured for all service conditions.

2.2.3 Thermal Requirements

A proper switching sequence of the contact system must be ensured over the entire permissible liquid temperature range (typically -25 to +115°C). Within this temperature range, the liquid viscosity varies by several orders of magnitude. Ester liquids show a higher viscosity than mineral oil which may lead to certain limitations in very cold liquid. In the same manner as the liquid cools the windings of a transformer, the liquid is responsible for the cooling of current-carrying contacts and the transition impedance of the tap-changer. In resistor type OLTCs, the transition resistors carry the load current and the circulating current during a switching operation and produce large amounts of heat energy. Depending on the step capacity of the transformer, significant heating of the liquid inside the tap-changer oil compartment may occur.

2.2.4 Arc-Quenching Requirements

Even if the switching arcs inside the diverter switch are encapsulated inside vacuum interrupters, another source of electrical arcs can be found at the change-over selector (which is a part of the tap selector) when reversing the regulating winding or switching a coarse tap winding. Due to the capacitive coupling of the regulating winding to neighbouring windings and the core or tank walls, sparks and low-power arcs may occur which may not stand too long and cause a short within of the regulating winding or coarse tap winding.

2.2.5 Material Compatibility

Many different high-tech materials are used inside a tap-changer to achieve high electrical and mechanical functionality and a long working life. Numerous plastic materials have to withstand high thermal and mechanical stresses and must electrically insulate at the same time. Different gaskets in numerous shapes care for tightness to over- and low-pressure. It is obvious that all materials must be compatible with the insulating liquid used and may not deteriorate during the whole lifetime of the tap-changer. This also applies to supplementary equipment, such as oil-flow relays, Buchholz relays and Pressure Relief Devices (PRDs).

2.3 Properties of Natural and Synthetic Esters

2.3.1 Natural Esters

Natural Esters are composed using a blend of suitable seed oils (e.g. soybean, rapeseed, sunflower) or palm oils plus some additives. Sourced from renewable resources, natural esters are principally available in unlimited quantity to cover all future demands.

However, an expansion of agricultural land for producing these liquids may not cater for the market demand. Natural Esters consist of fatty acids which may be polyunsaturated, monounsaturated or saturated. While unsaturated fatty acids are prone to oxidation, saturated fatty acids can be very viscous. It is the optimal mixture that results in a compromise between sufficient oxidation stability and acceptable viscosity, thus rendering these esters applicable as an electrical insulating liquid. Figure 1 shows different compositions of ester liquids which have been investigated in[4].

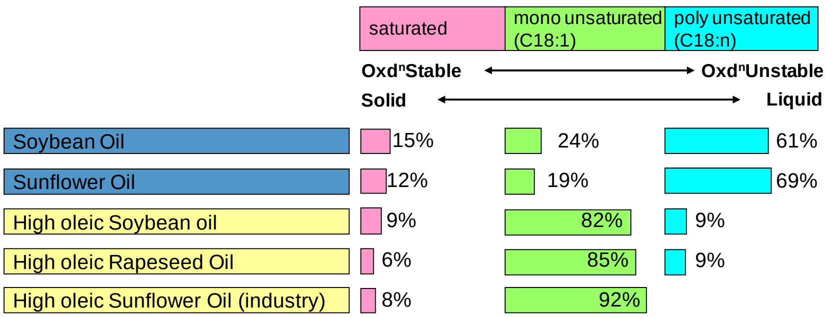

Figure 1 Examples of Natural Ester Blends

Depending on the ratio of saturated to unsaturated acids, additives are necessary to achieve an acceptable pour point and oxidation stability. The total additive content is usually lower than 2% to comply with OECD biodegradation requirements. IEC62770 specifies a maximum permissible additive weight fraction of 5%. For different natural esters, which are available on the market as insulating liquids, pour point and oxidation stability differ significantly. Highly saturated sunflower liquids show much better oxidation stability than soybean liquids, due to their high content of oleic acids[5]. Nevertheless, none of them should be used in free-breathing equipment. Depending on the liquid and the individual breathing conditions of the application, oxidation will lead to an accelerated polymerisation of the unsaturated fatty acids which first causes an increase in viscosity and ends up in jelly or solid state[6, 7].

2.3.2 Synthetic Esters

Synthetic esters are synthetically manufactured compounds consisting of alcohols and saturated fatty acids (carboxylic acids). Due to the manufacturing process employed, they have precisely defined characteristics, whereby the length of the hydrocarbon chains of the carboxylic acids determines viscosity. Synthetic esters used as insulating liquids have a viscosity similar to natural esters, but not such a high variance in the length of the hydrocarbon chains. The length has been chosen so that a low pour point can be achieved. Synthetic esters are also biodegradable and very moisture-tolerant; that is, they retain their favourable electrical characteristics even under very high amounts of dissolved humidity (Figure 2).

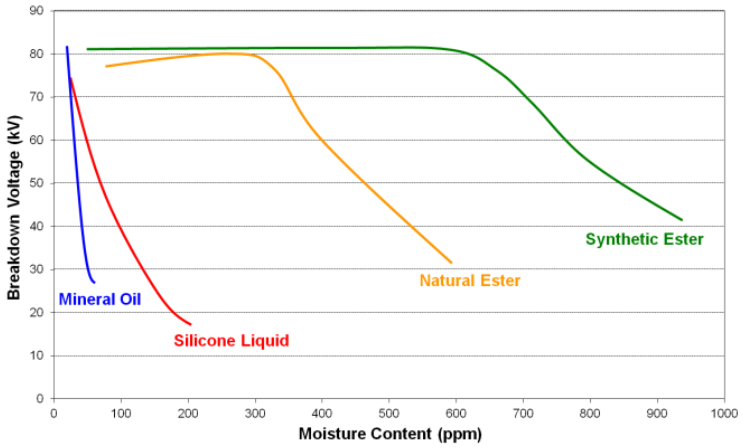

Figure 2 Breakdown Voltage over Water Content, T=25°C

The sole presence of saturated fatty acids provides high oxidation stability such that, synthetic esters can be used in free-breathing equipment. This is a special benefit with regard to retrofitting free-breathing mineral oil-filled equipment. The complex manufacturing process and the advantages mentioned above result in a comparatively high price point for these liquids.

3 Constraints for the Application of Esters with Tap-Changers

3.1 Test Results

Extensive testing has been complete to reveal potential impacts of natural and synthetic esters on the performance on vacuum type OLTCs. Numerous full-scale tests on different OLTC models and tests on model setups have been performed over the last ten years in the author's company test field. They covered:

- Mechanical Tests
  a) Temperature tests on different diverter switch types to determine the switching behaviour at different liquid temperatures, covering a temperature range of -25…+125°C
  b) Mechanical endurance tests on complete tap-changers with 1.5 million switching operations
  c) Additional tests on model setups to investigate the friction on contact arrangements and the lubricating capabilities of various liquids
- Electrical Tests
  a) Determination of withstand voltages for all relevant insulation distances by destructive high voltage tests with AC and LI

b) Switching tests to determine the switching capacity of reversing / coarse change-over selectors of different tap selector models

- Material Compatibility Tests

a) All materials used in vacuum type OLTCs and DETCs have been stored for six months in hot liquid to detect possible incompatibilities.

As a result of all these tests, limit values have been derived which ensure a safe operation; see Table 2[9, 10]. The values show the maximum permissible percentage of the values valid for mineral oil, which are indicated in the technical data of the specific tap-changer model.

Table 2 Limit Values for Tap-Changers in Synthetic and Natural Ester Liquids

Percentage Levels of Mineral Oil Values			**Synthetic Ester**	**Natural Ester**	**Mineral Oil**
Withstand voltage (Test voltage)	Phase to Ground, Phase to Phase	1.2/50 μs (LI) [%] 50/60 Hz (AC) [%]	100 100	100 100	100 100
	Tap Range, Tap to Tap	1.2/50 μs (LI) [%] 50/60 Hz (AC) [%]	70 – 74 80 – 83	63 – 65 74 – 77	100 100
Recovery Voltage	Change-over Selector / Coarse Tap Selector		60	72	100
Temperature Range [°C]			-15 – -18..+115°C	-10..+115°C	-25..+115°C
Pressure Range for Sealed Systems [bar absolute]			0.7 – 1.8		

Referring to dielectric strength, it can be seen that the withstand voltage values for the phase-to-ground and phase-to-phase insulation distances are not reduced (=100 %), but only the withstand voltages for the tap range and tap-to-tap distance (<100 %). This is due to the fact that these distances are somewhat inhomogeneous, necessarily because of functional needs. It has been found that ester liquids show a different discharge and breakdown behaviour on inhomogeneous electrode configurations which becomes apparent at gap distances greater than 10 mm. These effects have been deeply investigated and described[11, 12, 13]. The findings fully match with the results of the destructive breakdown tests performed on different tap selector geometries. As a result, the maximum permissible test voltage along the tap winding has to be reduced. In case the expected test voltage exceeds the permissible limit, varistors can cut down the voltage stress along the tap winding. Another option is to use a bigger size tap selector.

Homogeneous distances (phase to ground, phase to phase) can be stressed with the full test voltage levels as applicable for mineral oil. However, shielding rings should be coated to achieve a comparable residual breakdown probability.

The switching capacity of the reversing or coarse change-over selector is somewhat reduced due to the higher viscosity of ester liquids which cool and quench the switching arcs less efficiently than mineral oil. As a result, the maximum switching current can be maintained, but the recovery voltage has to be reduced. This restriction can be fully covered in most cases by appropriate tie-in resistors, which are designed by the tap-changer manufacturer.

For a low number of applications with through-currents reaching the maximum rated through-current of the selected tap-changer, the 20 K temperature rise limit for continuously current-carrying contacts (IEC 60214-1) may be slightly exceeded. This is technically not significant, because ester liquids remain stable under higher temperatures (compared to mineral oil) due to their higher

flashpoint. If this violation of standard limit values cannot be tolerated, the next stronger tap-changer model has to be used.
The lowest permissible liquid temperature is determined by the limit values for the timing of the sequent switching steps of the OLTC mechanism and depends on the tap-changer model. For natural ester, the limit had to be set to -10°C, due to the beginning solidification of the longest hydrocarbon chains in the liquid[10]. For synthetic esters, the higher viscosity limits the use to -15..-18°C.
The mechanical endurance tests proved that ester liquids show excellent lubricating capabilities. The mechanical wear of contacts, gears and bearings was equal or lower than with mineral oil. There are no limitations concerning mechanical load and lifetime, when compared to mineral oil.
The many different materials used in tap-changers generally showed no abnormalities, except gaskets made of nitrile rubber. Some of the applied rubber mixtures became hard and brittle in synthetic ester, others swelled in natural ester and became weak. To avoid this, flour polymer gaskets (VITON®) should be used instead.

3.2 Tested Alternative Insulating Liquids

Table 3 gives an overview on the tested and approved insulating liquids which can be used in combination with vacuum type OLTCs and DETCs. Additional on-load tap-changer types and models of the MR product range are available on request.

Table 3 Approved Alternative Insulating Liquids for Tap-Changers

OLTC Type	HMWH *(BETA-Fluid)* *MICTRANS-G*	Synthetic Ester *MIDEL 7131* *ENVIROTEMP 200*	Natural Ester *ENVIROTEMP FR3* *MIDEL eN1215* *SunOhm Eco* *MIDEL eN1204*	Silicone Oil *Dow Corning 561* *ShinEtsu KF96-20*
VACUTAP® VV	✓	✓	✓	✗
VACUTAP® VM (except VM 300)	✗	✓	✓	✗
VACUTAP® VRC/VRE	✓	✓	✓	✗
VACUTAP® **VRS/VRM/VRL/VRF**	✗	✓	✓	✗
DEETAP® DU / **COMTAP® ARS**	(✓)	(✓)	(✓)	(✓)

✓: Approved (✓): Case by case clarification ✗: Not approved

3.3 Fire Safety

Both natural and synthetic ester liquids have a fire point greater than 300 °C, combined with a low "low heat value" (the energy available to support a fire). The energy, which is necessary to raise the liquid temperature to fire point and ignite a fire, is around 3 times as high for ester liquids than it is for mineral oil. In the highly unlikely case of a fire, much less smoke is produced than from burning mineral oil. These benefits have led to relaxed regulations for the installation of ester-filled transformers[8]. According to FM Global[i], firewalls and fluid containment areas are no longer necessary and clearance areas can be significantly reduced. For transformers installed in environmentally sensitive areas, dams instead of fluid containment vessels are sufficient to keep ester liquids away from open water.

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[i] FM Global: A mutual insurance company, with offices worldwide, that specializes in loss prevention services primarily to large corporations throughout the world in the Highly Protected Risk (HPR) property insurance market sector. (www.fmglobal.com).

3.4 Sealing Solutions for Natural Esters

Expansion tanks, generally installed on top of the transformer, are required to cover the temperature-related change in liquid volume. Their size is designed so that the minimum permissible liquid temperature (-25°C) leaves a residual amount of liquid in the expansion tank, while the expansion tank is filled to approximately 80% at the highest permissible operating temperature (115..125°C). In this temperature range, the liquid volume changes for 10..15% of the total volume and causes the same amount of intake and blow-out of ambient air ("breathing"). A dehumidifying unit (dehydrating breather) at the aperture prevents the ingress of humidity into the air headspace inside the expansion tank.

Natural esters should be prevented from contact with ambient air (see 2.3.1). Whenever this is required, measures must be taken to handle the temperature-related change in liquid volume. For this, different methods have been developed, which use flexible rubber balloons, nitrogen cushions or flexible tank walls and radiators. Figure 3 shows common solutions.

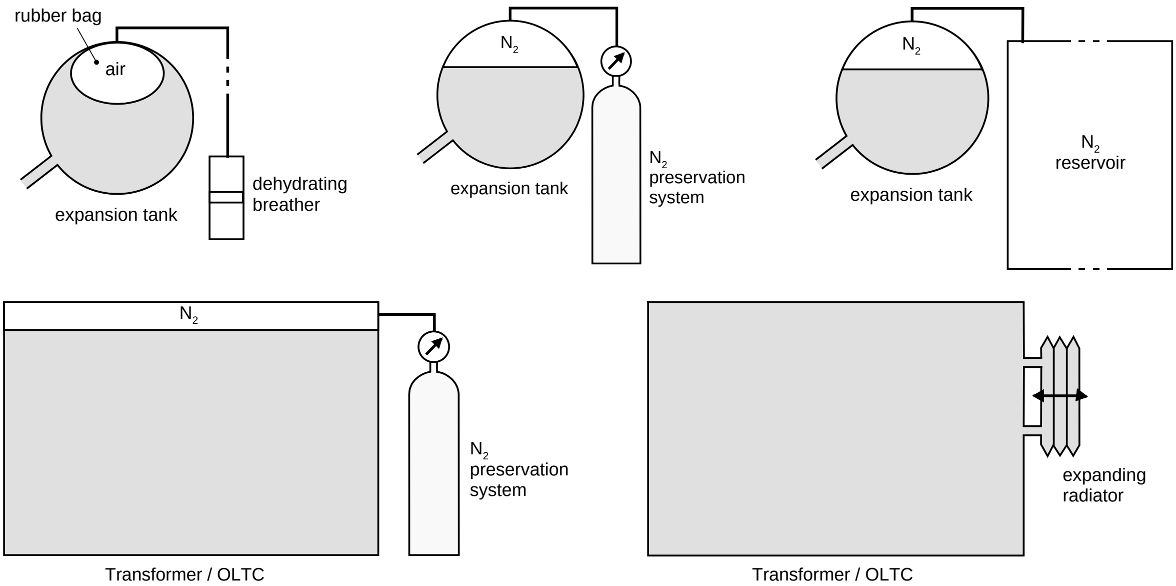

Figure 3 Common Technical Solutions for Preventing the Insulating Liquid from Contact with Ambient Air (Sealing Methods)

According to IEC 60214-1, the tap-changer must be equipped with a protective device in order to minimize the risk of fire or explosion which can result from an internal failure within the diverter or selector switch compartment. The protection concept is different for free-breathing and sealed applications. For free-breathing applications, an oil-flow relay acts as protective device and triggers the circuit breaker in case of a fault inside the tap-changer oil compartment. In sealed transformers, the reliable operation of the oil-flow relay cannot be guaranteed, because the sealed expansion tank may impede the oil flow. In many cases the applied sealing solution is unknown to the tap-changer manufacturer. Therefore, a pressure-relief device (PRD), mounted on the tap-changer head cover, shall act as protective device (see Figure 4).

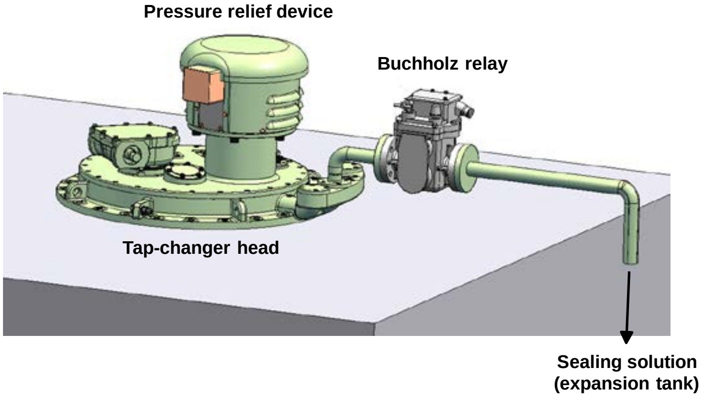

Figure 4 Protection Concept for Sealed Tap-Changers (In-Tank Type)

The PRD guarantees extremely responsive, effective protection of the OLTC which always triggers under the same, precisely defined conditions. This is the only way of implementing a protection concept that ensures reliable function under all operating conditions, regardless of the solution chosen for hermetic sealing and independently of the pipe geometries. Additionally, a Buchholz relay should be provided to detect and signal free gases which may accumulate in case of an incipient fault.

In the case of using a rubber bag or a nitrogen blanket for sealing, an oil-flow relay can be used alternatively as protective device in the same way as it is applied as standard for free-breathing applications. Reliable OLTC protection is ensured because the rubber bag and nitrogen cushion do not increase the system pressure measurably if correctly set.

3.5 Combination of Transformer and Tap-Changer Liquid Households

Vacuum type tap-changers show a very low generation of dissolved gases which is comparable to the gas generation in the transformer. With this, Dissolved Gas Analysis (DGA) and other methods which are commonly applied to evaluate the condition of the insulation liquid of the transformer become applicable also for the tap-changer liquid (with slight adjustments)[14, 15]. Due to a special design of the transition resistors, the resistor surface temperatures are kept so low under all operating conditions that no free gases are formed. It is no longer necessary to isolate the two liquid volumes of the diverter switch and main transformer tank from each other. A common expansion tank or, pending further development, an “open” diverter switch compartment becomes feasible and offers cost benefits. Pipes, gate valves, dehydrating breather and oil level indicator, which have been necessary for the expansion tank for the tap-changer liquid, can be omitted (see Figure 3). Researches in the test laboratory and initial experiences with transformers in operation have confirmed that the transformer gas-in-oil analysis (DGA) is not measurably influenced by the tap-changer oil[16]. The merging of transformer and tap-changer oil is applicable to free-breathing transformers (open type) as well as for sealed transformers (closed type). For sealed applications, the protection concept described in 3.4. is fully supported. If a separate tap-changer gas warning is not required, the Buchholz relay of the transformer can adopt this function. Figure 5shows an optimised solution for sealed applications.

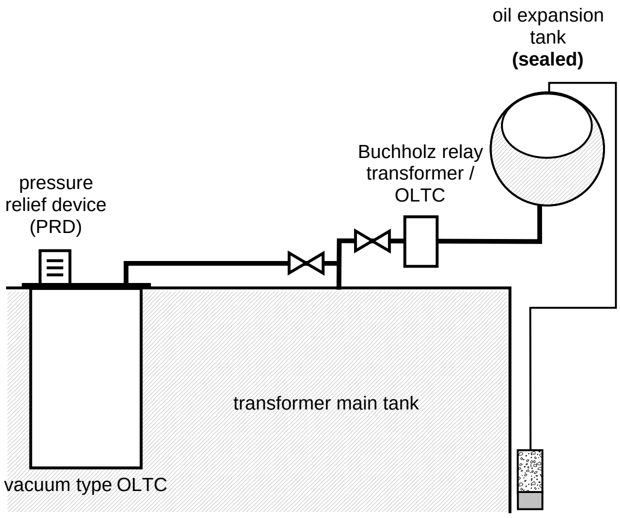

Figure 5 Combination of Transformer and Tap-Changer Liquid by Using the Same Expansion Tank (Sealed Units, Optimized Solution)

It must be noted that in this case, a possible source for free gases cannot be located. Approximately 10 years of positive operating experience on several regulating transformers with combined liquid households are evidence that these concepts have proven themselves.

3.6 Retrofitting

When retrofitting mineral oil-filled transformers or tap-changers with ester liquids, special considerations are necessary to ensure a safe and reliable operation with the new liquid. Principally, all items described in Section 3.1 will have to be checked.
If one or more limit values defined in Table 2 are violated, adequate measures must be applied:

- A temperature lockout must be installed to prevent the tap-changer from switching at liquid temperatures below the permissible limit temperature.
- Tie-in measures may need adaption.
- Unsuitable gaskets should be exchanged to avoid leakage 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 persisting contact with oxygen from ambient air.
  Depending on the individual situation, an adequate protection concept has to be adopted.
- 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 be applied (like surge arresters or varistors). In rare cases, an exchange of the tap-changer with a bigger size can be appropriate.

4 Options and Implications for Network Operators

4.1 Retro-filling Options with Ester Liquids

This section provides an evaluation of esters as insulating dielectric liquid from a utility perspective.
There are several applications where an energy utility or asset managers could consider an ester liquid as an alternative to mineral oil in their transformers. The driving factor for changing the liquid type for new equipment or for retro-filling existing units is to improve safety or reduce the risk to the environment. It should be considered whether the traditional insulating dielectric liquids used historically in transformers are still the best solution when there are several suitable alternative

products in the market. Despite esters being more expensive initially, there can be savings in certain project applications. The following outlines the scope, aim, transformer suitability study and feasibility analyses when compared to the retro-fill benefits and trade-offs.

4.1.1 The Scope of the Pilot Project

The pilot project presented in this paper is to replace an aged Transformer 5 MVA, at a rural substation with a retro-filled, 66/22 kV, 6.3 MVA mineral oil-filled strategic spare transformer (Wilson Transformer Company, WTC). The transformer in question is equipped with an on-load tap-changer model MR VVIII 250D 76 12 23 3G and motor drive unit TAPMOTION® ED100-S, both manufactured by Maschinenfabrik Reinhausen GmbH.

The asset manager was faced with the several site issues:

- Small existing concrete block bund
- The replacement mineral oil filled transformer is larger in physical size and oil capacity
- A 4 m separation distance between transformers on site

In this case, the asset manager considered retro-filling the spare power transformer to help alleviate some of the site constraints and therefore reducing costs for site extensions and reducing environmental harm. Environmental regulations can vary by country, state and local community therefore review in conjunction with the analyses. The asset manager requested an independent toxicity and environmental study be performed and has reviewed the following legislation, regulations, standards, and guides:

- Queensland Nature Conservation Act 1992
- Queensland Environmental Protection Act 1994 (EP Act)
- Environmental Protection Regulation 2008 (EP Regulation)
- Queensland Urban Drainage Manual (Department of Energy and Water Supply (DEWS 2013)
- Queensland Water Quality Guidelines 2009 (Queensland EHP 2009)
- Australian and New Zealand Guidelines for Fresh and Marine Water Quality (Australian and New Zealand Environment and Conservation Council (ANZECC)
- AS 1940-2004 The storage and handling of flammable and combustible liquids

4.1.2 Aim of the Pilot Project

In this particular project, the asset manager intended to reduce installation costs by retro-filling with an ester fluid, over installing a traditional mineral oil-filled transformer and completing extensive site works.

The asset manager estimated savings in the following areas:

1) Capital Expenditure (CAPEX) costs
    a) Reduction in containment and fire protection requirements (containment bunding, separation, blast walls, site size)
2) Operating expenditure (OPEX) costs
    a) Reduction in sill remediation (considered non-hazardous) [23]
    b) Savings on installation costs

Section 4.1.3 will discuss the retro-fill process and steps for verifying if the case study transformer is a suitable candidate for retro-filling with esters.

4.1.3 Method used for Checking the Transformer Suitability and Feasibility

Retro-filling of power transformers requires an engineering assessment, as it may require design considerations to accommodate the differences between mineral oil and such alternative liquids[24].

Asset owners should consider each retro-fill as unique and this list below is to be used as a guideline. Other design considerations may be required. Therefore it is recommended to work with the original equipment manufacturer (where possible), component manufacturers and liquid supplier.

In this case study, the transformer was manufactured in 2012 and the original equipment manufacturer (OEM) could apply the knowledge, modelling and rules developed for new ester-filled transformers to exactly predict the performance of the transformer when retro-filled with the alternative liquid. Both natural and synthetic esters were considered as part of this case study.

In case the design information is not available, engineering judgements must be made to estimate the performance of the transformer when filled with ester liquids[25].

In the particular case the transformer compatibility check was sub-divided into following categories and verified by the OEM, component manufacturers and fluid supplier:

- Transformer materials assessment
- Dielectric and thermal performance
- Residual oil in solid insulation
- Internal and external components

The OEM provided an engineering feasibility report providing information about suitability of the subject transformer for ester oil covering the sections above.

In some transformer designs, the OEM indicated that the following additional checks may be required:

- Acceptance of static electrification level due to forced liquid flow mode of transformer cooling system.
- Dynamic transformer loading limits
- Heating of the conductive transformer components due to magnetic stray flux
- Heating of the core due to no-load losses at nominal voltage level and overvoltage level

4.1.3.1 Transformer Condition Assessment

Firstly, it was critical to verify the overall condition of the transformer as well as the reliability of the installed components. The 2012, 66/22 kV, 6.3 MVA mineral oil-filled has been maintained according to the manufacturers recommendation and was in a good condition. A basic condition assessment prior to retro-filling should include oil analysis, field inspections and tests[25].

4.1.3.2 Dielectric and Thermal Performance

The OEM determined that the dielectric voltage withstands values of the core and coil assembly does not reduce the applicable voltage class of this transformer by verifying the following:

- Axial clearances, radial clearances and ducts within windings: Does not put any restriction on use of this transformer with ester oil.
- Bushings: Bushing withstand voltages and current ratings do not change adversely and thus maintains the required voltage class and MVA rating of the transformer.
- On-load tap changer (OLTC): In this specific case the reduced withstand voltage levels of the OLTC does not limit the transformer operation.

In regards to the thermal performance is critical to consider the thermodynamic properties of the different ester liquids as it affects the cooling performance of the transformer. At the normal operating temperature of a transformer, the viscosity of both natural and synthetic ester liquid is

higher than that of mineral oil. This reduces the liquid flow. Higher top oil, mean oil and winding hotspot temperatures were observed in the OEM thermal performance simulation for both natural and synthetic ester.
Table 4 shows the comparison of simulation results while maintaining the temperature limits of relevant standards.

Table 4 Liquid Temperatures Comparison: Mineral Oil and Esters

Temperature rise (°C)	**Mineral oil**	**Natural ester**	**Synthetic ester**
Top oil	86.1	4.5 higher	3.0 higher
Mean oil	80.6	0.3 higher	0.1 higher
Winding hotspot	106.8	11.3 higher	8.4 higher

4.1.3.3 Residual oil in solid insulation calculation

Residual mineral oil (typically 3 %–7 %) can reduce the ester liquid fire point below 300 °C and hence lose their "less flammable" listing and K fire hazard classification[25]. A certain amount of the original oil will remain in the unit, saturated in the solid insulation. The OEM determined the total solid insulation (kgs) from drawings and material quantities in manufacturing and take in the oil absorption rates. In this case study, the residual oil in the transformer would be within the acceptable limits for both natural and synthetic esters. This calculation also helped determine if the retro-fill can be completed at site or if it was required to be taken back to the factory to minimize the volume of residual mineral oil inside the transformer. Information relating to the ratio of the residual mineral oil that can be tolerated before the properties of the new replacement liquid become affected can be obtained from the individual liquid manufacturers. More details on the retro-fill process in section 4.3.1.

4.1.3.4 Internal and External Components

All Internal and external components should be thermally and chemically compatible with the chosen insulating liquid. Experience on the following components have been included below.

Tap-changers: The manufacturer of the tap-changer was consulted as the insulating liquid was changing from the conventional mineral oil to an ester liquid. As per Table 3, this tap changer is approved to operate using both natural and synthetic esters, provided the measures described in Section 4.3.2 are taken.

Bushings: In this case study, the OEM has determined that special high-temperature or over-sized bushings are not required. However, special attention should be given to the gasket material selection. In case of higher operating temperature, the condenser body of conventional bushings might be damaged due to thermal runaway[24].

Buchholz protection relays: A review of the alarms and limits of the Buchholz relay is required because of the different amounts of fault gasses generated with the alternative insulating liquid. The compatibility of the relay with the alternative liquid must be ensured.

Oil preservation system: The OEM recommended a conservator replacement, including the OLTC conservator with bladder bag for both type of esters. The existing conservator tank may not have enough capacity to hold the volume of liquid under higher operating temperatures, as mentioned in Section 3.4. Likewise, for sealed units, it must be clarified with the OEM what pressure range will develop in the gas space. It may be at a level where the pressure relief device will operate, or in the case of nitrogen pressurized units, excessive bleeding of the N_2 gas will lead to frequent N_2 bottle replacement.[26]

Material compatibility check: The OEM determined the materials used in the core and winding assembly of the transformer, in bushings, tap-changers and accessories, especially gaskets and insulating materials, is suitable for both esters. Additional information on material compatibility can be found in Section 2.2.5 or confirmed by the transformer manufacturer or liquid supplier.

4.1.4 The Cost-Benefit-Analysis

This section analyses the benefits and trade-offs with the different ester liquid.

Table 5 Ester liquid benefits and trade-offs versus conventional mineral oils

Benefits	Trade-off
Readily biodegradable and non-toxic greatly reducing the environmental impact.	Limited experience with esters regarding the long-term effects on the transformer
High fire point (class K) and explosive limits – reducing the risk of transformer fire and explosion.	Costs associated with the transformer re-design and additional liquid.
Savings on site works and redeployment of unit costs.	

The cost of the natural ester was just over half the cost of the synthetic ester in this retro-fill. However, there are potential savings and reduced risk with respect to the transformer design and tap-changer works if the synthetic ester was used.

Table 6 below shows the breakdown of the overall project costs in comparison to using a spare mineral oil transformer in this case study.

Table 6 Cost considerations for Retro-filling with Natural, Synthetic Ester compared with Mineral Oil and Site Work.

Costs (p.u)	**Retro-fill with Natural Ester**	**Retro-fill with Synthetic Ester**	**Mineral Oil Transformer**
Unit Base Price	1	1	1
Fluid	0.14	0.23	Not applicable
Tap-Changer Modifications	0.11	0.05	Not applicable
OEM Design	0.08	0.08	Not applicable
Mobilisation / demobilisation of retro-fill equipment to site	0.06	0.06	Not applicable
Civil works - Additional firewalls or other constructional measures on site	0.1	0.1	0.88
Transformer site works	0.25	0.25	Not applicable
Total costs	1.74	1.77	1.88

In this case, the costs for the new liquid, design modifications, resources to retro-fill and timeframe were a cost effective solution for the alternative bunding, firewall and site extension. Additional benefits for a utility include spares turnover, increased fire safety and a reduced environmental impact.

4.1.5 Conclusions of the Pilot Project

The use of alternative liquids in this particular design does not impose major design modifications. The adaptations can be made on site without significant costs and provide a suitable alternative to mineral oil.

4.2 Transformer Specification Changes for Esters

Ester liquids show a higher viscosity than mineral oil, which may limit the cold-start capability and may require modifications of the thermal design, e.g. increased cross sections of the oil ducts. Such modifications also affect the electrical design of the transformer. Additionally, the permittivity of ester liquids is significantly higher than the permittivity of mineral oil, which influences the electrical field distribution. While the field strength in the oil gaps is reduced, the field strength in the solid insulating material increases. As indicated in section 3.1., the dielectric breakdown characteristic of ester liquids on long oil gaps is different from mineral oil. The more inhomogeneous the field distribution, the greater is the difference between ester liquids and mineral oil. These facts may require an adapted design of the insulating system, avoiding inhomogeneous arrangements and providing increased clearances and additional barriers[22].

4.3 Implications for Operation and Maintenance of Transformers Filled with Esters

IEEE Guide C57.147[23] provides comprehensive guidance on how to maintain a sufficient liquid quality during the service life of a natural ester-filled transformer. It contains tables on acceptance values of relevant liquid properties for new liquid prior to energization as well as for in-service liquids, grouped by voltage-class. It also gives advice for screening tests and specifies reconditioning and reclaiming measures. In an annex, it is depicted how to use an OLTC with natural ester liquids.
For synthetic esters, IEC61203 contains similar information.

To avoid handling multiple liquids within a company, an asset owner may also want to evaluate which ester type would be best for them overall considering the overall costs of a retro-fill and future asset management costs of the unit.

- Natural esters are less oxidation stable. They are recommended for use in sealed transformers and therefore if an asset owner is buying a new transformer, the OEM can provide a suitable design for natural esters.
- Synthetic ester based liquids can be used in sealed and breathing transformers. Synthetic esters allow retro-filling of breathing type transformers, avoiding modification of the conservator.

It is important to consider all additional safety measures such as sealing, OLTC modifications etc. and not just the comparison of the price difference in liquids as this case study will demonstrate.

4.3.1 Implications for the Transformer Refurbishment

One important point to be observed is that the retro-filling of a transformer will never replace completely the mineral oil, as many litres are impregnated in the paper. As a result every ester liquid manufacturer (synthetic or natural) specifies a safe percentage of residual mineral oil which will not compromise the performance of the ester.
Also each liquid manufacturer determines a proper procedure to be followed during the filling with the ester in order to minimize the remaining quantity of mineral oil inside the transformer.
Specifically regarding natural esters, a higher care needs to be taken in order to fix the actual leakages and assess the quality of all seals to guarantee that no future leakages will appear, as the leakages will provide a point of entrance for the oxygen which will oxidize the ester (causing the same problem as leaving the transformer as a free-breathing system).

4.3.2 Implications for the OLTC Refurbishment

Depending on the chosen liquid for the retro-fill, some different measures need to be taken to ensure the reliable operation of the tap changer.
The following measures are listed specifically for this particular project.

4.3.2.1 FR3 and Midel eN1215

In order to use these soya-based natural esters, it is required to perform the following modifications:

- Verify the compliance with the electrical distances specified in Table 2;
- Replace the nitrile gaskets by Viton ones;
- Replace the head cover by a unit with provision for Pressure Relief Device (PRD) and thermal probe;
- Install a thermal probe (e.g. PT100);
- Modify the electrical circuit of the motor drive unit to block the operation under low temperatures, where the viscosity of the ester increases inadmissibly and can lead to a malfunction of the tap-changer;
- Replace the protective relay of the tap changer by a Buchholz Relay as gas warning device;
- Install a PRD as protective device for the OLTC;
- Guarantee that the system will be sealed and the ester will have no contact with the exterior air;
- Ensure that the drive shafts are still free to operate the tap-changer after the performed changes.

In this specific case the drive shaft was passing exactly on the same position where the PRD was to be installed. This difficulty leads to two possible solutions.

The first one being the complete disconnection of the tap-changer from the regulation winding, rotating the tap changer to a position where the drive shaft could operate freely and then adjust the leads (cutting or extending) from the regulation winding to the new sizes, to finally reconnect the leads to the tap-changer. This solution has been discussed with the transformer OEM responsible for the project and was found not feasible to be done on site.

The second solution was the replacement of the actual Motor Drive Unit (MDU) TAPMOTION® ED by the TAPMOTION® TD-ISM, which is a MDU in which the motor is located on the top of the tap changer, and not inside the control box. This solution allows the replacement of the drive shafts (both vertical and horizontal) by an electrical cable. This solution also provides the possibility to implement an online monitoring system on the transformer.

4.3.2.2 Midel eN1204

To use this rapeseed-based variant of natural ester (canola oil), the following modifications need to be performed (considering the sealing system as a nitrogen-filled expansion tank or a rubber bag):

- Verify the compliance with the electrical distances specified in Table 2;
- Replace the nitrile gaskets by Viton ones;
- Replace the head cover by a unit with provision for a thermal probe;
- Install a thermal probe (e.g. PT100);
- Modify the electrical circuit of the motor drive unit to block the operation under low temperatures, where the viscosity of the ester is higher and can lead to a malfunction of the tap-changer;
- Guarantee that the system will be sealed by appropriate means so that the ester has no contact with the exterior air.

For sealing systems other than a nitrogen-filled expansion tank or a rubber bag, specific protection measures need to be determined.

4.3.2.3 Midel 7131

To retro-fill the tap changer with a synthetic ester, fewer modifications are needed, but some still need to be done as follows:

- Verify the compliance with the electrical distances specified in Table 2;
- Replace the nitrile gaskets by Viton ones;
- Replace the head cover by a unit with provision for a thermal probe;

- Install a thermal probe (e.g. PT100);
- Modify the electrical circuit of the motor drive unit to block the operation under low temperatures, where the viscosity of the ester is higher and can lead to a malfunction of the tap-changer.

5 Conclusions

Suitable natural and synthetic ester liquids can be principally used in transformers of all sizes, from distribution transformers to power transformers with the highest rating. Every application has to be regarded individually and the advantages offered by ester liquids have to be balanced out with the challenges required by the individual conditions of the application. As tap-changers require the highest demands on the liquid, the tap-changer manufacturer should carefully analyse each application and give assistance in selecting and configuring the proper tap-changer model. The author's company has accompanied over 600 tap-changer installations with alternative liquids worldwide, including special applications such as traction transformers, test-field transformers, transformers for off-shore wind parks, desert mining facilities and explosion-prone environment. Examples may be found in existing studies[17]. The largest transformer ever filled with natural ester owns a rating of 300MVA/405kV±11% and has been put into service in Germany a few years ago[18]. During the last years, an increase in numbers of installations and a trend towards higher ratings is clearly sensible. In Figure 6, the blue columns represent the units delivered over 30 years (from 1980 to 2010), while the red columns represent an interval of 7 years thereafter (2011-2017). The strong increase of OLTC applications with natural and synthetic ester is clearly visible, while HMWH applications slowly fade out.

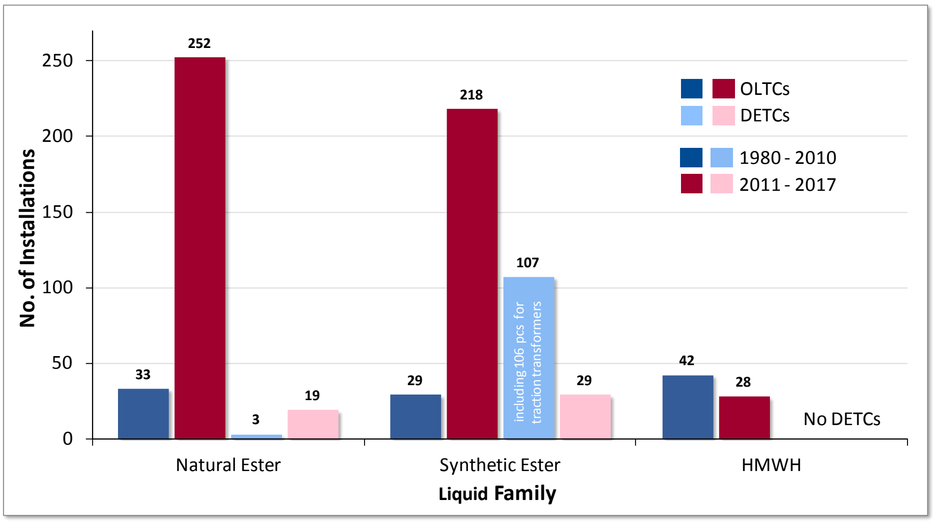

Figure 6 MR on-load and de-energized tap-changers filled with alternative liquids; units delivered 1980-2010 and 2011-2017

The extensive tests performed on ester liquids and the unique experience of the main author's company led to approvals for certain natural and synthetic ester liquids which represent the highest market demand[19]. For these liquids, processing guidelines have been set up to allow an efficient configuration and reliable operation. These guidelines are also introduced in international guides and standards (IEEE, CIGRE, IEC).

As development proceeds, various natural esters with limited local dispersion show up on the market. It is not efficient to subject all these liquids to the comprehensive test program for approval. To evaluate and approve such liquid, a simplified test program is being set up which allows a

qualitative comparison with approved liquids. If necessary, a "safety margin" will be added to ensure a secure operation long-term.
In future, natural esters will be used favourably (see Figure 6), even if their development is far from completion. Many open questions, such as gassing behaviour, flow electrification, long-time ageing behaviour and liquid diagnostics require further investigation and improvement[20, 21]. Retrofitting free-breathing mineral oil-filled transformers (and tap-changers) with ester liquids needs attention paid to gasket materials as well as to dielectric issues. For natural esters, an adequate hermetic solution (prevention from contact with oxygen) must be back fitted. So, despite of the higher price, synthetic esters may be a better alternative for retrofit projects, as they do not need hermetic sealing. Other less-inflammable insulating liquids, such as silicone liquids or high molecular weight hydrocarbons, will only play a minor role for applications with very special requirements.

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