ALTERNATIVE LIQUIDS FOR TAP-CHANGERS.

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1. Introduction

Electrical grids and power transformers are used in electrical power supply to regulate and control the load flow. Regulated power transformers are equipped with on-load tap-changers (OLTC) or de-energized tap-changers (DETC) that change the transmission ratio, which allows them to then adapt the output voltage of the transformer based on the respective conditions. This keeps the power supply grid stable, even under changing load conditions. Tap-changers are sophisticated mechanical devices that must also satisfy high-voltage technical requirements. This combination makes them unique components in the area of power supply technology.

The vast majority of regulated power transformers are filled with an insulating liquid. The main purpose of this liquid is to provide electrical insulation and dissipate the heat losses. In order to do this, the liquids must have the appropriate dielectric strength to withstand the electrical stresses imposed in service. They must also have an adequate combination of thermal conductivity, specific heat and viscosity to ensure sufficient heat transfer. In addition, they have to be compatible with all materials used in the transformer design and must neither deteriorate themselves nor the material in a manner that would impair proper functioning. With respect to tap-changers, they must also have sufficient lubricity and a good arc-quenching capability. The most common insulating liquid that meets all these requirements is mineral insulating oil, following the specifications given in IEC 60296, ASTM D3487 or comparable standards. Insulating oil refined from crude oil is proven and comparatively cheap. The use of GTL oils (GTL: gas-to-liquid) is new. These oils are synthesized from natural gas (methane) in a complex production process [1]. GTL oils follow the same standards as conventional mineral oil due to their similarity to mineral insulating oils and the absence of a dedicated standard. Mineral oils and GTL oils are sensibly used in all areas where increased fire safety or environmental protection is not necessarily required.

However, the increasing energy consumption in metropolitan areas implies that high-voltage lines are increasingly being routed directly into cities, which is fueling the demand for power transformers to be installed in urban areas. The applicable safety regulations place high demands on high-voltage installations in the direct vicinity of residential areas. These demands are related to fire protection, the formation of (toxic) smoke and damage resulting from explosions due to a malfunction in the system. The use of less flammable or non-flammable insulating liquids is advantageous for these types of applications. Certain insulating gases (SF6 and its more environmentally friendly substitute gases with lower global warming potential, as well as nitrogen and air) offer comparable advantages, but are only used infrequently (mainly due to technical reasons).

The expansion of water catchment areas has led to the situation that an increasing number of primary substations, which were originally built in greenfield areas, now find themselves in environmentally sensitive areas. Since these areas are often flood plains, open oil pans in the foundation of the transformer are generally not sufficient. Biodegradable liquids should be used in these types of systems.
2. Less flammable insulating liquids for electrical engineering applications

Since the use of polychlorinated biphenyls (PCB) in electrical devices gradually ceased in the mid 1970s and the use of PCBs was banned worldwide in 2001 due to their bioaccumulation, various insulating liquids have been developed to replace PCBs. Not all of these non-mineral liquids are less flammable, such as low-viscosity aromatic hydrocarbons, which are not considered here [2]. Liquids with a flash point >300 °C are categorized as “less flammable” (K-class liquids). These liquids can be divided into four categories.

a) HMWH: High molecular weight hydrocarbons were among the first, more environmentally friendly alternatives after the worldwide ban on PCBs. They are produced from paraffinic, refined crude oil that is purified until the oil has achieved electrical grade. Their long-chain hydrocarbon molecules ensure a relatively high viscosity and excellent lubricity. However, their use in cold regions is limited. HMWHs are predominantly used in distribution transformers. Nowadays, regulated power transformers are hardly ever equipped with HMWHs due to their disadvantages (low-temperature performance, limited bio-degradability) and the availability of better alternatives.

b) Silicone liquids consist of silicon oxide chains that have been saturated with methyl groups and are produced synthetically. The combination of its high flame resistance with high temperature stability makes it the preferred insulating oil for heavy-duty, compact transformers such as traction transformers. Silicone liquids have a viscosity that is largely unaffected by temperature and a very high flash point. However, their lubricity is insufficient and their behavior when subjected to arcs and electric fields is outside of the permissible tolerance range. Jelly-like deposits of silicon oxide (silica), which can create bridges in the insulating gap (Fig. 1), form on uncoated electrodes. In turn, this can significantly reduce the dielectric strength of the insulating gap. In addition, the pyrolytic degradation caused by switching arcs creates silicon sand, which can have a disastrous effect on the service life of the moving tap-changer components.

c) Synthetic esters (pentaerythritol-tetra-fatty acid esters) are synthetically produced compounds consisting of alcohols and saturated fatty acids (carboxylic acids). The liquid parameters can be defined precisely during the production process and the vis-

Figure 1: Silicon oxide flakes after three weeks at 20°C, at a maximum field strength of 2 kV/mm
cosity can be specified by the length of the hydrocarbon chains of the carboxylic acids (generally between C8 and C10). The viscosity of synthetic esters used for electrotechnical applications is between that of mineral oil and HMWH. Synthetic esters are biodegradable and highly tolerant to moisture, meaning that they can bind to large quantities of moisture and still maintain good electrical properties [3].

d) Natural esters (triglycerides) are produced from renewable resources (vegetable oils). All vegetable-oil based esters for electrotechnical applications currently available worldwide are based on soybean oil or rapeseed oil. In locally limited markets, insulating oils based on sunflower oil, nut oil or palm oil are offered as well. Hybrids of various oil seeds are also available. Most vegetable-oil based esters consist of polyunsaturated, monounsaturated and saturated fatty acids. Unsaturated fatty acids are prone to oxidation, but saturated fatty acids are not. However, the latter can be very viscous. The optimal mixture of various fatty acids results in a compromise between sufficient oxidation stability and an acceptable level of viscosity. The addition of additives (inhibitors, stabilizers, pour-point depressants) improves these properties, but they still cannot currently compare to the capabilities of mineral insulating oil. An exception to this is palm oil (PFAE: palm fatty acid ester), which only contains saturated fatty acids (good oxidation stability) but also has very low viscosity (low pour point). The lubricity of PFAE is excellent, but it does not achieve K-class in terms of flammability.

The use of HMWH and silicone liquids in tap-changers is limited due to the aforementioned disadvantages. As a result, liquids based on natural or synthetic esters are a significantly better choice, particularly when biodegradability and fire safety are both required. An indisputable advantage of natural esters compared to their synthetic counterparts is their low CO$_2$ footprint. Natural esters are CO$_2$-neutral, meaning that the carbon dioxide absorbed by plants during their growth is released back into the atmosphere in the same quantity when the oil is disposed of (Fig. 2).

On the other hand, the long-term oxidation stability of natural esters is insufficient. Oxidation results in a detrimental change of various properties, such as an increase in viscosity [4]. An increase in viscosity worsens the liquid flow in the transformer, thus influencing its cooling properties. In tap-changers, a high viscosity decelerates the switching process in an unacceptable manner. Therefore, suitable measures must permanently prevent the ingress of ambient air into the transformer and tap-changer compartment. Typical solutions for hermetical sealing of power transformers and suitable tap-changers employ nitrogen blankets, rubber bags or membranes inside their expansion tanks (conservators). In free-breathing systems, only synthetic ester liquids should be used.

Figure 2: CO$_2$ footprint of natural esters
3. Requirements for suitable liquids for tap-changers

In transformers, the task of the insulating liquid is to cool and electrically insulate the active part and bushings. An appropriate design and skillful employment of insulating materials are applied to achieve optimal cooling and a dielectric field distribution that is as homogeneous as possible. The latter is not always possible in tap-changers due to their function. Every tap-changer necessarily features moderately inhomogeneous electrode arrangements (contact geometries) with uncoated or coated metal surfaces. These are designed either as pure oil gaps or, in combination with solid insulating materials, as longitudinal oil-solid interfaces. In conjunction with the many different potentials of the taps on the tap winding, this results in complex insulation arrangements.

The requirements of a tap-changer for an insulating liquid depend on the type of tap-changer (OLTC or DETC, non-vacuum or vacuum switching technology). As it is shown in Table 1, the “classic” non-vacuum type tap-changers (current breaking and making occurs in the oil) place the most stringent requirements on the medium. For example, sufficiently good arc-quenching behavior is indispensable for these tap-changers. The limit values for arcing times defined for mineral oil must also be maintained in alternative liquids to ensure a fault-free diverter switch operation.

A tap-changer consists of numerous mechanically moving parts (gears, selector contacts, etc.) that are designed in accordance with a transformer service life of approx. 40 years and up to 1.2 million tap-change operations. The surrounding liquid must provide sufficient lubricity to ensure a corresponding endurance. This becomes especially relevant at high liquid temperatures as the lubricity decreases with higher liquid temperatures (decreasing viscosity). Within the entire permissible operating temperature range (generally, from -25 to +125 °C), the viscosity changes by a factor of 100. In this viscosity range, it must be guaranteed that the contact system of the spring-driven diverter switch carries out tap-change operations correctly within the specified time.

Furthermore, many different high-tech materials are used in state-of-the-art tap-changers to ensure a high level of electrical and mechanical functionality and a long service life. All of these materials must be compatible with the insulating liquid used.

Tap-changers are basically designed and optimized for being immersed in mineral insulating oil. The use of alternative liquids causes different stresses. Due to the variety of requirements placed on it, the tap-changer is the crucial component that has to be considered when evaluating the usability of an alternative insulating liquid.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Transformer</th>
<th>DETC</th>
<th>OLTC</th>
<th>Diverter switch/selector switch</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Selector</td>
<td>Non-vacuum switching technology</td>
</tr>
<tr>
<td>Electrical insulation</td>
<td>■ ■</td>
<td>■ ■</td>
<td>■ ■</td>
<td>■ ■</td>
</tr>
<tr>
<td>Cooling</td>
<td>■ ■</td>
<td>■ ■</td>
<td>■ ■</td>
<td>■ ■</td>
</tr>
<tr>
<td>Arc-quenching capability</td>
<td></td>
<td></td>
<td>■</td>
<td>Change-over selector</td>
</tr>
<tr>
<td>Viscosity</td>
<td>■</td>
<td>■</td>
<td>■ ■</td>
<td>■ ■</td>
</tr>
<tr>
<td>Lubricity</td>
<td>■ ■</td>
<td>■ ■</td>
<td>■ ■</td>
<td>■ ■</td>
</tr>
<tr>
<td>Compatibility</td>
<td>Environment</td>
<td>Materials</td>
<td>Materials</td>
<td>Materials</td>
</tr>
</tbody>
</table>

Table 1: Requirements on liquids for transformers, de-energized tap-changers (DETC) and on-load tap-changers (OLTC)

■ important ■ ■ very important
4. Suitable tap-changers for alternative liquids

The high arc energy during the normal operation of tap-changers with non-vacuum switching technology causes severe liquid degradation which, in mineral insulating oil, leads to the formation of acids and soot and cracking products. For alternative insulating liquids, the arc-quenching behavior is still largely unknown as it is determined by numerous parameters, namely the viscosity, thermal properties and molecular composition of the liquid. Switching arcs trigger a pyrolytic degradation of the oil. During this process, volatile and toxic degradation products may form [5].

Conversely, with vacuum switching technology (current breaking and making occurs in vacuum interrupters), the switching arcs are fully encapsulated inside the hermetically sealed vacuum interrupters. With this, the arc-quenching behavior of the liquid becomes less important. Therefore, OLTCs with vacuum switching technology are ideal for operation in alternative liquids because they feature the same switching capacity as in mineral oil. Because the oil only ages through heat and oxidation (as is the case in the transformer), additional advantages apply, such as expanded maintenance intervals of up to 600,000 tap-change operations. Therefore, in most cases the tap-changer oil does not need to be changed throughout the whole service life of the transformer. This also eliminates the need to dispose of used oil after a maintenance action. As is the case with the transformer itself, the quality of the tap-changer oil has to be checked regularly for breakdown voltage and water content.

Table 2 shows the possible combinations of MR tap-changers with alternative liquids.

Some OLTC types with non-vacuum switching technology (OILTAP®) are also suitable for being used with alternative liquids, provided that the oil compartment of the tap-changer is filled with mineral oil. The large variety of DEETAP® de-energized tap-changer models does not allow for an overall approval due to the extremely high test effort needed. However, individual approvals can be generated at any time. This may require use of a higher voltage class U_m or an individual adaptation of certain insulating distances.

Depending on the liquid family, there are different limits for the permissible withstand voltages (AC voltage and lightning impulse voltage), maximum through-current, operability at low liquid temperatures and switching capacity of the change-over selector.

Tap-changer models not listed in Table 2 are either generally unsuitable, or they have not yet been tested with alternative liquids due to a lack of market demand. If a non-approved tap-changer type is increasingly requested, MR will respond accordingly.

New developments of tap-changers with vacuum switching technology (VACUTAP®) guarantee maximum compatibility with natural and synthetic esters as their properties have already been included in the development process and tested accordingly.

<table>
<thead>
<tr>
<th>OLTC type</th>
<th>HMWH</th>
<th>Synthetic ester</th>
<th>Natural ester</th>
<th>Silicone oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>VACUTAP® VV</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>VACUTAP® VM (except for VM 300)</td>
<td>✘</td>
<td>✓</td>
<td>✓</td>
<td>✘</td>
</tr>
<tr>
<td>VACUTAP® VRC/VRE</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✘</td>
</tr>
<tr>
<td>VACUTAP® VRS/VRM/VRL/VRF</td>
<td>✘</td>
<td>✓</td>
<td>✓</td>
<td>✘</td>
</tr>
<tr>
<td>VACUTAP® RMV-II</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✘</td>
</tr>
<tr>
<td>ECOTAP VPD</td>
<td>✘</td>
<td>✓</td>
<td>✓</td>
<td>✘</td>
</tr>
<tr>
<td>OILTAP® V</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>(✓)¹</td>
</tr>
<tr>
<td>Mineral oil in OLTC oil compartment</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>(✓)¹</td>
</tr>
<tr>
<td>COMTAP® ARS</td>
<td>✘</td>
<td>✓</td>
<td>✓</td>
<td>✘</td>
</tr>
<tr>
<td>DEETAP® DU</td>
<td>(✓)¹</td>
<td>(✓)¹</td>
<td>(✓)¹</td>
<td>(✓)¹</td>
</tr>
</tbody>
</table>

Table 2: Possible combinations of MR tap-changers with alternative liquids
✓: permissible  ✘: impermissible  ¹ special case, please consult MR
5. Qualification of tap-changers for selected alternative liquids

Over the last fifteen years, comprehensive tests have been carried out with selected alternative liquids at the MR test center. The following factors were tested:

- Dielectric strength
- Cooling of current-carrying contacts
- Arc-quenching behavior on change-over selector
- Temperature behavior
- Lubricity
- Material compatibility

The majority of tests were performed 1:1 on tap-changers. Some tests were based on model arrangements in which the real conditions were reproduced with sufficient accuracy. The tested liquids were selected based on their market relevance and the real market demand. They were used “as delivered”. However, the oil quality (dielectric strength, water content) was continuously monitored to ensure realistic testing conditions.

HMWH behave similarly to traditional mineral oil due to their identical origin (crude oil). However, the major drawback of HMWH – their high viscosity – substantially limits the ability to use them in cold environment. While the higher viscosity of synthetic and natural esters has just a moderate effect on the switching behavior in cold-climate conditions, switching operations are not possible at liquid temperatures < 0°C.

The characteristic properties of silicone liquid limits its use to applications with a low number of tap-change operations and voltage classes \( U_m \leq 72.5 \) kV. The formation of silicon-oxide bridges between screening electrodes can be avoided by limiting the maximum permissible field strength or, if possible, through coating or paper insulation.

With respect to dielectric strength, it has been found [6, 7] that, in ester liquids, a high propagation speed of the streamer breakdown channels develops at lower voltage levels than in mineral oil. This effect is not just visible in extremely inhomogeneous electrode arrangements (needle-to-plate setups) but is also observed in moderately inhomogeneous contact arrangements, which are present in many different forms in tap-changers (see Fig. 3, 4). For these arrangements, power frequency and lighting impulse withstand voltages are lower in ester liquids than they are in mineral oil. This may require selection of the next higher voltage class and/or the next larger selector size. Alternatively, the voltage stresses along the tap winding can be reduced, either by installing surge arresters or possibly by also changing the winding design.

On the other hand, in homogeneous shielding ring arrangements as they are found in phase-to-phase or phase-to-ground insulating arrangements (see Fig. 5), almost the same dielectric strength can be achieved in ester liquids as in mineral oil. In these arrangements, shielding rings can be coated to further reduce the probability of flashovers.
The cooling behavior of ester liquids is slightly lower than the cooling properties of mineral oil. This has an effect on the heating of contacts and transition resistors and may lead to a slight reduction in the maximum permissible through-current in order to ensure compliance with standard requirements.

Mainly due to the higher viscosity of HMWH and ester liquids, arcing times are somewhat longer than in mineral oil. This is also true for the capacitive low-energy arcs or sparks of the change-over selector (reversing change-over selector or coarse tap selector). In order to counteract this behaviour, the maximum permissible switching capacity has to be reduced. However, in most cases, this limitation can be fully compensated through an adapted design of the tie-in resistors [8].

Mechanical endurance tests with more than 1.5 million tap-change operations revealed that both HMWH and ester liquids have excellent lubricating properties. Due to the high level of mechanical wear that has been observed, silicone liquids can only be used in combination with de-energized tap-changers (DETCs) since these usually only reach a low number of tap-change operations. In addition, it has been shown that a standard test for determining the properties of low-wear liquids (ASTM D4172, Method B) reproduces the results of mechanical endurance tests sufficiently well. As a result, this test can be used as an equivalent substitute for time-consuming endurance tests.

The tests performed provide a complete and homogeneous picture of the tested alternative liquids. Limit values have been defined and application guidelines drafted for the approved tap-changer types (Table 2) and approved liquids (Table 3) based on the test results. The knowledge gained from the tests is unambiguous and enables a well-founded evaluation of all customer requests concerning the use of tap-changers with alternative liquids.

Alternative liquids that are new to the market (primarily natural and synthetic esters) are often very similar to some of the liquids that have been tested.
so far. Therefore, it is not always necessary to run through the entire testing procedure with every new liquid. As long as the liquid manufacturer can provide a sufficient amount of data regarding all the parameters relevant to tap-changers, it is possible to grant an approval based solely on a data comparison with a similar liquid that has already been tested [9]. To this end, a corresponding questionnaire was drafted which is sent to the liquid manufacturer. Sensitive data is protected by a non-disclosure agreement between MR and the liquid manufacturer.

6. Configuration of regulated power transformers for alternative liquids

Due to the wide variety of possible configurations, tap-changer applications with alternative liquids require special attention in the course of order processing [10]. The comprehensive tests that have been performed revealed that some evaluations have to be carried out on an individual, customer-oriented basis. Therefore, the operator, transformer manufacturer and tap-changer manufacturer should have a thorough discussion about the individual operating conditions of the respective application. In this regard, MR offers customers considerable expertise, ensuring that tap-changer applications are configured properly and function reliably. Thanks to more than 700 OLTC installations with alternative liquids around the world, including special applications such as traction transformers, test-field transformers, transformers for offshore wind farms and mobile emergency transformers for liquid temperatures up to 150 °C, MR disposes of a unique range of experience [11]. Our expert sales team collaborates with our development and order processing teams to diligently analyze every application and offers support in the selection and configuration of the optimal tap-changer. On request, our service team convoys the commissioning of first-time applications and supervises the initial operation of the tap-changer.

<table>
<thead>
<tr>
<th>Synthetic ester</th>
<th>Natural ester</th>
<th>Silicone liquid</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIDEL 7131 (M&amp;I Materials)</td>
<td>ENVIROTEMP FR3 (Cargill)</td>
<td>Dow Corning 561</td>
</tr>
<tr>
<td>Nycodiel 1255 / 1258 (Nycodiel)</td>
<td>MIDEL eN1215 (M&amp;I Materials)</td>
<td>ShinEtsu KF96-20</td>
</tr>
<tr>
<td></td>
<td>SunOhm Eco (Kanden Eng.)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MIDEL eN 1204 (M&amp;I Materials)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pastell NEO (Lion Corp.)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SK Supervolt Eco-M (Hanyu Energy)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BioTransol HF (Savita)</td>
<td></td>
</tr>
</tbody>
</table>

*Table 3: Approved alternative liquids for suitable MR tap-changers in accordance with table 2*
7. Outlook

The complete biodegradability of ester liquids makes them a great choice for environmentally friendly power generation, e.g. through wind and solar farms. Such systems are frequently found in sensitive areas (e.g. in nature-conservation areas) and therefore should have a high level of environmental compatibility. It is the use of natural or synthetic ester liquids that makes these systems truly environmentally friendly systems. Natural esters are the best compromise between usability, price and environmental friendliness. However, cultivating oil plants for industrial purposes is in competition with agriculture for food production. As is the case in other areas, the balance between social, economic and environmental concerns must be maintained. The continuing development of ever-higher yielding oil seeds could slow the further increase in cultivation areas needed for industrial vegetable-oil products. The use of PFAE as an insulating liquid for transformers is highly controversial due to the tolerated tropical deforestation in task of cultivation of oil palms.

The development of dielectric insulating liquids from renewable raw materials is still ongoing. Their quality should further improve with each new generation, particularly with respect to oxidation stability.

Ester liquids are also increasingly being used in larger power transformers up to 400 MVA; the system voltages are now up to 550 kV. In addition, use in urban environments and in industrial applications with more stringent fire safety and/or environmental protection requirements continues to increase. The diverse MR VACUTAP®, ECOTAP® and DEETAP® product ranges offer suitable solutions for transformers of all sizes.

8. References

Please note:
The data in our publications may differ from
the data of the devices delivered. We reserve
the right to make changes without notice.

PB 3518312/03 EN – Alternative liquids for tap-changers
F0310303 – 12/19 – dp –
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