Tap-changer know-how

Insulating liquids – Part I: Mineral oils

1. General

Regulated power transformers are equipped with on-load tap-changers (OLTCs) or de-energized tap-changers (DETCs) to change their ratio and, subsequently, adapt the transformer output voltage to the respective conditions. This enables the power supply network to be kept stable under changing load conditions. In order to avoid overloading and optimally utilise all network components, regulated power transformers are utilised to regulate and control the power flow.

Tap-changers are complex mechanical devices which must also adapt to high-voltage conditions. This combination makes them unique components in energy supply technology. Their tap selectors show numerous different potentials on their terminals, and mechanically operated parts such as contacts are optimized to perform more than a million operations. The combination of mechanical and electrical requirements enforces a compromise which necessarily leads to electrode shapes producing moderate inhomogeneous electrical fields.

While the insulating liquid in a transformer has the sole task of cooling and (in combination with the solid insulation) insulating windings and bushings with regard to high voltage, a suitable liquid for tap-changers must also fulfil other requirements (see Table 1):

a) The switching arc must be cooled and quenched.

b) The spring-driven diverter switch must continue to function properly in all occurring ambient conditions, i.e. within the entire permissible oil temperature range, typically -25 °C to +115 °C. Within this temperature range, the oil viscosity varies by the factor of hundred.

c) All mechanically moving parts (gears and selector contacts) must be sufficiently lubricated in order to reach a high mechanical life which correlates to the lifespan of the transformer (>30 years).

d) Finally, many different metals and non-metallic materials (glass-reinforced plastics, polyamides, rubber mixtures and others) are used inside the tap-changer to achieve high electrical and mechanical functionality and a long working life, all of which must be compatible with the insulating liquid used.

From Table 1 it can be seen that oil switching type OLTCs show the highest demands on the liquid, because arc-quenching is a very complex issue. The energy of the switching arc always burns some liquid, causing deterioration products, such as different hydrocarbon fractions, carbon particles and gases.

Vacuum type OLTCs are easier to handle than oil switching types. Because the switching arcs are encapsulated inside vacuum interrupters, the surrounding liquid does not deteriorate and so keeps its properties long-term. The conditions become similar as for the liquid inside the transformer.

At present, equivalent vacuum type OLTCs are available for almost all sizes of oil switching type OLTCs. Vacuum type OLTCs are preferred if liquids other than mineral oils shall be deployed.

Changing the transformation ratio, tap-changers adapt the transformer output voltage to the respective conditions and enable the power network to be kept stable under changing load conditions

Following the above said it is obvious that the insulating liquid is an essential component in high-voltage equipment. The exact knowledge of any possible interaction of liquid and tap-changer is a core competence for a tap-changer manufacturer. With this issue of Transformers Magazine, a regular column is started to discuss different tap-changer topics. In this issue, I will start with mineral insulating liquids (named "mineral insulating oils" below).

2. Mineral insulating oils according to IEC 60296, ASTM D3487 or comparable standards

Tap-changers are approved for mineral insulating oils according to IEC 60296. This approval also includes comparable standards which pursue the same objective, i.e. determining the properties and limit values for suitable mineral insulating oils for electrical purposes. Comparable standards to IEC 60296 can be local national standards for unused oils such as ASTM D3487 or CAN/CSA-C50, or standards for recycled mineral insulating oils such as IEC 62701 or BS 148-2009.

2.1. "Classic" mineral oils

Mineral oils have been used as insulating liquid for over 100 years. The origin of these oils is crude oil, which consists of thousands of different hydrocarbons with many different structures. Besides that, crude oil also contains sulphur, nitrogen and other elements. Crude oil is refined by adequate distillation and hydro-treatment processes to produce different raffinates for different needs, with different purity, oxidation stability and viscosity to suit different temperature ranges. For its use as insulating oil for electrical equipment, the market offers Standard Grade Oils, High Grade Oils and Super High Grade Oils,

While the insulating liquid in a transformer has the sole task of cooling and insulating, oil switching type OLTCs require arc-quenching as well

Table 1. OLTCs show the highest demands on the surrounding liquid

Parameter	Transformer	DETC	Tap-Changer		
			Tap selector	Diverter switch	
				Oil switching type	Vacuum type
Electrical insulation	■ ■	■ ■	■ ■	■ ■	■ ■
Cooling	■ ■	■ ■	■ ■	■ ■	■ ■
Arc-quenching			■	■ ■	■
Viscosity	■			■ ■	■ ■
Lubrication		■	■ ■	■ ■	■ ■
Material compatibility	■	■	■	■ ■	■ ■

■ important ■ ■ very important

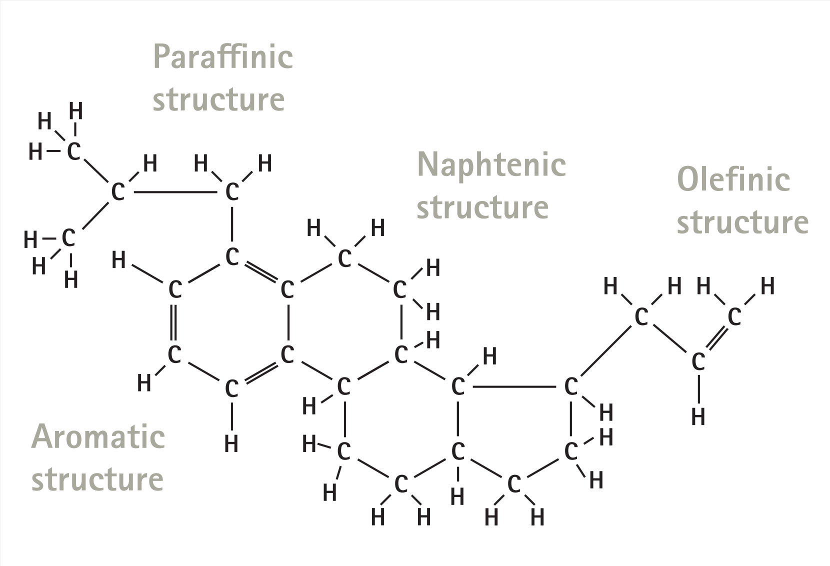

Figure 1. Typical mineral oil molecule with paraffinic, naphthenic, olefinic and aromatic structures

which mainly differ in oxidation stability. Super High Grade Oils contain up to 0.4 % additional inhibitors, such as DBPC (2,6-ditertiarybutyl para-cresol) or DBP (2,6-ditertiary-butyl phenol).

Fig. 1 shows a typical oil molecule with its different compounds.

Paraffinic structures principally consist of long chains of pure hydrocarbons. In oil molecules, they are branched to form isoparaffin. Olefine is unsaturated paraffin with a comparable structure and at least one carbon double bond (C=C). Oils with a major content of paraffinic structures are called paraffinic oils. They usually have a high viscosity, so severe refining processes and pour-point enhancing additives are necessary to achieve a sufficient behaviour at low temperatures.

Naphthenic oils (oils with a major content of naphthenic structures) show a lower viscosity than paraffinic oils, and therefore a better behaviour at low temperatures than paraffin. This is due to the compact structure of naphthene, which is a ring structure of carbon single bonds (C-C).

Usually, naphthenic mineral insulating oils contain a significant amount of paraffinic structures and vice versa. An oil is called naphthenic when ring structures form more than 40 % of the weight and paraffinic structures less than 50 %; see [1]. The rest (typically 2 to 12 %) are aromatic structures which influence the gassing tendency and the dielectric losses in ionization processes.

All crude oils additionally contain more or less natural sulphur, which acts as a natural inhibitor but often has negative effects on copper (transformer windings) and silver (plated tap selector contacts). This is also true for DBDS (Dibenzyldisulphid) which, formerly, has often been added by oil manufacturers to improve oxidation stability. Active sulphur must be filtered out or bonded to stay inactive. Nevertheless, there are still severe failures on transformers and tap-changers due to the formation of copper sulphide (conductive "needles") or silver-sulphide (black layers which can flake off and cause flash-overs). Mitigation techniques to prevent failures due to corrosive sulphur are actively discussed, e.g. in [2, 3]. The "sulphur problem" and its impact on tap-changers will be discussed in one of the next issues of Transformers Magazine.

2.2. Mineral oils for arctic applications

Insulating oils for arctic applications are basically the same as classic mineral oils, but with a lower pour point, which is achieved by pour-point depressant additives and/or oil molecules with adequate chain length. They show a better liquid flow at arctic temperatures and so provide better cold start properties. IEC 60296 specifies such oils with a LCSET (lowest cold-start energizing temperature) of -40 °C, which corresponds to a maximum viscosity of 2500 mm²/s and a pour point

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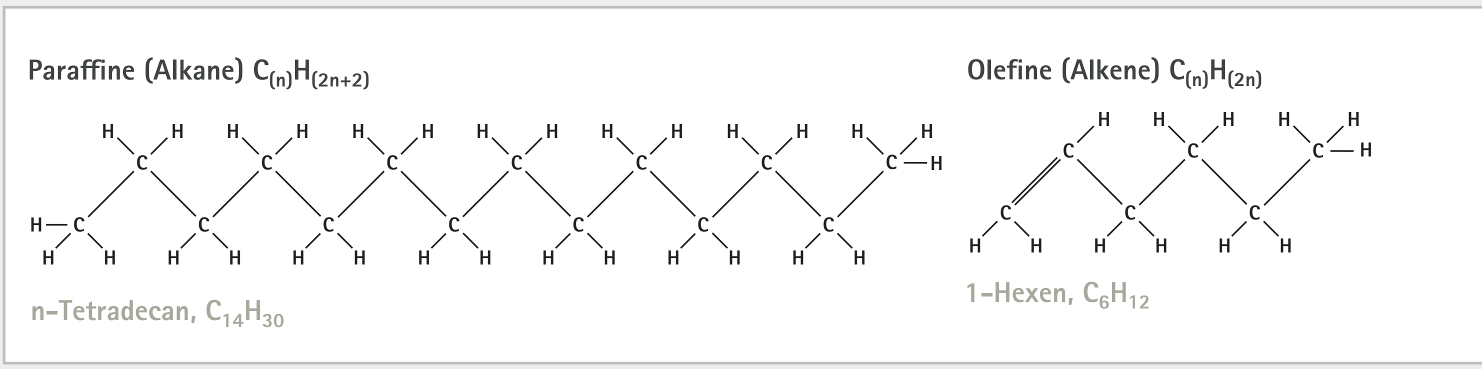


> **With tap-changers, the switching sequence depends on the viscosity and lubricating properties of the oil**

of max. -50 °C. The national Canadian Standard CAN/CSA-C50 specifies arctic oils as “Class A oils” with a pour point of max. -46 °C and a max. viscosity of 2500 mm^2/s at -40 °C. Such oils are mostly naphthenic, but, curiously enough, the transformer oil with the lowest viscosity known on the market, LUMINOL™ TR/TRi, is a synthetic isoparaffin liquid, which has been refined from crude oil by distillation, multi-stage hydro-treatment and anew distillation.

Concerning tap-changers, the switching sequence depends on the viscosity and lubricating properties of the oil. The diverter switch is a spring-driven device with limited spring energy. The accumulated spring energy is the only driving force performing the load-switching process within a closely defined time frame. If the oil viscosity is too high, the switching sequence cannot be completed, which will inevitably cause malfunction. To ensure proper function in cold climate situations, numerous tests with different insulating liquids have been performed to define the lowest admissible liquid temperature.

Table 2 shows the minimum oil temperatures for OLTC operation in mineral oils.

Because the lubricating capability decreases with increasing liquid temperature, the upper temperature limit (defined to 130 °C) has likewise been verified. It can be stated that all mineral oils show sufficient lubricating capability at these high oil temperatures.

Note: Arctic mineral oils may not be confused with “low-temperature switchgear oils”, which show a very low viscosity but have a flash point much lower than transformer oils (min. 105 °C versus min.135 °C, acc. to IEC 60296). Therefore, low-temperature switchgear oils may not be applied in transformers which show hot-spot temperatures up to 140 °C (limit acc. to IEC 60076-7, Table 4).

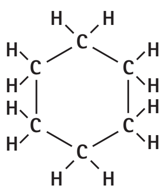
2.3. Oil manufactured from natural gas

Due to diminishing natural resources for low-sulphur crudes, petro industry has begun to generate oils from natural gas (methane, CH_4). The so-called “Gas-to-Liquid” process (GtL) is quite complex, with an interstage paraffin product (wax) which is being hydrocracked and then distilled to different fractions (e.g. GtL kerosene, GtL gas oil and GtL base oils). From the base oils an almost colorless oil is composed; very pure, absolutely sulphur-free, and with well-defined properties. All data comply with the general specifications of IEC 60296 (Table 2). Inhibitors are added

Table 2. Permissible temperature range for MR on-load tap-changers filled with mineral oil

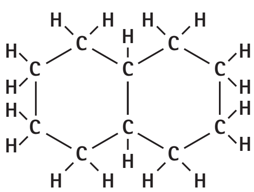
OLTC type	Mineral oil type / Brand name	Oil low temperature limit [°C]
OILTAP® V	Mineral oil as per IEC 60296 (LCSET -30 °C)	-25 °C
OILTAP® M, MS, MSE	Mineral oil as per IEC 60296 (LCSET -30 °C)	-25 °C
		-40 °C (Arctic operation)
OILTAP® R, RM	Mineral oil as per IEC 60296 (LCSET -30 °C)	-25 °C
		-40 °C (Arctic operation)
VACUTAP® VV, VR	Mineral oil as per IEC 60296 (LCSET -30 °C)	-25 °C
	NYNAS Nytro Polaris GX, VOLTESSO 35 / N36	-35 °C
	LUMINOL™ TR / TRi	-40 °C
VACUTAP® VM	Mineral oil as per IEC 60296 (LCSET -30 °C)	-25 °C
	LUMINOL™ TR / TRi	-40 °C
VACUTAP RMV-II	Mineral oil as per IEC 60296 (LCSET -30 °C)	-25 °C
		-40 °C (Arctic operation; with heater)

Naphtene $C_{(n)}H_{(2n)}$



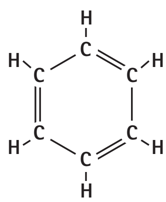
Cyclohexan, C_6H_{12}

Naphtene $C_{(n)}H_{(2n)}$



Decalin, $C_{10}H_{18}$

Aromate



Benzol, C_6H_6

Due to diminishing natural resources for low-sulphur crudes, petroleum industry has begun to generate oils from natural gas methane, called GtL (Gas-to-Liquid)

to upgrade this oil to Super High Grade status.

MR has tested the SHELL GtL product S4 ZX-I with vacuum type and oil-switching type OLTCs and found it comparable to classic mineral oils. Dielectric insulation, arc-quenching and lubrication behaviour showed similar figures. It was noticed that the viscosity was very similar to LUMINOL™ TR/TRi down to oil temperatures of approximately -35 °C but then steeply increased at lower temperatures. The pour point was reached at around -42 °C. This indicates that a) there was no pour-point depressant additive present, and b) molecule length and structure varied only in a very small bandwidth.

With high-quality crudes becoming rare, the use of recycled mineral oils starts to gain importance

Following our test results, a general approval for all tap-changer types could be issued for unlimited use in the normal oil temperature range (-25 to +115 °C).

One further noticeable difference was that switching arcs of oil-switching type OLTCs produced significantly higher amounts of carbon particles with smaller particle sizes than with classic mineral oils. In case an oil filter unit is used to keep the oil clean and so allows for prolonged maintenance intervals, one must be aware that the filter can get clogged preterm. Further investigation on this issue is advisable.

2.4. Recycled mineral oils

With high-quality crudes becoming rare, the use of recycled mineral oils starts to gain importance. Different qualities of recycled insulating oils are offered, depending on the recycling method. *Reconditioned oils* have been physically processed by filters to remove insoluble contaminants, dissolved water and gases. *Reclaimed oils* have been run through chemical and physical processes to eliminate soluble and insoluble contaminants. And finally, *re-refined oils* have undergone processes which are similar to the production of new insulating oils, including distillation and hydro-treatment. It is now up to the user to decide whether, and if yes, which quality of recycled oil he wants to use in a transformer or tap-changer.

As a guideline, IEC 62701 was issued in 2014 to clearly separate unused mineral insulating oils (acc. to IEC 60296 and comparable) from recycled oils. Both standards specify identical limit values, but nevertheless, there is a lively discussion if recycled oils are *really* equivalent to unused oils. The problem is that both specifications cover the *main* properties only, while there are other parameters not specified in the standards which may lead to differences in long-term performance. Recycled oils may contain dissolved metals, sulphur compounds or substances with unknown effect. The long-time experience with unused mineral insulating oils has proven their reliability and compatibility, but for the time being, this cannot generally be claimed for all recycled oils. There is no doubt that, by using appropriate recycling methods, it is possible to produce a recycled oil which is equivalent to unused oils, but due to the varying input quality, every batch may need adjusted recycling procedures, and every output must be tested thoroughly.

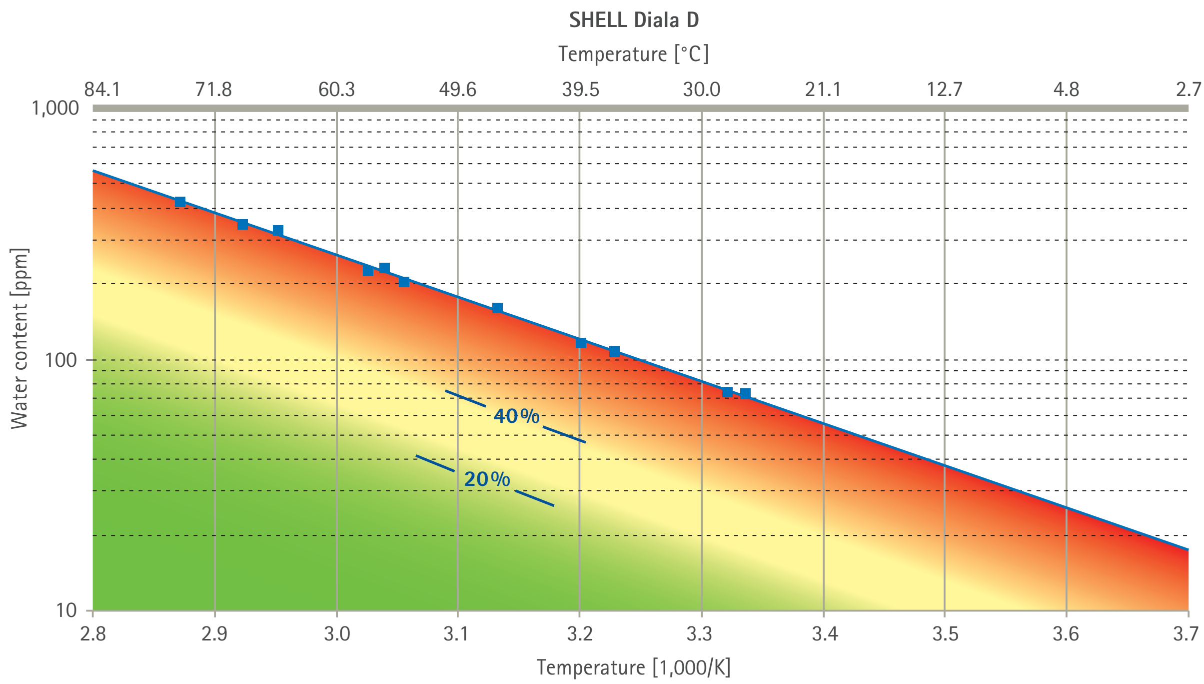


Figure 2. Water saturation curve for mineral oil SHELL Diala D with markers for 20 and 40 % saturation level

For the use in tap-changers, the really important parameters of mineral oil in field service are dielectric strength and water content

It has to be pointed out that IEC 62701 does not discriminate against recycled oils; it just intends to emphasize the provenance of their feedstocks. Nevertheless, the first issued version of the standard has been withdrawn due to legal challenges from manufacturers of recycled oils. Now, the future of IEC 62701 is uncertain, as there are different opinions on how to proceed. While one party votes for introducing recycled oils into IEC 60296, the other party aims for separate standards. There is a common understanding that it is not the task of standards to judge different designs or manufacturing processes, but to concentrate only on performance characteristics. As these are currently defined to be the same for unused and recycled oils, in my opinion two different standards, which complement each other, are necessary.

3. Significance of water for the dielectric strength of mineral oil

Due to their organic origin, mineral insulating oils feature a huge variety and wide range of properties, rendering them very special liquids. For their use in tap-changers, some dielectric parameters like dissipation factor, interfacial tension or gassing tendency have not been identified as crucial. The really important parameters in field service are dielectric strength (U_d) and water content (H_2O). U_d should be sufficiently high and H_2O should be as low as possible – simply stated. IEC 60422 defines detailed limit values for these parameters for mineral oil in service, depending on the category of equipment and the application (e.g. voltage class). If the water content is low, a "technically clean" oil will usually show a sufficiently high U_d at normal operating temperatures. "Technically clean" is an oil which is not excessively polluted by fibres or particles (such as soot or metal from abrasive wear), or by massive deterioration, which becomes visible through very high acidity values.

Figure 2 shows the recorded water saturation curve for SHELL Diala D, which was a widely-used uninhibited transformer oil (not available any more). For other mineral oils, the water saturation level can be slightly different. The water absorptive capacity increases with oil aging (oxidation) due to the formation of polar compounds in the oil.

Up to the saturation level of 20 %, any mineral oil will show good U_d values (>50 kV/2.5 mm IEC). Above 40 % saturation, U_d can be unacceptable (<30…40 kV/2.5 mm IEC). From this, one important message can be derived: *Keep your oil always dry!*

Figure 2 also shows that the water saturation varies strongly with temperature. This means that an oil with 12 ppm absolute water content is called "dry" at 25 °C oil temperature, but "wet" at oil temperatures below 5 °C, and then will likely show a U_d of less than 40 kV/2.5 mm IEC (at least). To complicate things, the water absorbed by the solid insulation materials also varies with temperature. Depending on the gradients in vapour pressure between oil and the solid materials, humidity from the oil diffuses into the solid materials when the oil gets cold, and is emitted again from the solids when the oil is heated up. This can cause significant variations in oil humidity, which follow the oil temperature changes with delay. This process is well-known for transformers, concerning the interaction between cellulose and oil. Here, the volume ratio between cellulose and oil can vary strongly, depending on the voltage class and transformer rating, and therefore the changes in relative water saturation can be high or low. For tap-changers, the ratio varies much less and can cause significant changes in the relative water saturation as a function of temperature.

All solid insulating material used in a tap-changer can hold a specific amount of water, depending on the material, and the total water amount can easily saturate the oil with water if not dried before initial use. So, the second message is: *Dry the diverter switch like the transformer before use!* Details how to do this are described in the type-specific installation manuals of the tap-changer.

In the next issue of Transformers Magazine, I will discuss non-mineral liquids and our experiences with these liquids. Please stay tuned.

Bibliography

[1] Ed Casserly, Ergon Inc., *Transformer Oil*, Doble "Life of a Transformer" Seminar, 2015, Lyon, France

[2] CIGRE TB 625, *Corrosive Sulphur Long Term Mitigation and Risk Assessment*, CIGRE WG A2.40, 2015

[3] J. Lukic, *Silver Sulphide Corrosion*, TechCon Asia-Pacific April 2015, Sydney, Australia

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