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NEW IMPACTS ON ECOLOGICAL TRANSFORMER DESIGN

Ernst Pagger[1], René Braunstein[2], Johannes Wisiak[2], Georg Pukel[3]

[1]EPP Consulting GmbH, Koschatstraße 15a 9400 Wolfsberg, Tel.: +436602367283, ernst.pagger@epp-consulting.at, www.epp-consulting.at

[2]Energienetze Steiermark GmbH; Leonhardgürtel 10, 8010 Graz; Tel.: +43 (316) 90555-52714, Fax.: +43 (316) 90555-22790, rene.braunstein@e-netze.at, johannes.wisiak@e-netze.at, www.e-netze.at

[3]Siemens AG Österreich, Transformers Weiz, Elingasse 3, 8160 Weiz; Tel.: +436648011771583, georg.pukel@siemens.com, www.siemens.at

Abstract: Mineral oil combined with cellulose is a reliable insulation system that has been used as the "classic insulation system" for nearly one hundred years. But because of their properties - low flash- and fire point and their environmental impact - their use must be seen critically. For example, more than one hundred people were killed in Dhaka (Bangladesh) because of a transformer fire in 2010. One of the environmental impact would probably be the discharge of oil or firefighting water into the soil, which could affect the water table. With the ester liquids, above all with the natural ester there exists an excellent alternative to mineral oil. These liquids have a high fire point (K-class), they are readily biodegradable and above all natural ester have a very low CO_2 footprint. But because of some divergent properties of these liquids compared to mineral oil, this must be considered in the transformer design. Generally, ester liquids have a higher viscosity and natural ester has a higher pour point compared to mineral oil. The natural ester is sensitive to oxygen and should therefore only be used in closed systems. After weighing up the advantages and disadvantages and verification by an external expertise, Energienetze Steiermark GmbH decided to install a pilot transformer filled with natural ester FR3™ fluid in the spring of 2017.

Keywords: transformer, mineral oil, natural Ester, synthetic Ester, FR3, fire, biodegradable

1 Environmental hazard because of the use of mineral oil

Transformer explosions caused by dielectric failure are responsible for over 50% of the disasters [1]. Due to the sometimes large amount of insulating oil and direct contact with high-voltage elements, transformers filled with mineral oil are one of the most dangerous electrical devices [2]. In case of the release of mineral oil as a result of a fire (fire-fighting water) or because of discharge in the environment very high remediation costs are generated. This is because of its poor biodegradability.

1.1 Flammability

The biggest driving force in search of alternatives to mineral oil is its flammability. As a result, accidents involving personal injury and severe environmental damage have occurred and are still occurring today. *Figure 1* shows the significant difference in the fire point of the insulating liquids – data taken from [3]. With a fire point of > 300 °C, natural esters are classified as K-class insulating liquid according to IEC 61039 [4]. This allows smaller distances to buildings and adjacent transformers [5], [6].

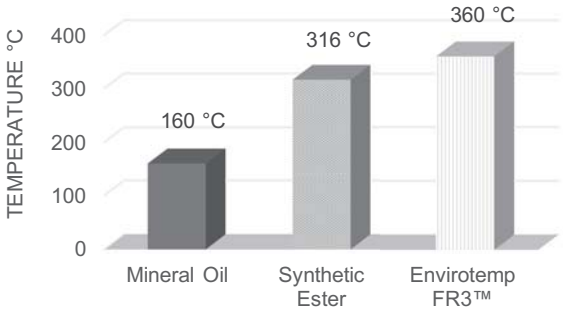

Figure 1: *Fire point of transformer liquids*

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Oil insulated equipment is the main source of substation fire. The question is, if an automatic spray system can protect against fire and can survive a transformer explosion. But firefighting systems can even be the reason for a transformer explosion. In Brazil, a transformer in a 500 kV substation was operating under normal conditions when the spray system was activated by a false alarm. As sprinkler head was placed facing the bushing instead of the transformer tank, an external arc was created which caused the rupture of the bushing and led to fire [7].

Fire prevention philosophy requires the selection of materials and design features that will prevent and lower the risk of transformer fire. “Using natural ester as a dielectric, for example” writes Duarte in [7].

1.2 Biodegradability

Accidents in the extraction and transport of petroleum and petroleum products, as very often evidenced by the media, have a devastating effect on fauna and flora. And this is because of the very bad biodegradability of these substances. *Figure 2* shows and compares the biodegradability of the main used insulating liquids [8]. The graph shows that the natural ester is complete degraded in less than 30 days, whereas the mineral oil is only degraded by about one third at this time.

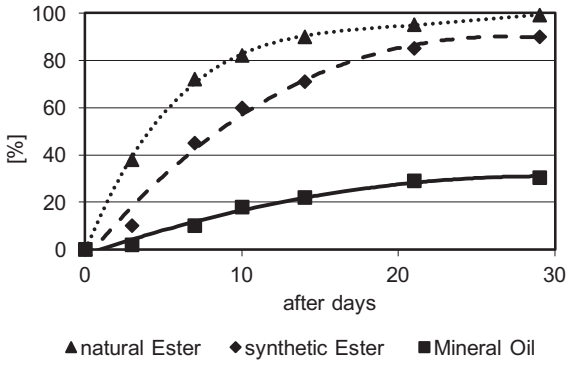

Figure 2: *Biodegradability of different insulating liquids*

1.3 Influence on the climate

The basis of the natural esters are vegetable oils stemming from renewable raw material, which is also reflected in the CO_2 balance compared to the mineral oil. *Figure 3* compares the CO_2 emission by using the natural ester FR3™ fluid with mineral oil over a balance period of thirty years (data taken from [9]). This low level of CO_2 emissions - in this case, that of soybean oil - is mainly driven by growth-induced carbon dioxide uptake during photosynthesis. No such data are available for synthetic ester liquids. In any case the basic for synthetic ester is mineral oil, too.

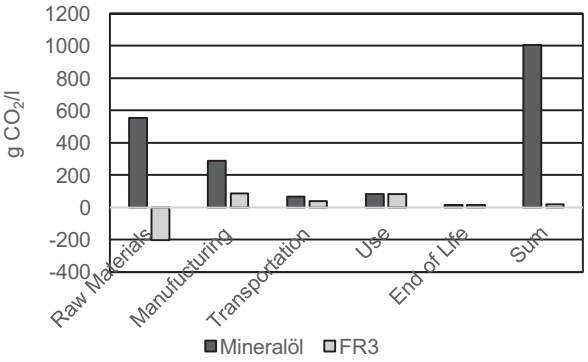

Figure 3: *CO_2 emission over a period of 30 years*

2 Material properties that influence the transformer design

Because of a number of exceptional properties over mineral oil, ester liquids are now being used in more medium and large power transformers [10]. Different material properties compared to the mineral oil must be taken into account in the transformer design.

2.1 Viscosity and thermal design

Figure 4 shows the dependency of viscosity on temperature of mineral oil (Nynas 4000x), natural ester (FR3™) and synthetic ester (Midel 7131) [8], [11]. The viscosity of mineral oil is significantly lower compared to the ester liquids. The difference between the ester liquids is not essential in the area relevant to the transformer operation. Because of the appreciably higher viscosity of ester liquids compared to that of mineral oil, the flow of ester liquids through the windings, core, and cooling equipment is lower than that of mineral oil, leading to a relative increase of top oil, windings, and core temperatures [10]. For liquids with higher viscosity, a reduction of the flow rate must be considered. At the same time, ester liquids have higher thermal conductivity and slightly higher heat capacity than mineral oil.

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The impact of ester liquids on the windings average and hot spot temperatures in a power transformer is mainly determined by velocities of the liquid in the windings, winding duct dimensions, and impact of the liquid characteristics [10]. For heat transfer the higher viscosity can partly compensated by the higher thermal conductivity [12].

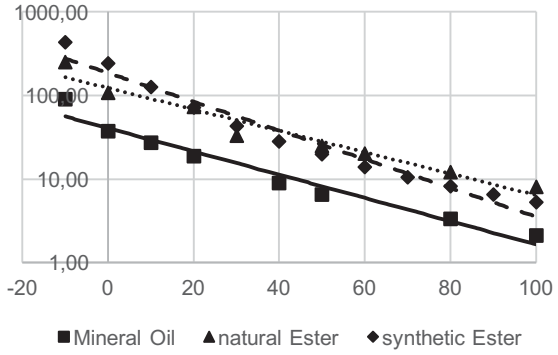

Figure 4: *Kinematic viscosity versus temperature*

2.2 Material compatibility

Because of the possibility to bind water chemically and physically, natural- and synthetic ester can dry out the cellulose. This means a large increase in transformer insulation life. Most transformer materials (copper, steel, aluminum, cellulose etc.) are compatible with ester liquids. Care must be taken for the gaskets. Elastomers including NBR types with higher nitrile content, silicone or fluoropolymer are recommended. Gaskets with higher temperature demands warrant the use of silicone or fluoropolymer (Viton) compositions [13], [14].

2.3 Oxidation stability

As oxidation processes dramatically increase the viscosity for the natural esters in open systems, an application in open breathing transformers should be avoided. To ensure and maintain optimum performance of natural esters, exposure to oxygen and moisture must be minimized. Compared with standard transformers the hermetic power transformer with a vacuum type tap- changer has not only the advantage of less ageing, it also requires less maintenance during the total lifetime [15].

2.4 Electrical stress

In an insulation system composed of liquid and solid insulating materials, the distribution of electrical stress between the solid and liquid dielectrics is governed by the relative values of the dielectric constant of both the liquid and solid materials. The dielectric constants of ester dielectric liquids are typically higher than that of mineral oil and closer to the dielectric constant of pressboard and insulation paper. Because of the better match of the dielectric constants in an ester liquid/pressboard system, the disparity in distribution of stresses between solid and liquid is lower than that in a mineral oil/pressboard system [10].

Pay attention - the differences in the liquid's electrical withstand properties between ester and mineral oil are not to be neglected. Specifically in the event of fast transient impulse stresses, esters tend to exhibit a significantly lower withstand capability in comparison to mineral oil [*16*].

3 Field test

After weighting up the advantages and disadvantages and in order to gain experiences with the above mentioned characteristics of natural ester liquids in practical Energienetze Steiermark GmbH started a pilot project and put the first natural ester based transformer in operation in May 2017.During the approval test in April 2017 several oil samples were taken before and after routine test, PD test, Lightning-impulse test and heat run.

The first analysis (*Figure 5, Figure 6*) show no significant abnormalities. The transformer is now in operation for almost a year without any problems.

In future oil sample tests of this transformer will be carried out in regular intervals, for example every three years, in order to gain more experience with this transformer oil.

The transformer with a rated power of 250 kVA replaced an old pylon transformer station with 100 kVA (*Figure 7*). The location is very close to a water protection zone.

Although mineral based insulating oil is the most common type of insulating oil in use, environmental and safety reasons encouraged Energienetze Steiermark GmbH to deal with this topic. From an actual point of view, it can be said, that transformers with natural esters will not yet be used on a large scale, but be-

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side their green footprint they can make a significant contribution to expand the possibilities of a distribution grid operator.

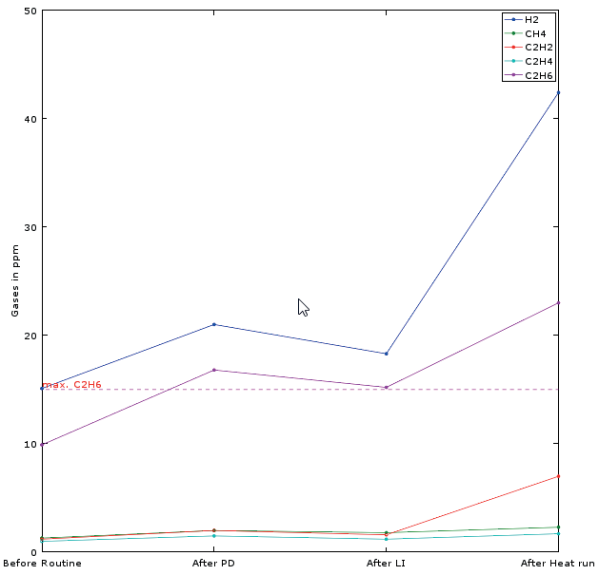

Figure 5: *Timeline of gas concentration during approval test*

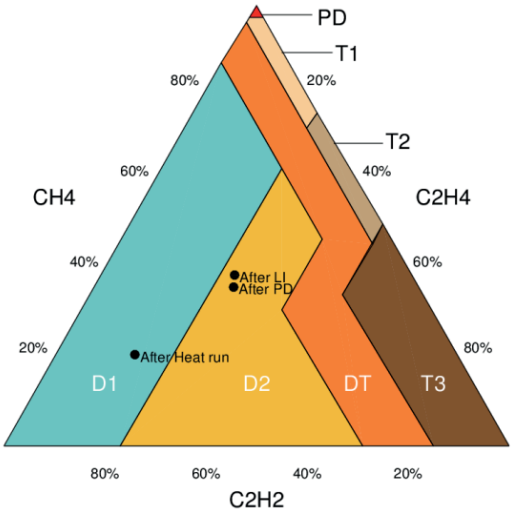

Figure 6: *Duval Triangle for natural ester liquids, for the approval test*

Figure 7: *100 kVA pylon transformer station replaced by a natural ester transformer*

The following *Figure 8* shows the locations of the actual natural based transformers in Styria, excluding a hand full of transformers in stock which will replace existing transformers in case of disturbances or damages.

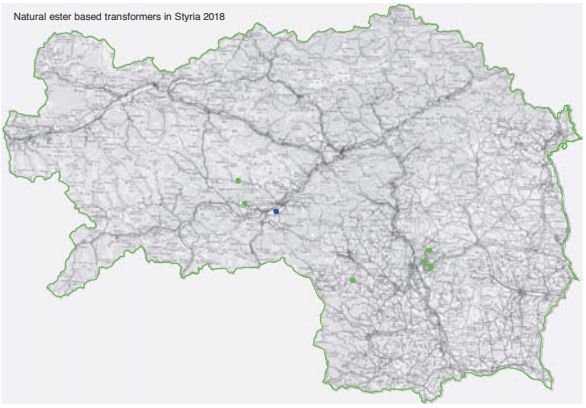

Figure 8: *Geographical disposition of natural ester transformers in 2018, blue … Pilot 2017, green …new transformers 2018*

The mainspring for this ongoing pilot-project is not the rapid economic success, it is the ecological success as well as the expansion of the application possibilities if you think on water protection zones or fire protection in crowded areas. At the moment the purchase prices are approximately 10 % above the prices for conventional oil transformers. However, it also has to be considered that in case of damage the costs are much lower. In addition to that the possibilities of more favourable insurance rates are proved at the moment.

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