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BIOTEMP® TRANSFORMERS IN THE MODERN SUBSTATION

SUMMARY

This paper presents some of the advantages and critical aspects related to the use of BIOTEMP® as a dielectric and cooling medium in transformers. Investigations on natural esters as an alternative to mineral oil started in the early 90's and already in 1996 the first small distribution transformers were manufactured and installed. Since that time, many transformers designed for mineral oil have also been retrofitted with natural esters. Nowadays this technology is known and gaining ground in larger units. Raising the current and voltage limits poses a number of problems to the designers and to the developers, since the cooling performance and the dielectric withstand of these fluids are quite different compared to mineral oil. A real case of thermal modeling is presented in this document and the calculated temperature rise values are compared to measurements on a real unit.

Considering the trends of the world energy demand and the evolution expected for the power grid architecture in the future, the BIOTEMP® transformer technology could answer many of the needs for a reliable, safe and sustainable power system.

Key words: BIOTEMP®, ester filled transformers, vegetable oil, fire safety, aging, overloading

1. INTRODUCTION

1.1. Requirements on modern power systems

Today's world energy scenario features unprecedented challenges. While the energy demand is steadily increasing especially in rapid developing countries, the impact of the traditional resources based on fossil fuels on the global warming and climate change in no longer acceptable. There is a strong need to integrate more renewable resources (solar, wind, etc…) in the modern power systems. Since such resources are inherently of intermittent nature, the traditional concept of centralized power generation and one-directional power flow will be changing into centralized and distributed generation with multi-directional power flow.

All infrastructures to produce, transmit, distribute and consume energy were designed decades ago, when the situation was not so demanding. The consequences of these new challenges are particularly important for the fleet of power transformers operating (and aging) in the electrical system.

For instance, their short circuit withstand capability becomes more and more critical as the network capacity increases. Their no load and load losses can exceed the currently acceptable values. In summary, since these transformers are required to operate close to their physical limits, their reliability can be the ultimate concern.

1.2. Requirements on modern transformers

Transformers are a rather mature product. Since their invention more than one century ago, many different design solutions and materials were applied trying to improve their performance, until the technology stabilized into the product we know today. There have also been some specific fields of application were stringent and non standard requirements were actually conditioning the design. In case of traction transformers, transformers for mobile substations, transformers installed in areas subjected to fire regulation or where the environmental impact is critical, furnace transformers, etc… variants and adaptations of the ordinary solutions were studied and applied. Example can be found in [1] - [3]. Some of the distinctive features developed within these applications can suitably meet the requirements of the modern power systems.

a) Extended power capacity. Especially when the space availability is limited, a natural choice is to increase the power density (rated MVA per kg) using upgraded insulating materials. This is a typical requirement not only for traction and mobile substation transformers, but also for transformers installed in highly populated areas, where it is more economical to embed spare capacity into the existing equipment than installing a new one.
b) Intermittent generation and changes in the power flow may result in prolonged overload conditions of certain network components. The ability to meet severe duty cycles without detriment to the expected life time of the equipment is a classic requisite for industrial transformers.
c) Reliability and availability of the power supply can become critical in case of disturbances to the electrical system. The risk for blackouts or catastrophic events like fire and explosions shall be mitigated. Transformers installed in areas with additional fire risk (refineries, tunnels, ships, populated areas, etc…) are normally designed against this type of events.
d) Sustainability and efficiency are two of the most important drivers of the future power grids. The concept of total owning cost is gaining attention among power system engineers, who nowadays are prescribing very low values of no load and load losses. The advantage is twofold because both the operational costs and the overall carbon dioxide emissions are minimized. The expenditures for maintenance and disposal of the assets are considered as well.

Already in 1890, i.e. just five years after the invention of the transformer, mineral-based oil was used by Brown Bovery & Cie as dielectric and cooling medium. Its combination with cellulose paper as solid insulation prevailed over any other insulation system, although alternative materials have been proposed over the years, in order to mitigate the inherent shortcomings of this fluid. One of the biggest disadvantages of mineral oil is its combustibility: important fire safety equipments have to be installed in order to mitigate the fire related risks. Another drawback is the environmental unfriendliness: oil spills must be treated as toxic waste and require expensive containment. Besides these traditional and well known issues, the availability of crude oil in the future and the fact that the price of this commodity is rising shall be taken into serious consideration.

As described in IEC/TS 60695-1-40 [4], Annex A, askarels were introduced in the 30's of the last century in electrical equipment (transformers, capacitors, etc…) as a way to mitigate the fire hazard. Although these fluids performance against fire was very good, their production and use was banned because of their toxicity. In the 70's, other types of fire resistant fluids, such as silicones and high temperature hydrocarbons, started to be applied. Their disadvantage was to have a low biodegradability. In the 80's, ester fluids started to be used. They combined excellent fire safety properties and environmental friendliness, as they were highly biodegradable.

In this paper, the remarkable benefits offered by natural esters in transformers are presented. The differences between an ester and a mineral oil filled transformer are mentioned together with the most critical design considerations.

2. BIOTEMP® TRANSFORMER TECHNOLOGY

2.1. Basic properties

BIOTEMP® is a natural ester fluid made from renewable and biodegradable vegetal based oil from sunflower seeds. It was developed in ABB during the 90's and successfully introduced in the market in 1999. Table I summarizes the most important physical properties of BIOTEMP® in comparison with typical values for other insulating fluids.

Table I – Properties of different fluids

Property	Mineral Oil	BIOTEMP®	Synthetic Ester	H.T.H.	Silicone
Specific Gravity (g/ml)	0.91	**0.91**	0.97	0.87	0.96
Flash Point (°C)	160	**330**	275	285	300
Fire Point (°C)	180	**360**	322	308	330
Pour Point (°C)	-40	**-15**	-60	-24	-55
Viscosity (cSt) @ 100°C	3	**10**	6	12	16
@ 40°C	12	**45**	29	110	38
@ 0°C	76	**300**	280	2,200	90
Breakdown Strength (kV) (ASTM D 877)	50	**52**	*> 75**	40	43
Power Factor (%) @ 25°C	≤ 0.05	**0.15**	0.10	0.01	0.01
Relative Permittivity (-)	2.2	**3.2**	3.2	2.2	2.7
Volume Resistivity (Ω.cm)	10^{15}	**10^{13}**	*> 5 x 10^{13}**	10^{14}	10^{14}
Biodegradability (%) (CEC L-33-A-93)	30	**99**	80	20	5

* Not measured according to the same Standard methods

BIOTEMP® is environmentally safer than other liquids used in transformer design, as it can be notices in Figure 1 which presents biodegradability measurements on different fluids carried out following the Coordinating European Council (CEC) method. BIOTEMP® is on average 99% biodegradable in 21 days, while mineral oil, for instance, is 30% only.

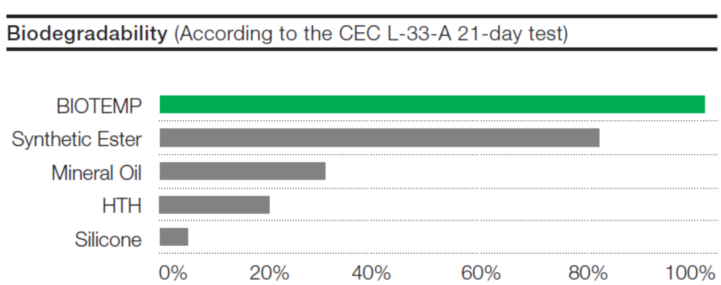

Figure 1 – Biodegradability of different fluids

Concerning fire safety aspects, BIOTEMP® fire point is greater than 300°C and its net calorific value is less than 42 MJ/kg, therefore it is classified as K2 insulating liquid according to IEC 61100 [5]. Factory Mutual (FM Global) and Underwriters Laboratories (UL) have listed BIOTEMP® as "less flammable" dielectric insulating fluid. Even if burning, it only generates carbon dioxide and water.

Another remarkable feature is the water saturation limit. Natural esters are made of very polar molecules which tend to attract water. For this reason, BIOTEMP® tolerates moisture better than mineral oil (which is not polar) at all temperatures, as shown in Figure 2.

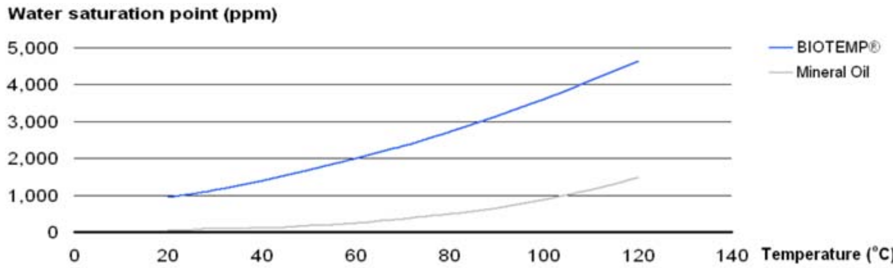

Figure 2 – Water saturation curves

Oxidation stability is another important topic to be considered when dealing with natural esters. The byproducts of oxidation are acids, which can negatively affect the lifetime of the transformer insulation system. At the same time, oxidation can cause an increase in viscosity up to a point where an efficient cooling is prevented. Although there is no universally accepted method to test the oxidation stability of natural esters [6], in general, silicon oils, synthetic esters and mineral oil are more stable against oxidation [7]. Results of the ASTM D 2440 oxidation test for BIOTEMP® showed 0.01% by mass sludge and 0.25 mg KOH/g neutralization number after 164 hours. These values are well below the limits prescribed by ASTM D 3487 for inhibited mineral oil.

Regarding dielectric characteristics, BIOTEMP® has a higher permittivity than mineral oil, while its breakdown strength is comparable (even slightly better) when tested according to ASTM D 877 and ASTM D 1816. Also in the presence of moisture, BIOTEMP® can retain its dielectric strength better than mineral oil. However, it must be mentioned that the flashover mechanism of natural esters and mineral oil are quite different, especially on long gap distances and under non-uniform fields, as described in [8].

Finally, the temperature distribution in transformers filled with BIOTEMP® cannot be determined through the models traditionally used for mineral oil. In fact, despite the better specific heat and thermal conductivity, natural esters have higher viscosity and this fact needs to be duly considered when designing the cooling system.

2.2. Advantages and critical aspects

All basic properties described in the previous section can bring interesting advantages to ester filled transformers. At the same time, there are some critical design aspects deserving special attention.

Among the advantages, the use of a vegetable-based oil not only reduces the carbon footprint (0.07 kg of CO_2 equivalent per kg of BIOTEMP® produced), but in case of spills, often hazardous waste disposal fees and penalties can be avoided. In some cases, containment pits can also be smaller.

BIOTEMP® helps mitigating the fire risk. FM Global has published that for transformers rated 10 MVA and below, water spray protection and barriers are not needed, provided that proper separation distances are maintained.

The greater ability to hold moisture has a direct consequence on the aging rate of the insulation. Under the same aging conditions, the life expectancy is approximately double for transformers filled with BIOTEMP® compared to mineral oil. The same can be seen also from a reliability perspective. Depending on the design, BIOTEMP® filled transformer can be continuously overloaded by approximately 10% and still have the same life expectancy of a fully loaded unit featuring mineral oil. New limits of temperature rises for BIOTEMP® transformers have also been proposed in [9].

Among critical aspects, special precautions have to be taken against the risk of oxidation: specific storage and handling procedures shall be followed. For the same reason, during operation any contact with the atmosphere must be avoided. Also the selection of main accessories (tap changers, bushings etc...) need to be carried out carefully. However, the biggest challenges to be addressed when designing an ester filled transformer are related to the dielectric and to the thermal design.

It is true that from a dielectric point of view, the solid and liquid insulation permittivities are closer in ester filled transformer. This is an advantage, as the field intensity in the fluid, which is in general the weakest material, is relieved. However, special rules and criteria have to be applied when checking the dielectric strength of ester fluids, considering that the discharge phenomenon can be more severe.

Concerning thermal design, the higher viscosity and therefore the lower velocity of the fluid through the windings, the core and the radiators shall be considered. As presented in [10], ester filled transformers have in general higher top oil and lower bottom oil rises, while the average oil temperature is comparable. The winding to oil gradients as well as the hot spot temperature rise can significantly increase. The only way to correctly predict such temperature rises is to use accurate models of transformer cooling which take into account viscosity, conductivity and heat capacity of the fluid.

3. THERMAL MODELING

The transformer described in this chapter is a 20 MVA BIOTEMP® filled unit with KNAN cooling. Normal temperature rise limits were prescribed according to [11]. Paper insulated strand conductors were used for the HV winding. Flow-directing washers were installed in order to impose a flow direction in the horizontal ducts (zig-zag flow type).

The unit was equipped with fiber optics for direct measurements of the hot spot temperature in the HV winding. Figure 3 shows a picture of the sensors while in Figure 4 there is a schematic drawing of their placement.

Figure 3 – Picture of fiber optic sensors

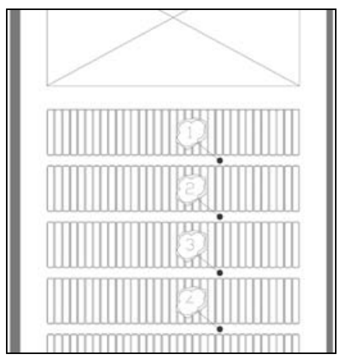

Figure 4 – Placement of the sensors at the HV top-most discs

The winding's radial and axial channels have to be properly designed in order to dissipate the heat and avoid hot spots. Suitable models based on thermo-hydraulic networks or on CFD (Computational Fluid Dynamics) are normally used to predict the fluid velocity and temperature distributions. The use of CFD modeling is particularly andvantageous for ester-based design applications due to the strong thermal stratification in the oil that is to be expected (higher oil Prandtl number as compared to mineral oil). This means that the thermal gradients ("hot streaks") that occur in the oil may have a significant impact on both location and strength of the hottest spot. The CFD approach allows to model the occurrence and effects of these hot streaks in much detail.

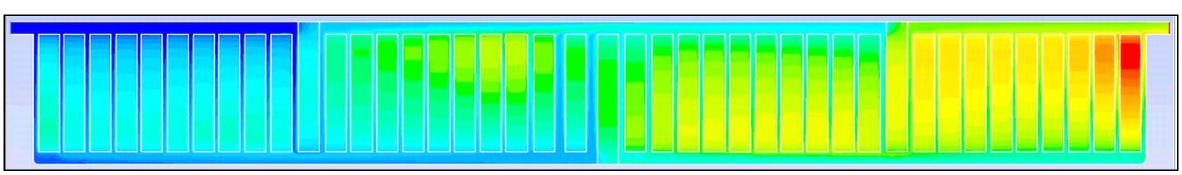

Figure 5 – Temperature distribution in the HV winding

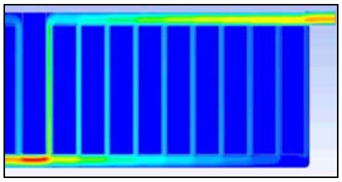

Figure 6 – Magnitude of the oil velocity

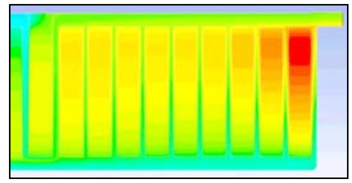

Figure 7 – Temperature distribution in the uppermost pass between the top-most washers

The CFD model used here takes into account geometry variations in spacer height. The model also includes the effect of the temperature depency of the oil parameters, of which the viscosity has the strongest influence. The effect of strands and insulation material on the thermal resistance of the discs has been included as well.

The results in Figure 5, Figure 6 and Figure 7 show well-behaved temperature and oil distributions. There appears to be some thermal stratification in the ducts (visible in the main cooling ducts) but for this particular design the effect of hot streaks does not appear to be very significant. The calculated hotspot temperature agrees well with the measured value, as presented in Figure 8.

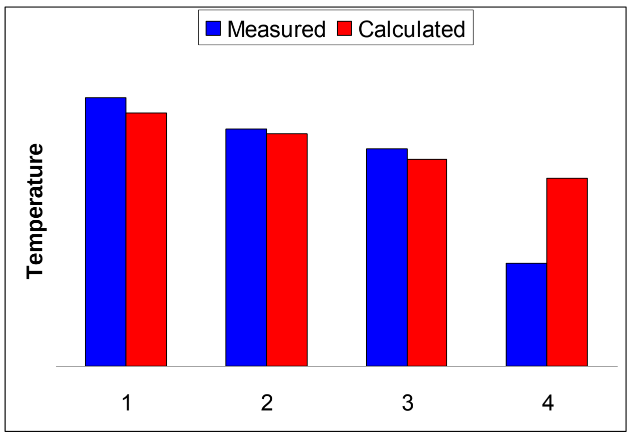

Figure 8 – Comparison between measured and calculated temperature rise

The differences between calculated and measured temperatures are within 1.5 °C, except for the sensor number 4, which indicates 8 °C colder temperature. Most probably, the contact between the sensor and the conductor was not perfect, so that the surrounding oil temperature was actually recorded.

4. CONCLUSION

In this paper, some basic properties of BIOTEMP® have been presented and compared to mineral oil and to other fluids. The most important advantages coming from the use of natural esters in transformers have been highlighted and related to the future developments of the power systems overall. This technology can represent an answer to the need for a more reliable, safer and environmentally friendly product. At the same time, the superior performance of ester filled transformers in terms of aging can allow extending the lifetime of the equipment or, vice versa, increasing its rating without undue aging of the solid insulation.

Some critical design and manufacturing aspects have also been mentioned, with specific reference to the cooling of the windings. Thermal models are available nowadays to correctly predict the temperature and velocity distributions, so that engineers can properly size the oil flow channels in order to remove the heat and keep hot spots under control. A case study of a 20 MVA BIOTEMP® filled transformer has been presented. The calculated temperatures have been compared to the direct measurements taken with fiber optic sensors.

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