Ester fluids for power transformers at >100 kV

Design considerations for the use of alternative fluids

ABSTRACT

Typically for high voltage power transformers mineral oil is used for both cooling and electrical insulation. However mineral oil has some shortcomings in terms of fire safety and environmental impact. The answer to these concerns is to use a more fire safe and environmentally friendly alternative liquid, such as an ester. In order to do this at higher voltages, designers need to understand any differences in thermal and electrical properties. This article aims to give a brief overview of the relevant properties of ester liquids and how this can affect transformer design.

Keywords

ester, safety, environment, natural, dielectric

1. Introduction

The behaviour of mineral oil is well understood and designers have established rules for the construction of transformers through research, as well as trial and error, over many years. In modern times the design of power transformers has become more and more sophisticated, with both electrical and thermal computer modelling now widely used. This allows designers to push the designs to their limits, whilst being relatively confident that the transformer will pass final test if the manufacturing process is without fault.

Despite mineral oil being an effective coolant and dielectric medium, the downsides with it are well known. It is both flammable and environmentally damaging if it leaks or is spilled. There

are numerous occurrences of large mineral oil transformer fires and in each case a large amount of damage is caused, along with costly clean up of the surrounding area if the tank has ruptured in a catastrophic manner. The answer to these problems lies in the use of alternative fluids for power transformers, which are far less flammable and in the case of esters, much more environmentally friendly.

For distribution transformers the use of esters is very well established and synthetic esters have been successfully used for voltages up to 66 kV for over 30 years. When it comes to higher voltage power transformers there is less experience, since the benefits of using a fire safe, environmentally friendly solution have not been realised in the past.

The demand for fire safe, environmentally friendly power transformers is growing and ester fluids are an ideal dielectric solution for this type of equipment.

At higher voltage levels (>66 kV), it is not always possible to use a mineral oil designed transformer with an ester fluid, some design changes may need to be made to accommodate the different chemical makeup of the ester fluid. However the past decade has seen a rapidly growing list of examples around the world where transformers over 66 kV, up to a maximum of 420 kV have been designed for running with esters, and have used them extremely successfully.

Despite the possible need to change designs there are a growing number of enquiries being placed with transformer manufacturers for larger transformers with ester, as the industry starts to see the great advantage these newer fluids can bring. In terms of cost saving, even if the fluid and transformer are more expensive, the removal of ancillary equipment such as fire extinguishers, or reductions in containment can give big savings and very quickly offset the extra capital expense. In addition, there is evidence to suggest that kraft paper will live much longer if immersed in an ester, when compared to a mineral oil, and this extra lifetime can significantly reduce overall cost of an installation if considered over the whole lifetime. There will be situations where mineral oil is the preferred solution, but there is definitely a need to better understand the properties of ester fluids.

2. Permittivity difference

The permittivity of ester fluids is higher than that of mineral oil. This is important for design as the electrical stress in any dielectric structure under AC fields depends on the permittivity distribution. In the ideal scenario materials with the same permittivity will be used for both solid and liquid insulation, since this provides an even distribution of stress across structures.

Fig. 1 shows how the stress distribution in an insulation structure can be calculated by using the permittivity values for synthetic ester. This is a simplified version which does not take into account the stress distribution at the interface between the materials. The stress is inversely proportional to the permittivity, so those structures with higher permittivity carry lower levels of stress.

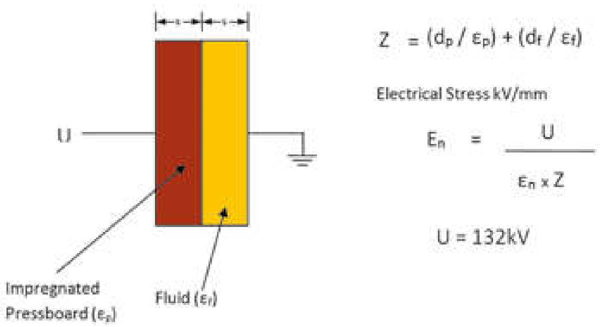


Figure 1: Multi-layer insulation model [1]

This can be demonstrated with an example using an applied voltage of 132 kV and the formula in Fig. 1. The dimensions of the fluid and pressboard gaps are in mm. Note that impregnating the paper with different fluids slightly changes the relative permittivity ε of the impregnated paper; this must also be taken into account when looking at design.

Table 1: Voltage stress comparison

Mineral Oil		Synthetic Ester	
Fluid ε	Impregnated Paper ε	Fluid ε	Impregnated Paper ε
2.2	4.4	3.2	4.7
Fluid Stress	Paper Stress	Fluid Stress	Paper Stress
17.6 kV/mm	8.8 kV/mm	15.7 kV/mm	10.7 kV/mm
Stress Difference Paper-Fluid		Stress Difference Paper-Fluid	
8.8 kV/mm		5 kV/mm	

Table 1. shows that the voltage stress in the fluid is reduced by changing from mineral oil to synthetic ester; the voltage stress in the paper is increased. Generally the paper is considered to be the stronger of the two dielectrics so having a higher voltage stress in the paper is desirable. The difference in stress between the paper and fluid is lower for the ester, indicating a more even distribution.

The effect of reducing liquid stress can be seen when looking at the behaviour of oil wedges in breakdown tests of pressboard. Especially with thick pressboard synthetic ester which gives a better breakdown performance than mineral oil, despite the fact that in terms of oil breakdown, the two fluids are equal at the gap size tested. The result in Fig. 2 from a study by the University of Manchester shows this difference. [2]

The relative permittivity of dielectrics effects the electrical field distribution in winding structures and must be taken into account when designing transformers

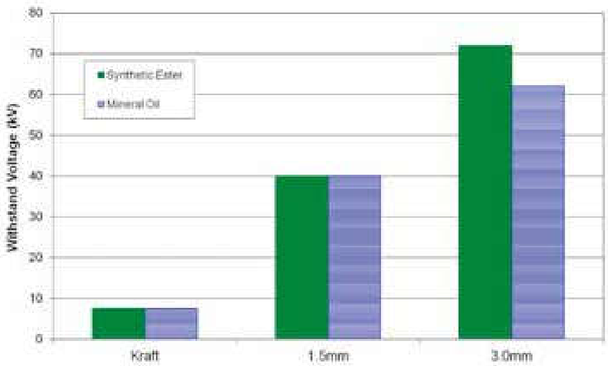


Figure 2: Breakdown voltage of impregnated pressboard

The main reason for this difference in performance is down to the oil wedge, as shown in Fig. 3, where the breakdown initiates due to high local electrical stress. In synthetic ester the stress level in this area will be lower, for the same applied voltage, meaning that a higher breakdown voltage is possible.

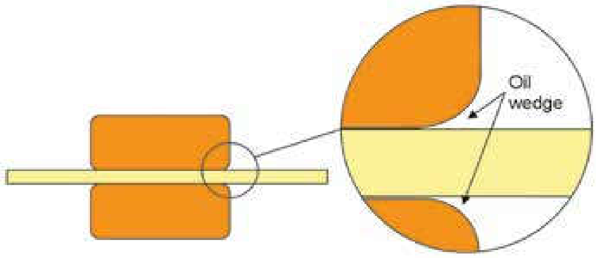


Figure 3: Oil wedge in test electrodes

Where this is less straightforward is in non-homogeneous structures and here a little more care needs to be taken to ensure that peak field strengths are kept within limits. Taking another example shown in Fig. 4, it can be seen that despite the lower stress in the synthetic ester around the winding end the peak stress is higher for an ester at 20.51 kV/mm, compared to 17.97 kV/mm for mineral oil, given the same structure.

However if this is understood, then it is perfectly possible to redesign to reduce stress in key areas, usually at the winding ends and around static rings.

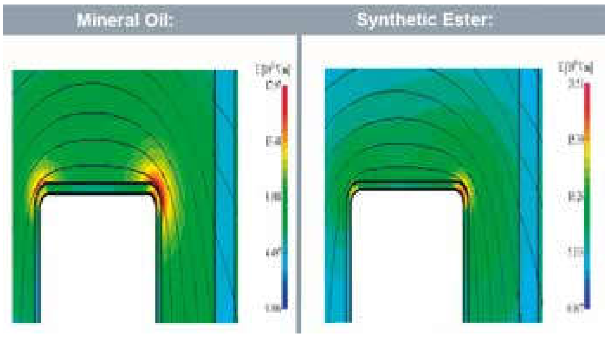


Figure 4: Stress plot for winding arrangement [3]

3. Thermal design considerations

Viscosity is the main parameter that affects thermal performance of fluids for cooling, especially in naturally cooled systems. Other parameters such as specific heat capacity and thermal conductivity come into play, but essentially the ability for the fluid to flow unimpeded around and through the windings governs the ability to remove heat. When manufacturers consider the use of an alternative fluid for a power transformer, it is important that the fluid characteristics are taken into account. Thermal modelling of windings allows designers to evaluate the difference in temperature rise for an ester filled transformer, compared to standard mineral oil. Fig. 5 shows an example of a thermal calculation for a winding, taking into account three different fluids.

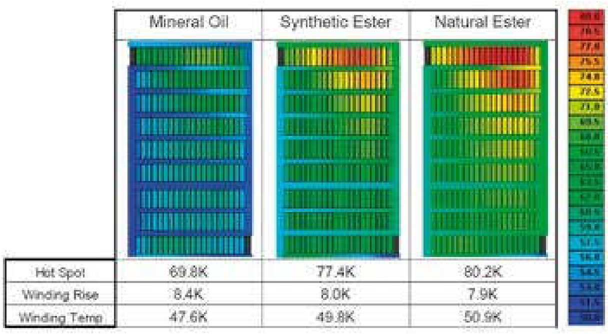


Figure 5: Thermal model comparison [3]

To counteract the higher temperature rise for esters, it is possible to have larger cooling channels in the windings and between windings and barriers. The down side to this is that electrical stress is increased in the fluid as the cooling duct becomes larger. This is offset somewhat by the permittivity difference between mineral oil and ester, but ultimately a balance has to be met between cooling efficiency and electrical performance.

The temperature limits are set by the ageing rate of cellulose paper for the majority of transformer designs in the power category. Unless the manufacturer moves to use a hybrid or semi-hybrid design with high temperature insulating materials such as aramid paper, then they are restricted to the maximum acceptable hot spot. There is evidence to suggest that paper will age more slowly in ester fluid than it does in mineral oil. In this case it may be possible to accept a higher temperature in the ester transformer hot spot, while still retaining the life of the transformer. The latest revisions of the IEEE and IEC thermal standards give some extra guidance on this aspect of esters.

There is compelling evidence from laboratory studies that ester fluids can have a beneficial effect on paper lifetime, which allows higher hot spot temperatures.

4. Case studies

Despite the need for some design adjustments, there are a growing number of high voltage transformers now using ester fluids. The following are some examples of where the benefits of esters have outweighed the higher capital cost of utilising these fluids.

4.1 KWO Switzerland

Kraftwerke Oberhasli AG (KWO) is one of the leading hydropower companies in Switzerland and they have nine power plants, with 26 turbines and a total capacity of 1,125 MW. These are spread over eight reservoirs on the Grimsel and Sustenpass. In total they produce around 7% of the electricity coming from Swiss hydroelectric power plants.

For a specific project KWO needed four 50 MVA converter transformers along with a number of auxiliary distribution transformers for an underground installation. In the past these transformers had always been filled with mineral oil, which necessitated the installation of a complicated fire suppression system. An alternative solution which was proposed was to use synthetic ester filled transformers and remove the requirement for fire suppression. In order to do this, a comprehensive risk assessment had to take place to ensure that the ester solution was of equal safety to the mineral oil with fire suppression. The Swiss Institute for the Promotion of Safety and Security (SWISSI) were engaged to carry out the study and their conclusion was that the ester solution was viable and in some cases superior to using mineral oil with suppression. Subsequently KWO ordered and installed transformers filled with synthetic ester, without any extinguishing system. This saved them cost in both initial installation, but more importantly ongoing maintenance. Without a complicated automatic fire extinguishing system there is no need for expensive routine checks and repairs, which would also require downtime on the transformers. In this case the savings far outweighed the extra cost of using synthetic ester in the transformers.

4.2 Vattenfall 238 kV GSU transformer

In 2002 Vattenfall AB identified a need for a new transformer for their underground hydropower station Stalon, located between Lake Malgomaj and Lake Kultsjön by the Ångermanälven River in northern Sweden. There were certain issues that came up in relation to this transformer, which meant that mineral oil was a less desirable option. In the first place the transformer was to be placed underground, so fire safety was critical, secondly, and just as importantly, the power station was located in an environmentally sensitive area, where spillage of mineral oil could cause large amounts of damage.

When the transformer was put out for tender VA Tech (now Siemens Austria) offered the option of using synthetic ester as the cooling fluid, in place of mineral oil, as it is both fire safe and readily biodegradable. This meant that they could solve both their client's problems with one solution and the transformer was successfully tested at their factory in April 2004.

Then came time to ship the transformer to site, this brought added complications since it had to be drained and refilled in place, due to weight restrictions on Sweden's roads. Despite the more complicated installation process, VA Tech successfully installed the transformer, filled it with ester and the transformer entered operation in June 2004.

Since this time the transformer has run without incident, and following the success of this unit Vattenfall AB has installed several more synthetic ester filled power transformers on their network, including two more at 220 kV and one with a power rating of 200 MVA.

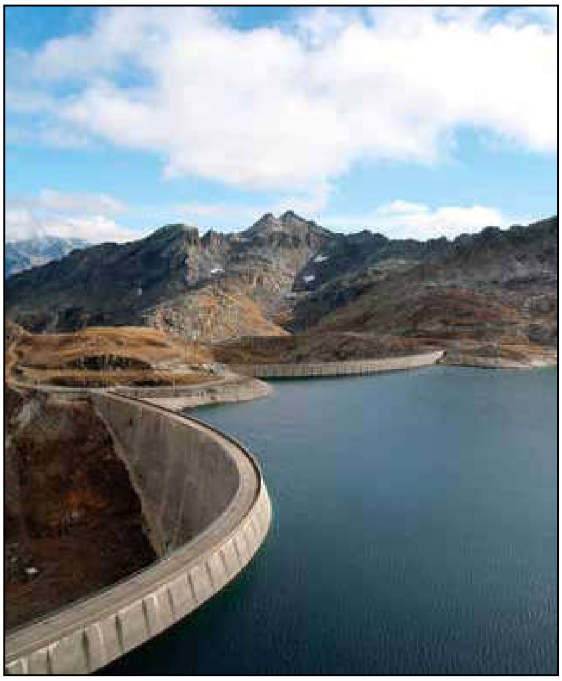
By using ester fluid filled power transformers operators can benefit from reduced fire protection measures, thus saving costs in both capital expenditure and maintenance.

4.3 TransnetBW 420kV natural ester transformer [4]

TransnetBW are the transmission grid operator for the Baden-Württemburg region of Southern Germany. They provide electricity to around 11 million customers in the area and operate over 80 high voltage power transformers. TransnetBW chose to invest in a natural ester filled 420 kV power transformer to link the 380 kV ultra-high voltage level with the 110 kV distribution grid. The main driving force behind the selection of this transformer fluid was environmental, since the natural ester has non-water hazardous status in Germany. This meant that the transformer could be installed without additional collecting vessels and separation systems, which presents a significant civil cost saving. The non-water hazardous status of esters also means that Germany will permit their use in transformers installed within water conservation areas or in zones subject to stringent environmental protection restrictions.

Conclusion

There is a growing demand for more fire safe and environmentally friendly power transformers for voltages above 100 kV. In order to achieve this dielectric fluid inside the transformer needs to be changed from mineral oil to ester based, during the design phase.



With the realisation of the benefits they can bring, ester fluids are now being used in transformers in transmission projects at 400kV plus.

References:

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[2] *A comparative study of the dielectric strength of ester impregnated cellulose for use in large power transformers*, D. Martin, Z.D. Wang, P. Dyer, A.W. Darwin, I.R James, ICSD Winchester, UK, July 2007

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It has become apparent through research in respected Universities that some design changes can be needed to accommodate ester fluids in power transformers and these, coupled with the higher price of esters when compared to mineral oil do increase the transformer price. However, when considering the whole installation and lifetime running costs, esters can still be a very attractive proposition.

Through research and experience there are now a number of major manufacturers who have the in depth design knowledge and can supply ester filled power transformers to customers. It is possible to envisage a time when 400 kV ester transformers are commonplace on electrical networks, especially if the overall lifetime cost of the installation is taken into account.

Author

Mark LASHBROOK received a BEng (Hons) degree in electrical and electronic engineering from Loughborough University in 1995. Following graduation he has worked in a number of engineering roles within the semiconductor, manufacturing and power industries. He is currently employed as a Senior Applications Engineer for Midel ester fluid products. Mark is a member of the IET.