Typically for high voltage power transformers mineral oil is used for both cooling and electrical insulation. 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 such as MIDEL 7131 have been successfully used for voltages up to 66kV for over 30 years. When it comes to higher voltage power transformers there is less experience, since the benefits of using a fire safe solution have not been realised in the past.

More recently there has been a large amount of research work carried out looking at the electrical and thermal properties of esters in order to utilise their many advantages at higher voltages. For projects where there is high risk of fire, or environmental concerns esters present an ideal solution, since they are both fire safe and environmentally friendly.

At higher voltage levels (>66KV), it is not usually possible to use a mineral oil designed transformer with an ester fluid, some design changes 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 66kV, up to a maximum of 238kV have been designed for running with esters, and have used them extremely successfully. In the near future it is expected that large power transformers of up to 400KV will be designed for ester, and will become increasingly widespread.

Despite the 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 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 understand the behaviour of ester fluids better.

This article will set out some of the known differences between esters and mineral oil, when it comes to electrical and thermal performance. It will also aim to give some idea as to what this may mean for transformers designers, in terms of adjusting their designs. The article will also discuss some case study examples of where synthetic ester has successfully been used in power transformers and how the users came to select this fluid.

**Permittivity Difference**

The permittivity of synthetic 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.

Figure 1 shows how the stress distribution in an insulation structure can be calculated by using the permittivity values. 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.
This can be demonstrated with an example using an applied voltage of 132kV and the formula in Figure 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 $\varepsilon$ of the impregnated paper; this must also be taken into account when looking at design.

Table 1 - Voltage Stress Comparison

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Impregnated Paper</th>
<th>Synthetic Ester - MIDEL 7131</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2</td>
<td>4.4</td>
<td>3.2</td>
</tr>
<tr>
<td>Fluid</td>
<td>Stress</td>
<td>Paper Stress.</td>
</tr>
<tr>
<td>17.6 kV/mm</td>
<td>8.8 kV/mm</td>
<td>15.7 kV/mm</td>
</tr>
<tr>
<td>Stress Difference Paper-Fluid</td>
<td>Stress Difference Paper-Fluid</td>
<td></td>
</tr>
<tr>
<td>8.8 kV/mm</td>
<td>5 kV/mm</td>
<td></td>
</tr>
</tbody>
</table>

Table 1 shows that the voltage stress in the fluid is reduced by changing from mineral oil to MIDEL 7131; 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 MIDEL 7131, 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 MIDEL 7131 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 Figure 2 from a study by the University of Manchester shows this difference.

Figure 2 - Breakdown voltage of impregnated pressboard

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 Figure 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 20.51kV/mm, compared to 17.97kV/mm for mineral oil, given the same structure.

Figure 4 - Stress plot for winding arrangement

The main reason for this difference in performance is down to the oil wedge, where the breakdown initiates due to high local electrical stress. In MIDEL 7131 the stress level in this area will be lower, for the same applied voltage, meaning that a higher breakdown voltage is possible.
However if this is understood then it is perfectly possible to re-design to reduce stress in key areas, usually at the winding ends and around static rings.

Based on the above points it is important for a designer to take into account the permittivity difference between mineral oil and synthetic ester, such as MIDE 7131. This may bring benefits in certain areas of the insulation structure, but require changes to reduce stress in others.

Impulse breakdown

There have been many laboratory experiments carried out with the aim of understanding the impulse behaviour of esters. For a small electrode gap under AC stress there is very little difference between esters and mineral oil and this is seen in the standard electrical breakdown test methods such as IEC 60156 and ASTM D877.

When under impulse testing however there is a difference between esters and mineral oil, which can be attributed to the difference in chemical structure. A study from the University of Manchester showed that the lightning impulse breakdown voltage for esters can be around 20% lower than mineral oil when using a standard impulse breakdown test cell and different test methods, the results are shown in Figure 5.

Figure 5 - Impulse breakdown testing results

In addition to these small electrode gaps much larger gaps have been tested under inhomogeneous needle to plate configurations. In this case the breakdown voltages of the ester fluid is also lower than mineral oil and hence more care needs to be taken in areas with long oil gaps and divergent fields, such as that around lead ends. It may be necessary to introduce more pressboard barriers for an ester fluid filled transformer, in order to ensure that the unit passes the impulse tests.

Thermal Design Considerations

Viscosity is the main parameter that affects thermal performance of fluids for cooling. 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. Figure 6 shows an example of a thermal calculation for a winding, taking into account three different fluids.

Figure 6 - Thermal model comparison

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 NOMEX 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.
Impregnation of cellulose

Studies have found that impregnation speed in cellulose is closely related to viscosity, with more viscous fluids requiring longer to impregnate than less viscous ones. The way to counteract this is to impregnate at a higher temperature. For example with MIDEL 7131 a temperature of 60 °C would give a slightly quicker impregnation rate than mineral oil at 20 °C, this can be seen in Figure 7.

![Figure 7 - Impregnation of cellulose](image)

One way to retain a higher temperature during impregnation is to cycle the fluid through the transformer and a vacuum treatment unit to keep the temperature elevated for the whole impregnation time. In this way the same impregnation time can be gained for ester fluids as would occur with mineral oil.

Nearly all the differences between mineral oil and esters will lead to a higher initial capital cost for an ester filled transformer, when compared to a mineral oil unit. However there are a number of users who adopted synthetic ester for higher voltage transformers, despite this extra capital cost, since they have high risk installations and can save very significant amounts elsewhere. This makes the ester transformer a very attractive option.

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 power plants 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.

Vattenfall 238kV 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 MIDEL 7131 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 Midel 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 Midel filled power transformers on their network, including two more at 220kV and one with a power rating of 200MVA.

**Göteborg Energi Underground Rock Stations**

Göteborg Energi are responsible for the larger Göteborg region of Sweden which encompasses 50 or more power transformers (40MVA and larger) which range from 1 year old to 53 years old. They also are responsible for over 2000 distribution transformers of 630kVA and larger rating. As part of their operation Göteborg Energi have a number of rock stations where the main transformers are housed underground. In each rock station there is typically three transformers, with two online at any one time. Fire safety is critical for this type of installation; hence they decided to use synthetic ester MIDEL 7131 for the transformers. These 135kV, 40MVA transformers were installed in 2010 and have operated successfully since that time.

**Conclusion**

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

It has become apparent through research in respected Universities that some design changes are 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.

In the early days of ester filled power transformers designers opted to just use a mineral oil design at a higher BIL level, however as more is understood about designing for ester the cost will come down, making this an even more attractive proposition than mineral oil.

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 200kV ester transformers are commonplace on electrical networks, especially if the overall lifetime cost of the installation is taken into account.

[Views expressed are of the Author & not of ITMA]

---

Russell is the Technical Manager at M&I Materials, Manchester, in the UK, where he leads the Technical Development and Application Innovations for ester transformer fluid. He has a PhD in Chemistry from Sheffield University in the UK, is a Fellow of the Royal Society of Chemistry, and contributes to various CIGRE, BSI and IEC technical groups to expand and improve the industry knowledge of transformer fluid behaviour and performance.

He has successfully led the Cigre Working Group on Alternative Fluids (WG A2-35, technical brochure now published, 2010), IEC MT 36 (maintenance of IEC 61099 and IEC 61203 standards for synthetic ester ; updated IEC 61099, 2010 now published) and contributes to several other important Cigre and IEC groups. He is also Secretary of the BSI GEL 10 group which the UK National Committee which maintains and develops fluid standards for the electrical industry.

He was awarded the Cigre Technical Committee Award for his outstanding contribution to the work of the A2 (Transformer) division in 2010, and was also awarded the IEC 1906 Award in December 2011 for leading his IEC team in the rewriting and updating of the standard IEC 61099 (Synthetic Esters for Electrical Purposes). In addition he works with the High Voltage Research Team at the University of Manchester, which is looking at the use of Alternative Fluids for Power Transformers. He has extensive experience in Production and Technical Management, Further Education Teaching, and has run a small Independent Consultancy Business before joining M&I Materials.

Mark Lashbrook received a BEng (Hons) degree in electrical and electronic engineering from Loughborough University in 1995. He is currently an independent engineering consultant, specialising in alternative fluids for electrical applications. Previously Mark worked for M&I Materials Ltd as a Senior Applications Engineer for Midel ester fluid products. Mark is a member of the IET.

Nitin has a BE (IE) Degree and is employed with M&I Materials Limited, India where he leads the Technical Application related innovations for esters transformer fluid in India. He has technical knowledge to expand and improve the industry knowledge of transformer fluid behaviour and performance.