ABSTRACT

Risk reduction is a cornerstone of good asset management and maintaining a reliable transmission and distribution network. Much time and expense is spent in risk mitigation and the established methods of preventing accidents with mineral oil transformers add substantial costs to transformer installations. In addition the operating temperature of mineral oil transformers is limited, especially in the Indian climate, where high ambient temperatures are the norm.

A newer approach to risk management gathering pace across the world is to employ ester-based liquids in transformers. Ester liquids have a number of advantages over mineral oil; they have higher fire points and lower gas conversion factors, reducing the risk of tank rupture and allowing installation closer to the load centre. This can be especially useful in distribution networks where transformers need to be located close to the population. In addition ester-based liquids are more environmentally friendly, offering reduced risk in the event of a spillage or leakage.

Mineral oil limits transformer performance since the liquid temperature must be kept below 100°C at all times for safety; if this is not done the results can be disastrous. In addition, cellulose ages rapidly in oil at higher temperatures. By using ester-based liquids the ageing rate of cellulose can be slowed, allowing longer transformer life, or increased operating temperatures for the same lifetime. This allows added flexibility in the network. The use of an ester also enhances the reliability of the transformers, reducing the risk of failures and outages.

This paper will provide a detailed look into the advantages of ester liquids directly related to the Indian distribution network, along with a number of recent case studies where transformers have been retrofilled with synthetic ester in order to substantially increase safety.

1 FIRE SAFETY

When considering risk the aspect of transformers that comes to mind is generally fire safety. It is well documented that mineral oil transformer fires occur throughout the world and that once started a mineral oil fire can be extremely difficult to extinguish. In addition the pool fire which is formed can cause extreme damage to surrounding equipment and pose a risk to life. For these reasons it is often necessary to segregate mineral oil transformers through the use of fire barriers, or to have costly active fire suppression systems.

When looking at fire protection there are two possible fire scenarios considered by designers and specifiers of substations, the first is the transformer as a “victim of fire” and the second the transformer as a “source of fire”.

1.1 Transformer as a victim of fire

For the victim of fire scenario the key considerations are how long will the transformer withstand the fire and then will the transformer contribute to the spread of fire? Looking at how long the transformer will withstand the fire it is possible to do a simple calculation based on the specific heat capacity of the liquid and the fire point temperature, shown in Table I. This assumes an operating top oil temperature of 100°C and no heat loss to surroundings, which is the worst case scenario.
Table 1: Heat energy required for 1000 litres to reach fire point

As shown in this example the ester-based liquids require over three times the energy to reach fire point, for a given volume, and hence will take at least three times longer to reach this temperature for a given power input.

This principle has been tested twice in practice with full scale transformers, both filled with K-class liquid. The first was carried out by Allianz by exposing a transformer to a wood fuelled fire for a duration of over one hour.[1] The second test was using an alcohol fuelled fire, along with radiant panels in a test which is based upon cast resin standards.[2] In both cases the transformer did not contribute to the fire in any way.

Table 2: Gas conversion factor comparison[3]

Fig 1: K-class transformers after external fire testing, a) Allianz[1], b) CG Power SLIM[2]

1.2 Transformer as a source of fire

For the source of fire scenario there are a number of possible causes. There could be an external fault which causes extreme overheating of the oil in the transformer, a large fault within the transformer which causes an arc, or the failure of an auxiliary component such as a tap changer or bushing. Again the high fire point of the ester liquid means that in the case of overheating the fault must be sustained for a very long duration. This is unlikely since protection devices exist to prevent long term faults. In the case where a fault large enough to rupture the tank occurs the likelihood of a pool fire is extremely low. In addition it has been found in recent research that synthetic ester has a lower gas conversion rate than mineral oil.[3] This means that for a given arc energy the ester will produce a lower volume of gas.

A comparison of the gas conversion factors from one researcher is given in table 2.

Table 2: Gas conversion factor comparison

Since the chance of tank rupture is lower and the risk of a pool fire is effectively eliminated it is possible to site transformers more closely to buildings safely. The enhanced fire behaviour also means that extra fire protection measures such as deluge systems and fire walls are no longer required. This saves significant cost in new installations.

Another consideration for the asset manager is existing equipment where urbanisation or other changes in the surroundings have increased risk to people or equipment. For example a mineral oil transformer may have previously been sited away from buildings, but recent development work has reduced the clearances. In this case there are usually four options.

1. Build new fire barriers around the transformer
2. Relocate the transformer to increase the clearance
3. Replace the transformer with a lower risk type

Liquid | Fire Point (°C) | Mass (kg) | Specific Heat (J/kg°C) | Energy (MJ)
---|---|---|---|---
Mineral Oil | 170 | 880 | 1860 | 115
Natural Ester | 356 | 920 | 1848 | 435
Synthetic Ester | 316 | 970 | 1880 | 394
4. Retrofill the transformer with a high fire point ester liquid

In most cases option 3 represents the most cost effective solution and retrofilling with ester is something that has been carried out in many thousands of transformers in the past to either lower fire risk, or meet stricter environmental guidelines.

2 ENVIRONMENTAL PROTECTION

Another risk factor for the asset manager to consider is environmental damage from spills or leaks. In the case of mineral oil, which is non-biodegradable and damaging to the environment there can be heavy penalties imposed for spillages.

A better option than mineral oil is to use a biodegradable ester-based liquid. These materials are non-toxic and expected to degrade rapidly in the environment if they are spilled, according to the results of testing to the OECD 301 standard for ready biodegradation.[4] This aquatic screening test provides a comparative measure of the rate at which microbes are able to break down different chemicals. There are three ratings available under the test
1. Readily Biodegradable
2. Inherently Biodegradable
3. Non Biodegradable

In order for a chemical substance to reach the highest category of readily biodegradable it must reach 60% degradation within 10 days after 10% has been reached. The OECD test method is very stringent and any material which achieves a readily biodegradable result is expected to rapidly and completely degrade in the environment.

An example of the chart for a readily biodegradable ester is shown in Figure 2, with the addition of the 10 day window to illustrate how the evaluation is conducted.

Fig-2 - OECD 301F test result for a readily biodegradable synthetic ester product

To be inherently biodegradable a substance must reach >20% by the 28th day of the test. This means many substances could meet quite a low level in the testing and still be termed “biodegradable”. A non-biodegradable substance is one which does not reach 20% after 28 days.

By choosing a readily biodegradable liquid in the transformer the risk to the environment is certainly reduced and may allow simplified containment, or the removal of costly oil water separators for larger transformer bunds.

3 HIGH TEMPERATURE OPERATION

Closely related to the fire safety aspects of ester liquids is the ability to operate transformers at elevated temperatures. The flash point of mineral oil imposes restrictions on the upper operating temperature and typically this is capped at 100°C for continuous operation. In regions where the ambient temperatures are low this may be acceptable, but it poses serious restrictions for designers who must take into account a higher ambient, such as those in the Asia region. Where the standard guidance will allow up to 60K rise for mineral oil[5] this must be reduced to 55K to remain within the limits if the maximum ambient is 45°C. The effect of direct sunlight can increase operating temperatures by another 10°C, so a cautious operator may want to have rise limits as low as 45K for oil.

Although ester liquids have higher viscosity than mineral oil, and hence transformers with the same design would run somewhat hotter, according to industry standards ester-based liquids can have a 30K higher top oil
temperature rise than mineral oil. This allows larger margin for designers and in addition it has been demonstrated that thermally upgraded paper will age more slowly in an ester liquid[5], which could allow increases in hot spot design temperatures without changing the solid insulation. If a designer employs a design using higher temperature insulation then the hot spot temperatures may be increased further. There are other options to create hybrid or semi-hybrid high temperature designs where only parts of the insulation system use the more expensive solid components.

Table 3 shows a comparison of different options, their top oil, average winding and hot spot temperatures based on the guidelines in IEC 60076-14[5]. In this case TUP represents thermally upgraded kraft paper and the increase in thermal class when immersed in ester is taken from the information in Annex C.

<table>
<thead>
<tr>
<th>Solid Type</th>
<th>TUP</th>
<th>TUP</th>
<th>NOMEX</th>
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<tbody>
<tr>
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<td>Ester</td>
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<td>Top Liquid Rise</td>
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<tr>
<td>(K)</td>
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<td>125</td>
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<tr>
<td>(K)</td>
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Table-3: Continuous Operating Temperatures[5]

Note: All values assume max ambient temperature of 40°C

For a region such as Asia where overheating is a real issue this extra safety margin can be extremely useful. It allows designers more scope to increase power output from a given footprint for new transformers, or allows operators to safely overload transformers at times of peak demand. For existing equipment swapping the liquid through retrofilling can instantly allow safer overload and more flexible operation, so long as the other materials in the transformer are rated to the higher temperatures.

4 REDUCTION IN MAINTENANCE

Although the up-front cost of a synthetic ester is higher than mineral oil one of the further benefits of using a synthetic ester based liquid in transformers is its robust nature, which can reduce the need for invasive maintenance. Experience from high temperature rolling stock transformers has demonstrated that a synthetic ester can provide a long lifetime without invasive maintenance, even when subjected to breathing configurations with very large load fluctuations. In addition the synthetic ester's ability to tolerate moisture ingress, while maintaining dielectric strength can be helpful in more humid climates. These two factors combined can mean less drying processes are needed and hence costs for ongoing maintenance can be reduced.

5 THE RETROFILLING PROCESS

Replacing the liquid in a transformer is a relatively straightforward procedure, which can be carried out without necessarily needing need to relocate the transformer to a workshop, but it is worthwhile having some precautions in the process to maximise the gains.

Residual mineral oil is one consideration when carrying out a retrofill. Any oil left in the transformer will have some effect on the fire point of the ester liquid and therefore it is best to minimise this as far as possible. A target for remaining mineral oil after retrofill would be around 3%, since this will ensure that the K-class rating is maintained.

The retrofill process can be broken down into a number of steps, as shown in the flow chart in Fig 3.

5.1 Pre-retrofill checks

There are two primary reasons for checking transformers prior to retrofill. The first is to assess whether they are suitable candidates and in good condition. This is usually achieved by a visual check, accompanied by an oil condition test including furan. This will tell if the paper is badly degrade. The second reason is to look for oil deadspots; typically there will be some dead space below the sample valve, which means that not all the mineral oil can drained out directly. A simple solution to this is to insert a tube to drain the remaining oil from
the dead space, or possibly to tip the tank to remove the final material.

5.2 Draining and Rinsing

After draining and allowing to drip down to let mineral oil out of the active part it is helpful to rinse the internal components with ester liquid. Rinsing the windings with a volume of ester liquid serves two purposes. The first is that ester liquids are very good at dissolving mineral oil sludge, especially synthetic esters, so the transformer active part surface will be cleaned by the rinsing process. The second advantage of rinsing is that it will dilute any oil left in the bottom of the transformer and hence reduce the residual percentage. A further drip down after rinsing can help reduce the mineral oil content further.

5.3 Filling and Post Checks

Refilling the transformer is usually best achieved by utilising a mobile oil treatment plant, to heat and dry the liquid as the transformer is filled. This aids the dispersion of air bubbles from the liquid. After the filling process is completed the transformer can be left standing for a time to allow gas bubbles to escape and to check that any new gaskets are not leaking. It is also prudent to take a sample of the liquid at this point as a baseline test.

6 CASE STUDIES

Over the past decade a number of retrofilling projects have been completed successfully in India using synthetic ester liquid. The two case studies presented here gives an overview of the Indian experience to date.

Case Study 1 – Tata Power Delhi Distribution

Tata Power Delhi Distribution Limited, formally known as NDPL, has a large operating network covering the North and North-West areas of Delhi, serving a population of 5,000,000 people. In common with other Indian utilities in densely populated areas they are under immense pressure from expanding demand on electricity and have embarked on programs to improve the distribution network.

There are a large number of mineral oil filled transformers on the Tata Power Delhi network that are in densely populated areas and even located in the basement of residential buildings. These transformers pose a fire hazard to the occupants of the buildings and a strategy to reduce the fire risk was needed. Following discussions with M&I Materials a plan was put in place to retrofill a number of distribution transformers in high risk areas of the city with MIDEL oil.

A large amount of support was provided throughout the process, including detailed procedures for pre-testing and retrofilling of mineral oil transformers. Personnel from M&I in the UK travelled out to India on a number of occasions to provide advice and guidance where necessary. When it came to starting the retrofills themselves the local M&I Country Head Nitin Satija and a UK expert were on site to oversee the retrofill process. They took an active role advising the customer and helping to iron out any issues that occurred on the day.

In total 21 transformers were successfully retrofilled in this project. These included units which were installed in the basement of apartment blocks. The method adopted by Tata Power Delhi was to transport the transformers back to the workshop and thoroughly
decontaminate them, flushing with MIDEL 7131 before refilling. This was in line with the guidance from M&I and has proved to be a very effective method, leading to remaining mineral oil percentages of less than 3% in most cases.

The retrofit meant the fire safety of the units was greatly improved and it also anticipated that a longer lifetime will be gained for these transformers now they are filled with MIDEL 7131.

Case Study 2 – CESC Kolkata

CESC Limited is a power utility in the Kolkata region of India. More than a century old, it handles the entire span of electricity business including Generation, Transmission and Distribution. It serves approximately 3 million consumers including domestic, industrial and commercial users. CESC operates on a wide range of assets in power generation and distribution. There are more than 8,000 distribution transformers in the system, the majority of which are rated between 315 and 500 KVA. CESC has been installing Dry Type transformers in densely populated areas since 1990. Today, around 25% of those assets are Dry Type Transformers. As an alternative to fire prone mineral oil transformers and costly dry type transformers, CESC is considering fire safe and environment-friendly ester oil filled transformers as a possible solution.

Fig-4: Retrofilled transformer at Tata Power Delhi distribution

Fig-5: Retrofilled transformer at CESC

CESC have completed two retrofills, the first was a 400kVA 11/6kV transformer located in a plastics factory in a densely populated area. The second retrofit was conducted on another 400kVA 11/6kV transformer which is located in a manufacturing workshop close to a school. In both cases the increased fire safety of using synthetic ester was a key driving factor for the retrofit. In addition the higher moisture tolerance and ability to run at increased operating temperatures safely provided the utility with enhanced benefits.

The two transformers were rigorously tested by CESC before placing into full service. Following the successful completion of this project CESC are now conducting more retrofills on their network to further improve safety.

7 CONCLUSIONS

There are many challenges faced by the Asia region with regard to transformer operation, primarily related to high ambient temperatures, high humidity and harsh operating climate. The use of an ester-based liquid in place of mineral oil can answer some of these problems. Ester liquids have a high fire point, which significantly reduces the risk of fire when a transformer overheats or is subject to a fault. In the 40 year history of ester-liquids there has never been a reported pool fire with the liquid and this is often the most damaging aspect of a mineral oil fire.

In addition the higher fire point of the ester allows higher temperature operation, which opens the door for designers to utilise high temperature insulation systems, to design more compact transformers. Laboratory studies have also demonstrated that cellulose insulation will age more slowly in an ester liquid than it does in mineral oil. This means that temporary
overload, or higher temperature running may be possible, without shortening the transformer lifetime. This provides enhanced flexibility for the asset manager of a network.

These principles and the opportunity to reduce maintenance on the network with a more robust liquid have already seen a number of users in Indian switch to synthetic ester through retrofilling. Many more projects are underway and the potential of this solution is attracting more interest daily.

8 REFERENECES

[2] CG Power, Fire Behaviour of Transformers - Challenges for reliable step up transformers and substations for multi-megawatt turbines