The Development of 400kV Transformers with Ester-based Dielectric Liquids

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Abstract — **Ester-based fluids offer the potential for safer and more environmentally friendly power transformers. This can save considerable civil costs in installations, but in order to use these fluids in 400kV transformers their dielectric and thermal behaviour must be understood. Over ten years of laboratory research and full scale testing have been carried out to evaluate the dielectric performance of ester-based fluids. This has included studies of fundamental behaviour as well as a wide range of dielectric testing of realistic insulation structures. Work has been carried out by both academic institutions and equipment manufacturers, which has led to a better understanding of the design implications of using these fluids. The large body of research conducted on the electrical behaviour of ester-based fluids has come to the conclusion that design changes are necessary for higher voltage transformers and this leads to a higher price for an ester transformer. Despite this the overall project cost can be reduced by full utilisation of the benefits of fire safe ester fluids and a number of recent projects are using this in practice.**

Keywords **— ester, 400kV, impulse**

I. INTRODUCTION

Mineral oil has been used in transformers to provide electrical insulation and cooling since the early days of electrical networks. While mineral oil is an effective coolant and dielectric medium, it is, however, inherently flammable and environmentally damaging if leaked or spilled. There have been numerous instances of large mineral oil transformer fires and in each case substantial damage has been 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, far less flammable fluids for power transformers (and in the case of ester fluids, much more environmentally friendly).

The behaviour of mineral oil in higher voltage transformers is generally 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 magnetic, 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.

At higher voltages, the use of esters insulating liquids in transformers has developed greatly over the thirty five years since their introduction. It is now the case that large power transformers used for transmission projects can and are being successfully designed and built with esters. This paper outlines the development history of ester-based transformers and discusses the latest projects that will see synthetic ester utilised for a number of 400kV transformers.

II. APPLICATION HISTORY OF ESTERS

A. Synthetic Esters

Synthetic ester dielectric fluids were developed to answer a difficult problem in the electrical industry, when PCB based fluids were effectively banned in the late 1970s. In the early days synthetic esters were used for retrofilling PCB units and to produce replacement transformers for locations of high fire risk. An early adopter of synthetic ester in the UK was British Steel, who installed a number of ester filled furnace transformers back in 1979. This was followed soon after by the Royal Mint who again had a need for fire safe transformers for their furnaces. Many UK and European projects then followed in hospitals, airports, public buildings and offshore oil and gas platforms, where transformers with high levels of fire safety were vital.

Another early adopter of synthetic ester transformers was the railway industry, starting with the retrofilling of PCB transformers on Amtrak rolling stock in the USA during the 1980s. The use of synthetic ester in rolling stock has continued over the last 30 years in a wide range of locomotive and electric multiple unit (EMU) transformers, including freight and high speed train sets. Standards in Europe now require the use of high fire point fluids, such as esters, in trains and recent developments in China will see ester fluids in transformers for 500km/h trains, working at the cutting edge of railway development. (Fig 1.)

Figure 1. CRH-5 High Speed Train with Synthetic Ester Transformers

B. Natural Esters

Another development in the late 1990s was the introduction of natural esters to the transformer market. These fluids, based on renewable seed oils, aimed to provide the ultimate in environmentally friendly transformer oil. Natural esters gained users in distribution transformers, predominantly in the USA and South America. There then followed development of power transformer applications with natural esters, including a number of retrofills where mineral oil was directly replaced with the alternative fluid. Since this time the use of natural esters has increased, with several utilities taking the step to change over from mineral oil to natural ester across their distribution fleet.

Laboratory studies have also shown that ester-based fluids have the potential to significantly increase the lifetime of insulating paper. This has been utilized by some manufacturers to produce more compact distribution transformers, which provide a higher kVA output from a reduced footprint.

C. Ester Differences

It is worth noting that despite both these fluids being named ester there are fundamental differences between synthetic and natural types. The key difference between the two is that natural esters can only be used in sealed transformers, while synthetic esters are suitable for either sealed or breathing configurations.

III. ESTER FILLED POWER TRANSFORMERS

The development of synthetic ester and natural ester power transformers has been conducted almost in parallel, with the majority of the natural ester projects being carried out in the USA and Brazil, while the synthetic ester transformers are mainly installed in Europe. With synthetic ester the approach taken has been to design and install new transformers, rather than retrofilling older units. Table 1 shows a short selection of the power transformer references for both synthetic and natural ester over the last 25 years. [1]

Table I. Ester Power Transformer References

SYNTHETIC ESTER			NATURAL ESTER		
High Voltage	**Rating**	**Year**	**High Voltage**	**Rating**	**Year**
110kV	25MVA	1999	115kV	15MVA	2004
151kV	110MVA	2002	161kV	200MVA	2004 (retrofill)
238kV	135MVA	2004	230kV	8MVA	2005 (retrofill)
220kV	100MVA	2010	161kV	25MVA	2006
154kV	200MVA	2011	110kV	40MVA	2008
400kV	240MVA	2016	138kV	40MVA	2009
433kV	120MVA	2016	420kV	300MVA	2014

IV. COST BENEFIT OF ESTER FILLED TRANSFORMERS

One barrier in the past to the more widespread adoption of ester fluids has been their price, which is higher than mineral oil. However in more recent times users are realising that there are significant savings to be made in overall installation costs if ester-based fluids are used in place of mineral oil. The fire safety benefits alone mean that fire barriers can be removed and active fire suppression systems are no longer required, since the safety is effectively built into the transformer. Factoring in the reduction in civil engineering costs and the potential longer life of ester transformers this solution starts to look very attractive.

KWO in Switzerland realised the considerable savings to be made and after an intensive risk assessment by the safety institute SWISSI they installed four synthetic ester filled converter transformers, without fire suppression systems, as shown in (Fig. 2). This saved them money not only in civil engineering, but also more importantly removed the need for large amounts of invasive maintenance on the firefighting systems, which will save a substantial amount of expenditure and downtime over the full life of the installation.

Figure 2. KWO Synthetic Ester Transformer Installation

Another key area where ester-based fluids can have a positive impact is in environmental protection. Ester fluids are classed as readily biodegradable, meaning that if they are spilled into the environment they are expected to quickly degrade to water and carbon dioxide through the action of micro-organisms found in nature. In contrast mineral oil is poorly biodegradable and likely to persist for far longer. This environmental benefit can be utilised in some cases to reduce the complexity and volume of containment required. Considering an installation with multiple mineral oil transformers, separate containment would be needed for each unit, along with oil separators for each. With ester-based fluid one combined containment system could be used, significantly cutting down civil engineering costs.

V. LABORATORY RESEARCH FOR 400KV AND ABOVE

Such is the demand for ester transformers at higher voltages that university research into alternative fluids has been conducted in many different research centres around the world. One example of a large scale collaborative project was the 8 year joint research project between National Grid, Alstom Grid, M&I Materials and a number of UK utilities which studied the fundamental behaviour of ester fluids in comparison to mineral oil. The aim of this project was to define what was necessary to use esters at 400kV. This research project incorporated five PhD theses on the subject of ester behaviour under electrical conditions and included both synthetic and natural esters. The outcome of this project was a vast amount of information on the electrical, thermal and ageing behaviour of esters.
Various other institutions have published work on ester fluids, in Europe the other notable independent researchers are Stuttgart University and the Schering Institute at Hannover University. Much of their work mirrored that carried out at the University of Manchester and discovered very similar results. Various other large transformer manufacturers have also carried out their own extensive research work into the use of esters, including Siemens and ABB.

In order to effectively use esters in large power transformers designers first needed to understand their fundamental behaviour, in comparison to the better understood characteristics of mineral oil.
The first factor which affects the design of ester transformers is the difference in permittivity between esters and mineral oil. This brings advantages within winding structures as the permittivity of ester is closer to that of paper, giving a more homogeneous electrical field distribution. Stress in the fluid is also lower with esters, for a given structure, with higher stress in the solid insulation. Since the impregnated solid is a stronger dielectric than the fluid alone this is also beneficial. On the other hand the difference in permittivity also means that peak stress in certain structures can be higher with esters, so small adjustments may be needed to reduce this stress to acceptable levels.

One of the key differences coming out the laboratory research is the behaviour of ester fluids under impulse conditions, where a somewhat lower dielectric strength than mineral oil has been observed. An example of this comes from testing carried out by the University of Manchester using the 1-shot per step (IEC method) and 3-shot per step (ASTM method), with the results shown in Fig. 3.[2]

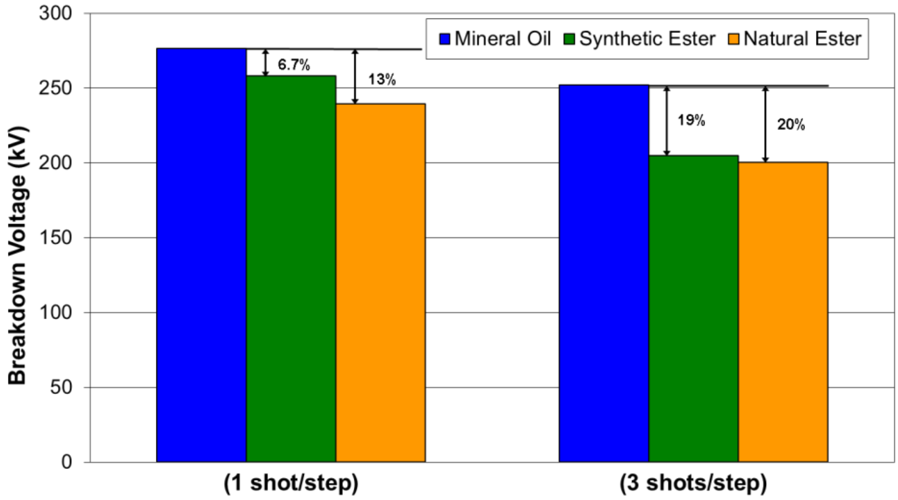

Figure 3 Impulse Breakdown Results

The larger difference in the ASTM method is most likely due to a higher chance of breakdown, caused by more impulse shots at each level. In simple terms these results indicate that design changes might be needed to make sure a power transformer with ester passes impulse test.

Larger differences were found in experiments using very divergent fields, with electrode setups such as needle to plane and needle to sphere. These were designed to produce focussed electrical fields, in order to exaggerate the effects and observe fundamental behaviours. In these experiments ester fluids were shown to have similar discharge inception voltages to mineral oil, meaning insulation structures would be similar, but propagation of streamers appears to happen more readily in esters. For design this indicated that adjustments needed to be made with long oil gaps and divergent fields in esters.

Observations such as faster discharge propagation in divergent fields give a clue to how esters will behave in real transformers, but does not give the full picture. In addition to the fundamental research a large amount of testing has been conducted on more realistic insulation structures, to feed into design calculations. This testing and experience gained by transformer OEMs with ester suggest that the differences between mineral oil and ester can be accommodated with some adjustments in design. These changes do add some cost to the transformers, when compared to standard mineral oil units, but this is still far outweighed by the potential cost saving benefits.

In terms of thermal behaviour the higher viscosity of ester fluids mean that cooling channels may need to be widened, in order to maintain the same operating temperature rises. This in turn impacts electrical design to a degree. Although esters will give a higher temperature rise than mineral oil for a particular design a large amount of laboratory work has also shown that insulating paper ages more slowly in esters than it does in mineral oil. Since the lifetime of the insulating paper is often the life limiting factor for a transformer this is critical. In designing transformers well established temperature limits are applied for mineral oil and cellulose combinations. The evidence published in IEC 60076-14 [3] and IEEE C57.154 [4] over the last two years indicates that higher temperatures can be accepted with esters, without loss of life. This can work to offset the difference and perhaps even allow the design of more compact power transformers if the full benefits of esters indicated in the standards are used.

VI. CASE STUDY 1: NATIONAL GRID UK

It is clear from the past history and laboratory work that ester fluids behave in a different way to mineral oil at higher voltage levels; however, the challenges are not insurmountable. The benefits that esters can bring in fire protection and increased transformer life can financially outweigh the extra cost of using an ester.

This is illustrated by the fact that there are a number of large transformer projects under development globally, using both synthetic and natural esters. One key project for synthetic ester which directly followed the NIA funded research is being carried out by National Grid in the UK. Following the many years of research and development, as well as the full scale test rig made by Alstom Grid, the decision was made to install three 400kV synthetic ester transformers in a critical substation located in Highbury, in the centre of London. This substation is part of the London Tunnels project which is aiming to provide long term security of electrical supply to the UK capital.

One of the hurdles to conducting any project on this scale in a dense urban area is obtaining planning consent, which requires many adjustments to the design in order to meet the needs of local residents and the immediate community. The plan for the London site in Fig. 4 shows the main transformer and switchgear building, along with a range of residential buildings surrounding the site. [5][6]

VII. CASE STUDY 2: LETSI HYDROPOWER STATION SWEDEN

Swedish power company Vattenfall has used synthetic ester power transformers since 2002, when it installed a unit rated at 151kV and 110MVA. Since then the company has steadily increased its fleet of synthetic ester generator units, moving up to 238kV in 2004. Following the positive experience with these transformers, Vattenfall decided to utilize synthetic ester for a major refit project at the Letsi hydro power station. This hydropower plant has been in operation for over 40 years and the underground mineral oil transformers were ready for replacement.
Due to current safety standards it was deemed unacceptable to have new underground mineral oil transformers, specifically for fire safety reasons. After careful consideration the decision was taken to install synthetic ester transformers, in order to significantly increase fire safety. There will be four 433kV 120MVA single phase units installed during 2016 [6]

Figure 4 Plans for National Grid Highbury Development

VIII. Conclusions

For over thirty five years ester-based transformer fluids have been successfully employed in a wide range of transformer applications. Most of these have been at distribution voltage levels or for specialist applications such as traction and wind turbines. The use of ester fluids in larger power transformers has developed over the last 20 years and for the last 10 years synthetic esters have been used successfully in units at up to 238kV. The large body of research work that has been conducted on esters also gives an excellent background for design adjustments and the understanding of ester behaviour is increasing all the time. All this means that nowadays a range of equipment manufacturers are able to offer ester transformers for transmission projects, moving the use of esters to the 400kV level.

The built in fire safety of ester fluids offers asset managers an excellent solution to reduce overall installation costs, as well as lifetime running costs when factoring in the removal of fire protection systems. The fact that pool fires cannot occur with ester fluid means that the complexity of containment systems can possibly be reduced, for example having single containment pits for multiple transformers. The favourable environmental behaviour of ester fluids may also offer the opportunity to reduce containment systems, further reducing civil engineering costs.

The culmination of this work will see two major projects in 2016 where synthetic ester filled 400kV transformers will be installed. More projects at this voltage level and higher are expected to follow as users recognize the benefit of deploying ester-based fluids.

References

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