CIGRE SOUTHERN AFRICA

8TH SOUTHERN AFRICA REGIONAL CONFERENCE

14 - 17 NOVEMBER 2017

Electricity Supply to Africa and Developing Economies –

Challenges and Opportunities

Technology Solutions and Innovations for Developing Economies

Natural Ester Oil Power Transformer Solution for PPC Slurry Substation in Eskom's North West Operation Unit.

A SINGH, B MGQUBENI, R GOVENDER, G MOLABE, A.G SWANSON S NAYAGER.

Eskom, Trans African Projects, Powertech Transformers, University of KwaZulu Natal

South Africa

singhai@eskom.co.za

Keywords: Indoor Substation, Electrical Design, Natural Ester Oil, Power Transformers.

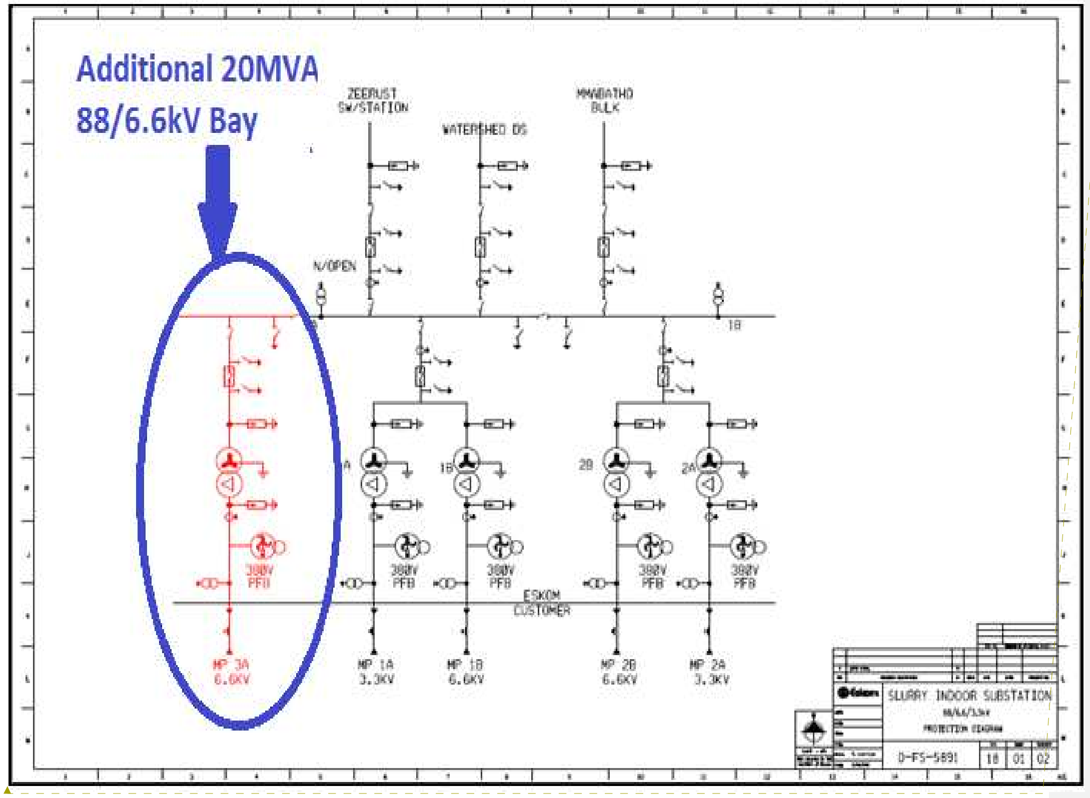
Abstract: This paper explains the decision to use natural ester oil as an insulating fluid in a 20MVA 88/6.6kV power transformer destined for service in Eskom Distribution's North West Operating Unit. The paper will show how the costs associated with constructing the indoor substation were reduced by using the natural ester oil and will discuss the challenges faced in the electrical design of Eskom's first natural ester oil-filled power transformer.

Introduction

Slurry PPC Substation is an indoor station fed via 88kV lines from both Watershed Transmission Station and Mmabatho Bulk Station. The existing substation is equipped with two 10MVA 88/3.3kV and two 20MVA 88/6.6kV transformers. The entire 60MVA is dedicated to a single customer, namely PPC Slurry, who then requested an additional 17MVA supply at 6.6kV due to their plant expansions. Due to space constraints, an outdoor extension of the station was not viable and the Operating Unit had no option but to proceed with an indoor type substation.

Part T of the South African Building Regulations has a major impact indoor substation design and manufacture [1]. The regulations are stringent with regards to fire safety and environmental impact especially when employing oil filled equipment.

This paper will detail how the use of natural ester oil as the insulating fluid of the power transformer aided the Operating Unit in meeting these requirements, while reducing the cost of the project. In addition, the paper will discuss the challenges faced in the electrical design of the first natural ester oil-filled power transformer in the Eskom Network, and the differences in the design from mineral oil-filled power transformers will be highlighted.



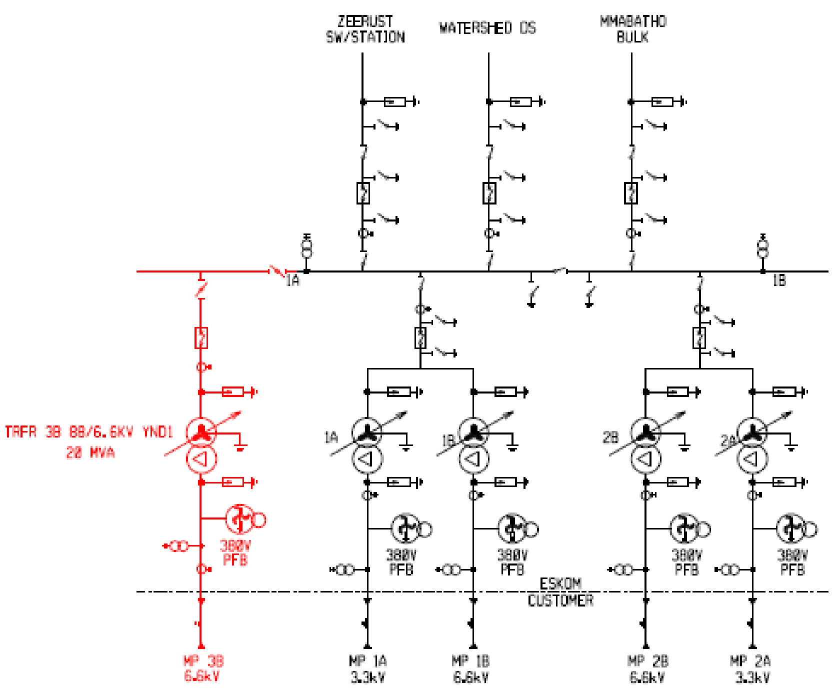


Figure 1 Station Diagram of PPC Slurry Substation

Formatted: Font: (Default) Arial, Bold

Formatted: Font: (Default) Arial, Bold

Transformer Oil

Insulating oil is a key component in the transformers makeup. It surrounds the core and windings, acts as insulant, coolant and provides an opportunity to perform diagnostics on the transformer.

It is important that the oil has good insulation and dielectric properties. This includes: low moisture content, high dielectric breakdown voltage and, good anti-ageing properties i.e., a low tendency to form oxidation breakdown products such as acids and sludge.

Mineral Oil

Mineral oil is produced from crude oil and is made up of hydrocarbon mixtures of three main types, i.e. naphthenic, paraffinic and aromatics as well as small quantities of sulphur, nitrogen and oxygen. This insulating oil has been used in transformers for over a century due to its excellent insulating properties and relatively low cost when compared to other options.

The only major drawbacks of mineral oil are the environmental impact as it is a pollutant to soil and water, as well as its relatively low fire point of ~120 C. In the case of PPC Slurry Substation, both these negatives presented a great risk in the building of the substation.

Firstly, there is an underground spring beneath the substation and any an oil spill has the potential for severe and irreversible environmental damage. Secondly, the low fire point of mineral oil is a fire hazard and causes safety concerns for staff that will conduct maintenance around the transformer. Possible solutions to the fire hazard would be to install either active fire protection systems such as:

- Fast depressurisation systems which assists in the prevention of the transformer from exploding, and
- Sprinkler system including a dedicated fire pipeline and water reservoir.

A typical fast depressurisation system for a 20MVA transformer would cost in the region of R5m. In addition to the cost, a complex valve and piping system would have to be installed to the transformer bay. The costs of the sprinkler system outweigh even that of the fast depressurisation system, and come with space requirements that are constrained at PPC Slurry Substation.

Natural Ester Oil

Natural Ester oils are derived from plant seed oils such as canola, soya, sunflower and sugar cane. The use of natural (and synthetic esters) in transformers has grown in popularity in the recent past and can be seen as a growing trend for use in transformers. Initially natural esters were used for distribution transformers but o~~f~~f late several energy utilities have specified medium and large power transformers, up to extra high voltage with natural ester fluids.

Several utilities have opted for natural ester fluid fill transformers based on the fire safety aspects (fire point >300 C) and environmental benefits (readily biodegradable~~ility~~, non-water hazardous, non-toxicity, carbon neutral). IEC publications also indicate that natural ester oil transformers have a greater life expectancy which increases the utility's return on investment on the asset [4]. These properties provided a strong case for the use of natural ester oil filled transformers at PPC Slurry Substation.

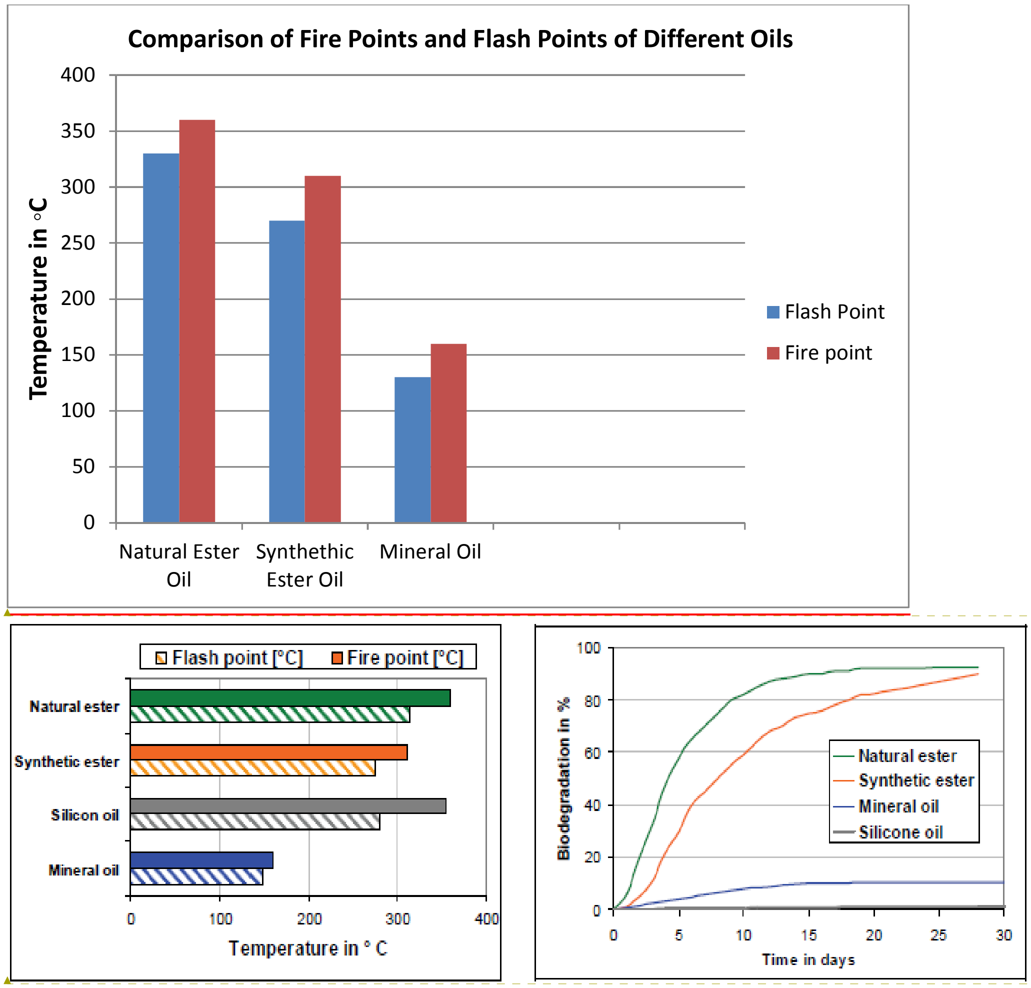


Figure 2 Comparison of Flash, Fire points and Biodegradability [3]

A guide for the life expectancy versus operating temperature for mineral oil and ester oil is illustrated in diagram below.:

Formatted: Font: (Default) Arial

Formatted: Font: (Default) Arial, Bold

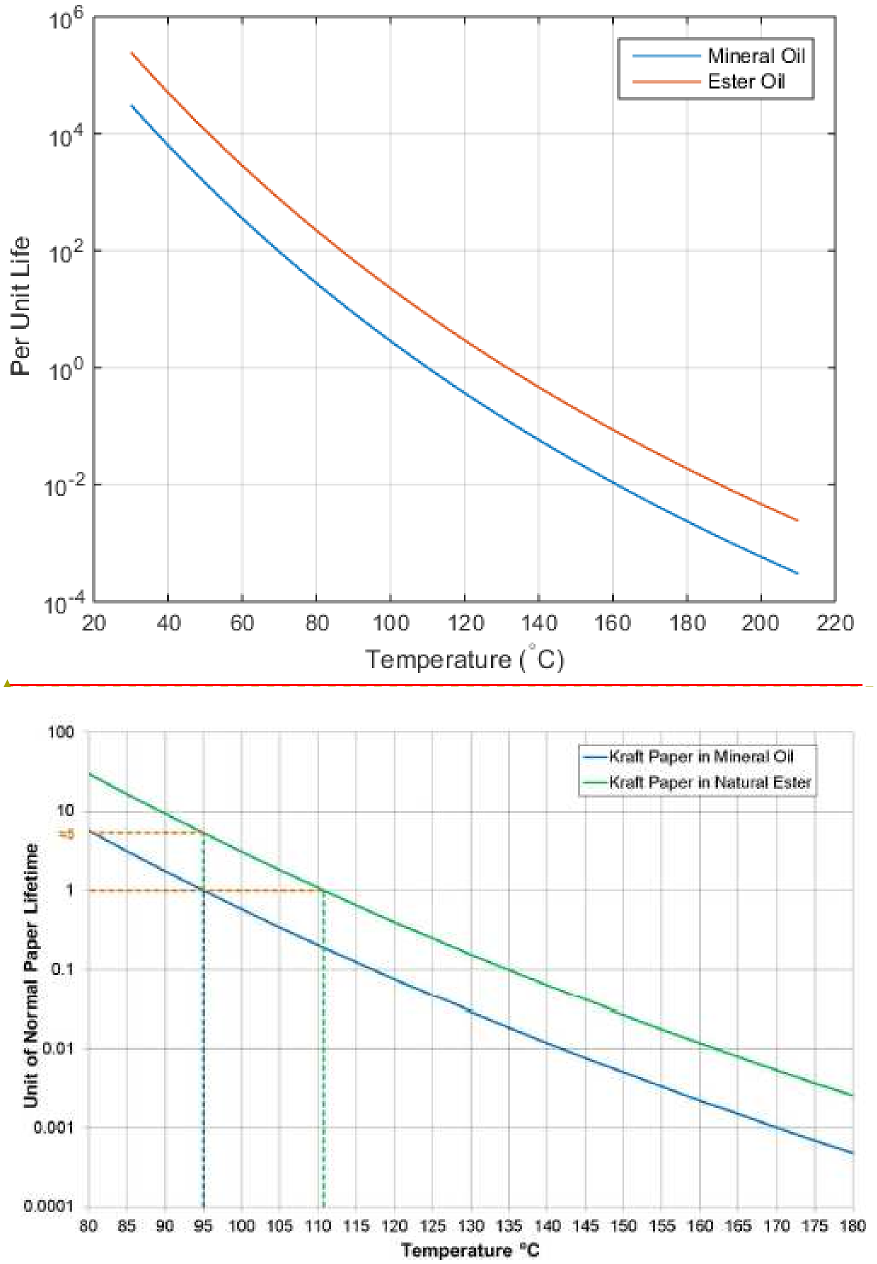


Figure 3 Comparison of Life Expectancy versus Temperature [4]

In addition to its increased fire safety, the higher point of natural esters can reduce build and labour costs at the substation as the IEC specifications allow for reduced clearances [2], and oil dams and the associated pipework are no longer needed.

Table 1 Recommendations of Separation distances between transformers and building as per IEC 61936-1 and CIGRE Guide 537

Transformer Type	Oil Volume (l)	Clearance to non-Combustible Building Surfaces (m)	Clearance to Combustible Building Surfaces

Formatted: Font: (Default) Arial

			(m)
Mineral Oil Insulated Transformers	**>1000 <2000**	**3**	**7.6**
	=>1999 <20 000	**5**	**10**
	=>20 000 <45 000	**10**	**20**
	=>45 000	**15.2**	**30.5**
Natural Ester Oil Insulated Transformers with Enhance Protection	**Clearance to Building Surfaces of Adjacent Transformers (m)**		
		Horizontal Distance	**Vertical Distance**
		0.9	**1.5**
Enhanced protection refers to tank rupture strength, pressure relief devices, low current fault protection, high current protection.			

The major drawbacks of natural ester oils are their oxidation stability; kinematic viscosity and reduced fast transient withstand capability as compared to mineral oil. However the transformer design can be altered to cater for these limitations while harnessing the benefits of the natural esters. Care must also be taken to ensure that the materials used in the construction of the transformer are compatible with the natural ester oil.

In the case of PPC Slurry substation, the higher cost per litre of the ester oil is negligible when compared to the costs associated with installing active fire protection systems.

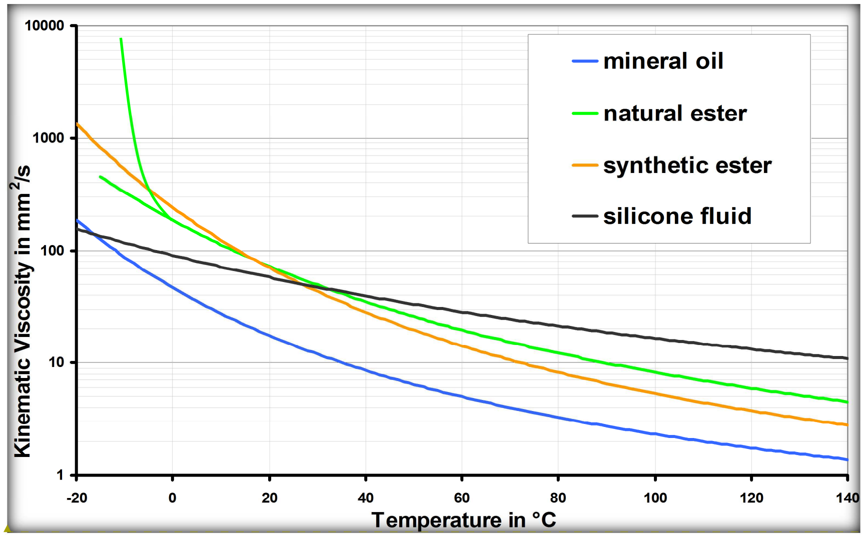
It was therefore decided to proceed with producing a natural ester oil filled transformer for PPC Slurry Substation.

Transformer Design Considerations

~~Kinematic~~ Viscosity

Challenge: Natural esters have a higher viscosity than mineral oil that's effects their flow thro~~w~~ugh ducts and channels designed for cooling in the transformer. The condition worsens in colder environments (pour point is approximately -10 C) and the transformer cooling design must be adjusted accordingly [3].

Solution: Duct sizes must be increased to allow for acceptable flow of the higher viscosity natural ester oil through the winding. The heat transfer factor from the winding through the insulation to the oil must be adjusted in calculations as this parameter differs from mineral oil transformers as the natural ester oil has a different specific heat capacity and natural ester oil designs require more insulation. The hydraulic resistance for the entire ONAN (Oil natural, air natural) system must be adjusted for natural esters.



~~Figure 4 Comparison of Viscosity versus Temperature [3]~~

Formatted: Font: (Default) Arial

Oil Impregnation of Solid Insulation

Challenge: Oil impregnation of the cellulose is critical to the insulation system in meeting its functional requirements. Natural ester oil has a density and viscosity that is different to mineral oil. Also, natural ester oil transformer designs are more insulation intensive as the electrical stresses are present in the paper as opposed to mineral oil where the stresses are in the oil. This is due to the higher permittivity of natural ester oil, which is closer to that of kraft paper than mineral oil [5].This is supported by electrical field simulations of "like" 88kV transformers in mineral oil and natural ester oil which show higher electric fields in the oil for mineral oil filled transformers while there are higher electrical stresses in the paper for natural ester oil transformers. The simulations were carried out using FEMM software and a sample of the results is shown below. Comparable results were obtained when simulating sections of the windings.

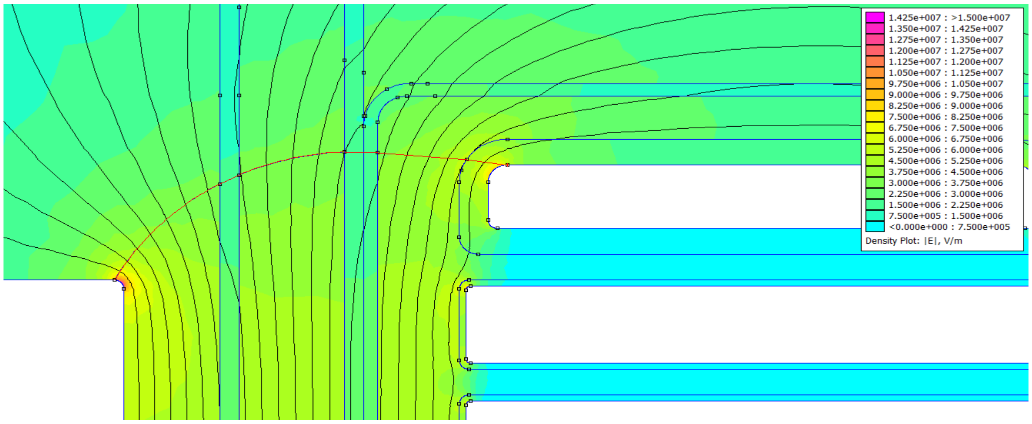


Figure ~~5~~4 Electric Field Intensity in Mineral Oil Transformer

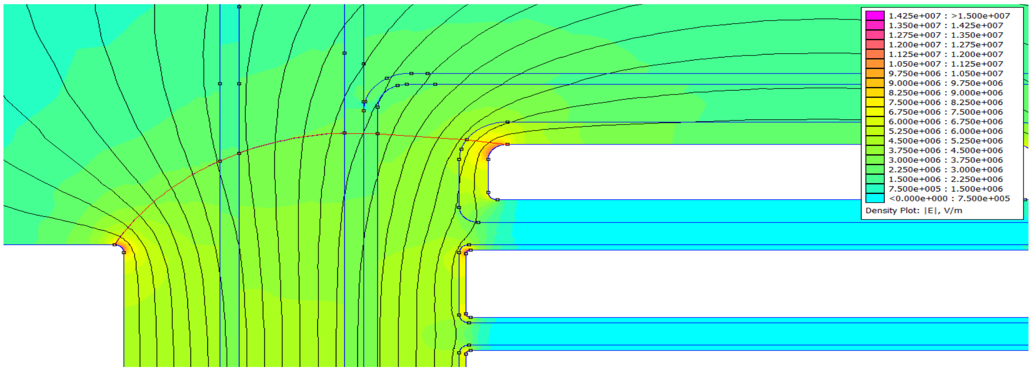


Figure ~~6~~5 Electric Field Intensity in Natural Ester Oil Transformer

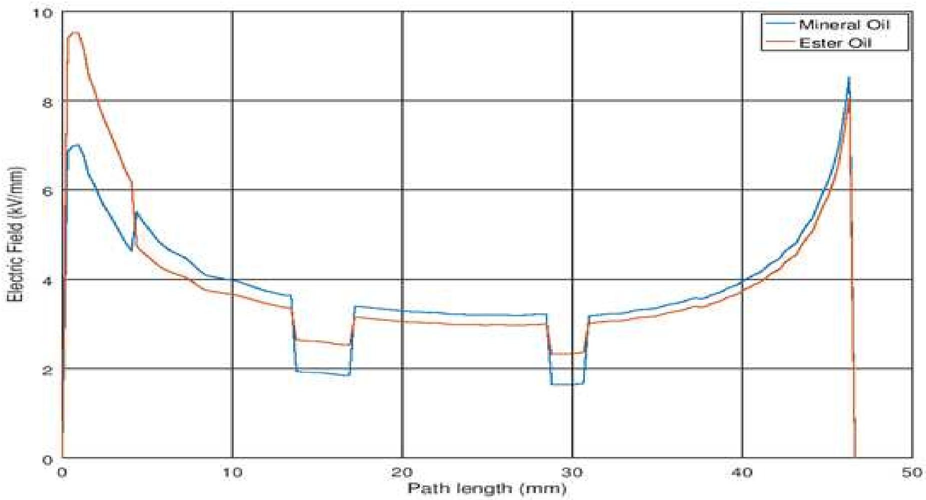


Figure ~~7~~6 Electric Field versus Path Length

Air bubbles formed in natural ester oil take longer to extinguish due to the higher density of the oil, which can cause partial discharge phenomena if the oil is not impregnated correctly.

Formatted: Font: Not Bold

Solution: The oil impregnation times for natural ester oils should be increased to accommodate for the higher viscosity and increased paper weight. The temperature of the oil during filling should be increased to facilitate oil impregnation and the intensity of vacuum drawn may be increased.~~.~~

Compatibility of Materials with Natural Ester Oil

Challenge: Some materials that are commonly used in transformers such as nitrile rubber are known to age prematurely in natural ester oil. There is also uncertainty over the reaction of the resin used in continuously transposed copper (CTC) windings with natural ester oils.

Solution: Reputable manufacturers of natural ester oils have performed compatibility test to ensure that suitable alternatives to all non-compatible materials are accessible. This database is readily available for transformer manufacturers to verify the bill of materials against. Electrical designs can be modified to use paper covered conductor instead of CTC.

Fast Transient Response in Natural Ester Oils

Challenge: Fast streamers develop more easily in natural ester oils than in mineral oils and are therefore able to bridge longer gaps.

Solution: Electrical designs must be modified such there are larger distances between live and grounded elements. A higher voltage class of tapchanger may be used to accommodate for the fast streamer response in natural ester. Vacuum tapchanger may be used to prevent switching from taking place in the ester oil.

Oxidation Stability

Challenge: Natural ester oils have lower oxidation stability than mineral oils and age considerably faster in the presence of oxygen.

Solution: Fit a preservation bag to the conservator to limit exposure to the atmosphere and prevent oxidation of the natural ester oil.

Summary of Costs of Using the Natural Ester Oil

Table 2 Summary of Costs of Using the Natural Ester Oil

	Savings	Additional Costs	Reasons
		R406,080.00	12690 liters of oil at R55 per liter Natural Esters versus R23 per liter Mineral Oil.
	R300,000.00		Reduced oil holding dam and piping.
	R5,000,000.00		Savings from not requiring active fire protection.
Total	**R5,300,000.00**	**R406,000.00**	
NET SAVINGS	**R4,893,920.00**		

Conclusion

The unique requirements of the additional transformer bay required at Slurry PPC 88kV Substation posed an interesting challenge to Eskom's engineers. The sensitive environmental conditions, space constraints and the fire risks associated with an indoor station made the natural ester oil an obvious choice for the insulating fluid in the transformers. The use of natural ester oil allowed for a compact station and considerable savings were made by avoiding costs associated with active fire protection and oil containment facilities, in spite of the higher cost of the natural ester oil in comparison with mineral oil.

The difference in electrical and thermal performance of the natural ester oils to mineral oil resulted in the following changes to the electrical design of the transformer (when compared to the equivalent mineral oil transformer):

- Increased duct sizes to accommodate for kinematic viscosity and the generally higher viscosity of natural ester oils,
- Increased paper insulation as electrical stresses occur more in the insulation than the oil for natural ester oil transformers,
- Amend processes for oil filling to occur at a higher temperature and allow for longer standing times to ensure adequate impregnation of the paper,

Formatted: Font: Bold
Formatted: Font: Not Bold
Formatted: Font: Not Bold
Formatted: Font color: Red
Formatted: Centered
Formatted Table
Formatted: Font: Not Bold
Formatted: Font color: Green
Formatted: Font: Not Bold
Formatted: Font: Not Bold
Formatted: Font color: Green
Formatted: Centered
Formatted: Font color: Red
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font: 12 pt
Formatted: Font: 12 pt, Font color: Green
Formatted: Font: 12 pt, Font color: Green
Formatted: Font: 12 pt, Font color: Green
Formatted: Font: 12 pt
Formatted: Centered
Formatted: Font: Bold

- Use only materials proven to be compatible with natural ester, including alternatives to CTC,
- Allow for larger distances between live and ground parts to cater for the lower fast transient response in natural ester oils, and
- Fit a preservation bag to the conservator to limit exposure to the atmosphere and prevent oxidation of the natural ester oil.

The natural ester oil filled transformer provided an innovative, safe and cost effective solution for a challenging project. Extensive research was conducted into manufacturing transformers with natural ester oils and the subsequent electrical design met all criteria specified in currently available compliance documents. The transformer is currently in production and more information will be available after the type tests are conducted in October 2017.

The North West Operating should give serious consideration to replacing all the mineral oil filled transformers in operation at PPC Slurry substation with natural ester filled equivalents to address the fire and environmental risks at the station.

Acknowledgements

The authors would like to acknowledge the contribution of Annalie Lombaard (Eskom), Willibald Felber (Felber Engineering), the North West Operating Unit and Powertech Transformers for their efforts in realizing this project.

References

[1] SANS 10400: Building Regulations part ~~T~~ ~~,~~,T, South African Bureau of Standards, 1990

[2] IEC 61936 -1 Power installations exceeding 1 kV a.c. Part 1: Common rules, International Electrotechnical Commission, 2010

[3] G Pukel, R. Schwarz, F Baumann, H Muhr, R Eberhardt, B Wieser, D Chu, Power Transformers with environmentally friendly and low flammability ester liquids, Elektrotech. ~~Inftech.,~~Inftech, 2013

[4] IEC 60076-14 Power transformers Part 14: Liquid-immersed power transformers using high-temperature insulation materials, International Electrotechnical Commission, 2011

[5] T. Prevost, Dielectric Properties of Natural Esters and their Influence on Transformer Insulation System. Design and Performance, ~~Thomas A. Prevost,~~ Power & Energy Society General Meeting, 2009 ~~Member IEEE~~

[6] IEC 62770 Fluids for electro technical applications – Unused natural esters for transformers and similar electrical equipment. International Electrotechnical Commission, 2013

[7] R Frotscher, D Vukovic, M Jovalekic, S Tenbohlen, J Harthun, C Perrier, M Schafer Behaviour of Ester Liquids under Dielectric and Thermal Stress –
From Laboratory Testing to Practical Use, Cigre, 2012