

Application of Natural Ester Insulating Liquids in Power Transformers

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ABSTRACT

Natural ester insulating liquid was recently specified for a 420 kV power transformer, which is the highest voltage unit designed and operating to date. Leading up to this new large power transformer, there are many other small, medium and large power transformers operating new since the early 2000's. If small power substation units are combined with medium to large power, there are many thousands of new and retrofilled transformers in operation that are being tracked. In total, there are over 600,000 natural ester transformers operating worldwide without a reported fire or environmental incident. Laboratory studies and field operation data provided from power transformers and reactors as reported in this paper indicate that natural ester liquids are reliable as dielectric insulation and as a coolant. A case history and laboratory testing data from samples collected during routine maintenance intervals indicate that natural ester fluid results can be used to reliably diagnose operating problems and suggest corrective actions.

Keywords — Power Transformer, natural ester liquid, insulation quality, retrofit, oil

1. INTRODUCTION

The earliest natural ester fluid-filled transformers were new distribution designs built and installed in 1996 [1]. Retrofilling existing mineral oil distribution transformers followed in 1997. These early units led the way for many new and retrofilled transformers that presently number over 600,000. The majority is distribution class, but small, medium and large power class numbers have increased to above 25,000 units. An overview of power transformers containing natural ester fluids will be provided in this paper.

The progression of natural esters as insulating liquids for electrical equipment could be described as still early in their utilization. The combination of environmental, safety

and thermal capability is important to users who have become increasingly driven to reducing cost. Figure 1 shows the progress of natural ester fluids from discovery through mature utilization [2].

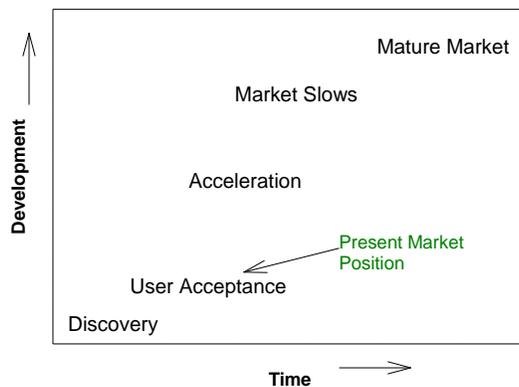


Fig. 1 Progress of natural ester fluid development and use

Behind this growing adoption trend it is well known that natural ester liquids have high flash and fire point temperatures more than two times greater than mineral oil. Their biodegradability and sustainability are significantly greater than all other insulating liquids used for transformers, making them the best in class regarding environmental benefits. Early lab and field performance studies provide confidence of the increased capability of natural ester liquids [3-6].

In this paper, the interactions of natural ester liquid with cellulosic insulation are reviewed in a case study. There is good agreement from multiple researchers that natural ester liquid protects cellulose insulation allowing longer life and increased thermal protection [7-10].

Laboratory studies led to early use in distribution transformers in 1996. New power transformers followed starting in 2003. A summary of the natural ester-filled power transformers will be provided in this paper, the latest being a 420 kV unit built by Siemens in Germany.

Field study and operating data analysis from a power reactor are presented as an interesting case study. The information provides confidence that analysis of in-use natural ester liquids to diagnose field performance is similar to expectations set by experience with mineral oil.

2. Natural Esters Used in Power

2.1. Overview

The number of power transformers in operation with natural ester insulating liquids is about 26,000 units using conservative estimates. It is probable that this estimate could be low by a factor of at least 1.5 to 2 times. There are many manufacturers that have market data that has been unavailable due to confidentiality or natural ester liquid purchases through stocking distributors. The numbers of natural ester liquid-filled units that are presented in this paper and the various transformer types are based on cu-

mulative data that has been collected since the earliest days of commercial availability.

The majority of natural ester-filled power transformers include over 25,000 small power substation units above 38 kV and between 2 to 10 MVA in power. Figures 2 and 3 provide a summary of the voltage and power ranges between medium to large power transformers containing natural ester liquids.

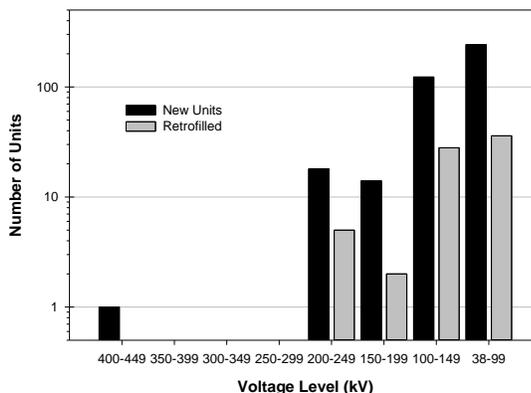


Fig. 2 Voltage level of medium to large power transformers filled with Natural ester liquid

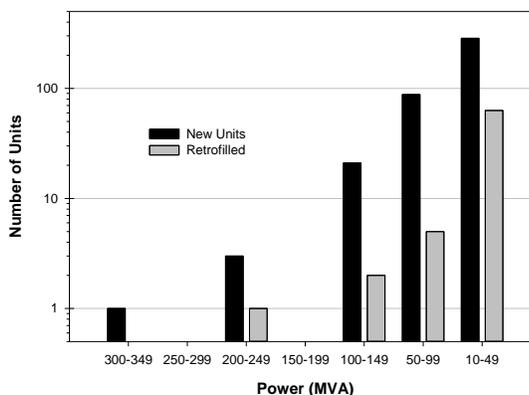


Fig. 3 power level of medium to large power transformers filled with Natural ester liquid

For the medium to large power transformers that are being tracked, there are nearly fifty units that are greater than 10 years old and over 160 units between 5 and 10 years old. The earliest new transformers were 69 kV 20 MVA units that have been operating since 2003, while the earliest retrofill was a 69 kV 50 MVA unit done in 2001.

There is a cumulative total of over 1000 years of natural ester-filled new power transformer field operation and almost 600 years for the retrofilled units. The median ages of the new and retrofilled trans-

formers are 5.4 and 7.6 years respectively. The types of new and retrofilled medium to large power transformers filled with natural ester liquids are presented in Table I.

Table I

Types of natural ester filled power transformers

Equipment Types	% of New Units	% of Retrofills
GSU	9.7	15.1
Substation	82.8	61.6
Autotransformer	0.5	1.4
Reactor	1.1	
Mobile SS	3.8	
Voltage Regulator	1.1	
Grounding Transformer	1.1	
1ph Transmission		5.5
Rectifier Transformer		9.6
Aux Power		6.8

2.2. First 420 kV Power Transformer

The current discussion of natural ester-filled power transformers would not be complete without reviewing the largest unit installed to date. In early 2014, TransnetBW commissioned a Siemens 420 kV extra-high voltage transformer filled and shipped with Envirotemp™ FR3™ Fluid, a soy-based natural ester insulating liquid. TransnetBW is a transmission network operator in the German state of Baden-Württemberg. The transformer shown in Figure 4 was installed at the Bruchsal-Kändelweg substation near Karlsruhe to link the 380 kV extra-high voltage level with the 110 kV grid.



Fig. 4 Siemens 420 kV extra-high voltage power transformer filled with Natural ester liquid

The rated power of the 420 kV transformer is 300 MVA with continuous overload capacity up to 400 MVA, which takes advantage of the higher thermal class of TUK paper immersed in natural ester liquid. The design and cooling characteristics of the transformer in accordance with standard IEC 60076-2 are expected to provide a longer life span than a similar mineral oil unit [11-12]. The transformer had a special partial discharge requirement of less than 10 pico-coulombs at 1.1 p.u. of rated voltage that was successfully achieved at factory acceptance testing.

The insulation system was designed in accordance with IEC 60076-14 for liquid immersed power transformers using high temperature insulation materials [2,13]. The use of thermally upgraded Kraft paper and natural ester liquid provides a significant advantage from the temperature limit of 130°C on the winding hot spot. The normal operation of the design is 105°C with KNAN cooling. Table II summarizes the design characteristics of the transformer.

Table II

Design Characteristics of Siemens 420 kV transformer [2,11]

Characteristic	Value
Rated Voltage	420 kV
Rated Power	300 MVA
Performance	180 / 300 / 400 MVA
Ratio	405 ± 11% / 115 / 22 kV
Cooling	KNAN / KDAF1 / KDAF2
Liquid	Soy-Based Natural Ester
AC Insulation Level	630 kV
Lightning Impulse Insulation Level	1425 kV
Switching Impulse Insulation Level	1050 kV
Operating Weight	400 ton
Liquid Capacity	97 ton

The 420 kV transformer is equipped with a Maschinenfabrik Reinhausen OLTC VACUTAP VR. The mechanical sealing in the transformer was accomplished with Viton fluor-elastomer.

2.3. Reactor Case Study

A three phase shunt reactor rated at 138 kV / 11.4 MVAR was designed, filled and tested in factory with FR3 natural ester liquid. Eletrobras/Eletronorte grid-company energized the reactor in 2006. The unit started showing signs of abnormal fluid behavior in the fourth year of operation. The fluid was monitored at regular intervals over the years [14]. Testing results indicated a variation of the fluid parameters very atypical, in comparison with other natural ester liquid-filled equipment owned by the company. Figure 5 is a graph of the neutralization number of several FR3 natural ester-filled transformers and reac-

tors at Eletronorte. The graph clearly shows the “outlier”.

In September 2014 an “on-site” inspection of the reactor was conducted and the cause of the abnormal behavior was identified: a failure of the rubber bag installation.

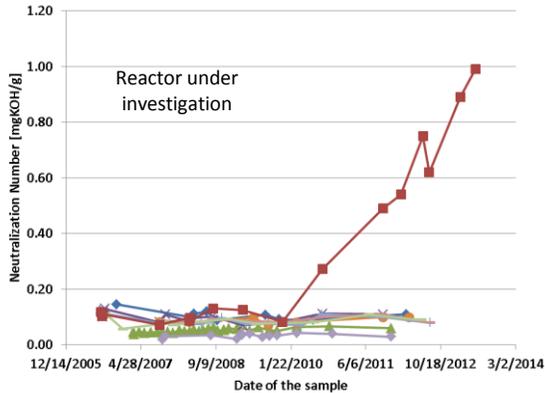


Fig. 5 Acid value of natural ester-filled transformers and reactors in service for about 7 years

The attachment point of the bag in the upper flange of the oil conservator was not properly assembled, allowing free entry of atmospheric air into the unit. Plainly, the vegetable oil immersed reactor was in a completely free breathing condition.

The map in Figure 6 indicates the climate conditions of the reactor installation region: hot and wet throughout the year (no dry season).

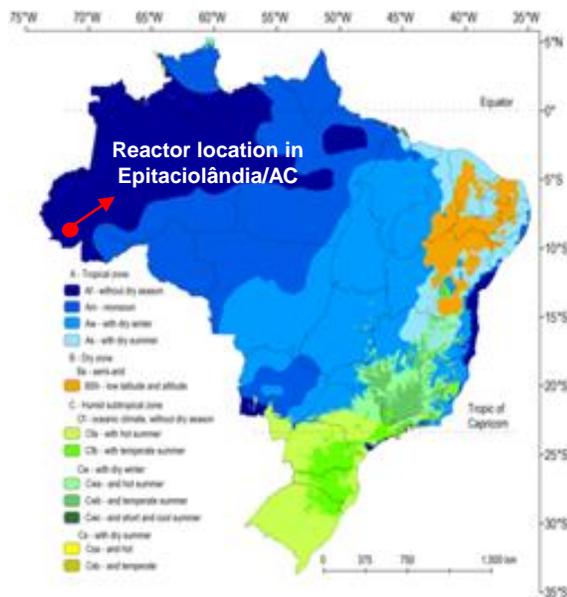


Fig. 6 Brazilian climate map showing the location where the reactor is installed

The reactor remained energized at rated voltage continuously (full load condition) during the seven years it has been in service. Figure 7 confirms that the outside of the rubber bag has been in open contact with atmospheric air, being possible to clearly identify a horizontal line of the “oil level”. The air was occupying the upper volume outside the bag.

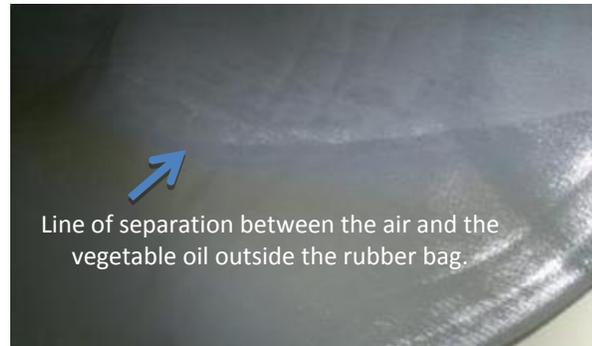


Fig. 7 Outside of the rubber bag, where the separation line indicating the “oil level” can be clearly seen

Application of natural ester liquids in free breathing equipment is not recommended. What happened with this reactor was unintentional, but serves as an actual field performance test.

It is important to take into account that the reactor has been operating in a region of very high moisture (it rains everyday), very hot (ambient temperature between 30 and 40°C), under "severe" thermal condition (24/7 full loading) and in a free breathing condition. According to the records, top oil temperature was typically around 90°C or higher.

The equilibrium condition of the natural ester liquid exposed to a hot wet climate should result in a relatively high moisture condition. However, the maximum moisture content measured in the liquid during the 7 years was 183 ppm, as shown in Figure 8.

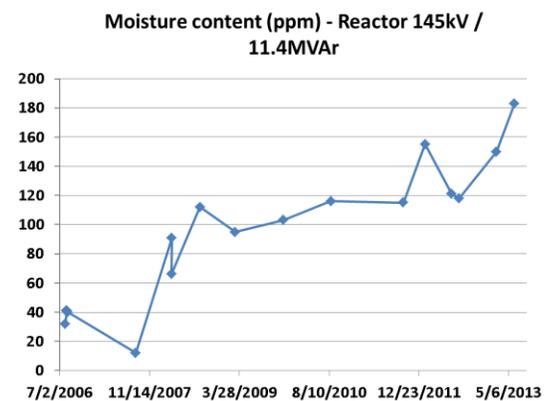


Fig. 8 Total water content in the natural ester during 7 years in service

Assuming a conservative average oil temperature of 70°C, the water saturation level of FR3 fluid would be about 2263 mg/kg, which results in 8.1 % maximum relative moisture content. Despite the existence of a silica gel absorbent that helped reduce the moisture ingress, this level is surprisingly low, being a very clear indication that the moisture absorbed from the atmosphere was consumed by a hydrolysis reaction with the natural ester liquid. The acid by-products of hydrolysis increased the neutralization value, but kept the fluid dry. As a result, the paper was also kept dry, even under very adverse environmental conditions.

During the on-site inspection a procedure for measuring the insulation moisture was performed. The tank was kept under vacuum for a few hours and then under dry air (dew point lower than -50°C) during 48 hours. The measurement of the dew point of this air in equilibrium with the inner tank condition is used to indicate the moisture content of the insulation. The measured dew point of -25°C for an ambient temperature of 31°C indicates about 0.90 to 1.05 % of moisture in the solid insulation inside the reactor. For this 138 kV unit, this moisture content is close to the requirements for new equipment.

This is the most important aspect of this case study, since it confirms that the natural ester liquid, despite having a very high availability of moisture from the ambient, was still providing moisture extraction from the solid insulation. Instead of equilibrium between the insulating paper and liquid, in this case the equilibrium included the outside ambient conditions. The liquid was strongly affected as the acid value shows, but the ambient moisture conditions did not really affect the solid insulation, which was in fact drier than would be expected in a heavily loaded mineral oil unit.

The dry-out effect [15] of the fluid to extract moisture from the paper and reduce the thermal degradation rate, in this case, was not cancelled by exposure to the ambient conditions. In fact, the long-chain acids produced by the hydrolysis reaction between water and the natural ester liquid is a key concept that is different compared to min-

eral oil. Short-chain acids from mineral oil catalyze the thermal breakdown of cellulose versus the long-chain acids from natural ester liquids provide increased stability to the cellulose via a transesterification reaction hypothesis described in [7] and [8].

Figure 9 shows a slight increase in viscosity at 40°C, but not seen at 100°C. This increase is not enough to indicate a critical oxidation of the natural ester. The increase of the neutralization value, as a result of the moisture ingress, was much faster than the possible oxidation caused by the continuous contact with ambient air. The quantity of oxidation inhibitor was not measured, but our recommendation would be to test and determine if additive addition is required.

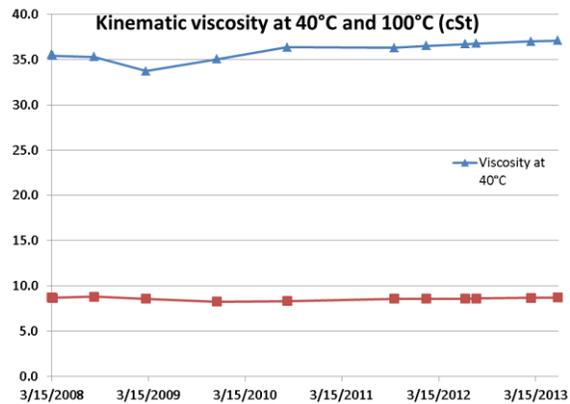


Fig. 9 Kinematic viscosity at 40°C and 100°C of the natural ester liquid during 7 years of field service in the 138 kV reactor

From Figure 5, taking into account that the suggested limit for neutralization no. for continuous operation of equipment is 0.3 mg KOH/g, an investigation should have been started in the middle of 2010. However, since the equipment was being continuously monitored and the dielectric strength shown in Figure 10 was not indicating any problem, no action was taken.

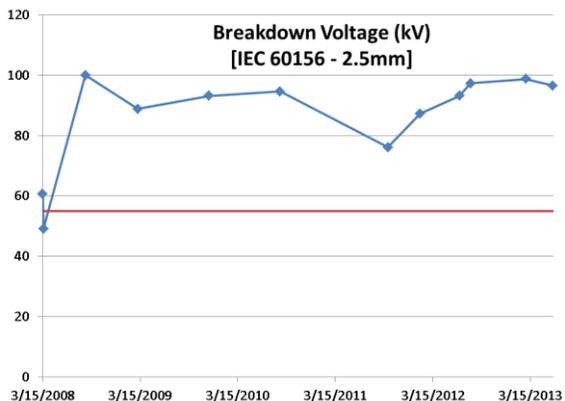


Fig. 10 Breakdown voltage of the natural ester from the reactor, with the red line indicating the suggested minimum value for the fluid after contact, prior to energization (new)

In late 2011, the dissipation factor investigation limit was surpassed, as can be seen in Figure 11. Likewise, the decision was to maintain operation and monitor. The dielectric breakdown voltage decreased slightly in late 2011, but this was probably test variability, not indicating any trend.

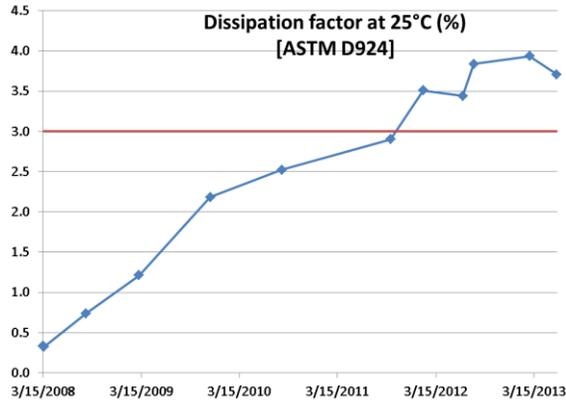


Fig. 11 Dissipation factor of the natural ester liquid from the reactor, with the red line indicating the suggested limit of continuous operation as per IEEE C57.147 [16]

The main conclusions drawn from the 138 kV reactor case study are:

- The increase of the neutralization no. due to natural ester hydrolysis with the ambient moisture is much faster than the effect of oxidation on the fluid viscosity.
- Despite not measuring the oxidation inhibitor content, the stability of the viscosity indicates that seven years while under the severe conditions was not enough to consume all oxidation inhibitor.
- The fluid behaved as a “sacrificial component” from the free-breathing and moisture caused by the incorrect installation, however, the degradation did not affect the dielectric performance of the fluid.
- It is not possible to estimate exactly, but the solid insulation moisture level expected for a reactor under similar conditions filled with mineral oil would be higher than what has been identified in this case.
- The soy-based natural ester insulating liquid is robust for “real world” applications, even when problems develop.

3. CONCLUSION

The progression of the use of natural ester insulating liquids is now starting the “acceleration” phase. After proving excellent performance in distribution transformers (up to 36 kV) for many years, the voltage and power have slowly increased, reaching the 420 kV and 300 MVA level about one year ago. Currently, there are a number of 500 kV projects and higher under study.

The natural ester liquid-cellulose interactions identified in the “Free-breathing reactor case study” in Section 2 and presented both in IEC [13] and IEEE [17] standards have been the basis for several utilities to increase the temperature rise limits of their transformers. The reduction of the paper degradation rate for the same temperature has a very positive financial effect on asset depreciation and net present value.

Additionally, this new and improved technology has been instrumental in equipment cost reductions, size and material reductions and improved thermal capability of electrical power equipment, which has added momentum to the adoption of natural ester filled transformers by utilities.

There are significant numbers and ages of natural ester filled transformers and reactors in service around the world without any critical issues caused by the liquid. This is the strongest evidence that natural ester liquids are a very robust and reliable solution as an improved liquid insulation for transformers and other electrical devices.

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Kevin J. Rapp graduated from the University of Wisconsin-Parkside with a B.S. in Chemistry after completing undergraduate research in Lipid-Cellulose Interactions Chemistry. Kevin began his career at the Thomas A. Edison Technical Center in 1976. In June 2012, the Envirotemp FR3 Fluid, which Kevin co-invented, became part of a new dielectric fluids business unit at Cargill, where he is currently Senior Chemist. Kevin is involved in standards work at ASTM as Chairman of D27.15 and D27.91 Subcommittees, and is the Technical Advisor for the United States National Committee, for IEC TC10 insulating fluids for electrotechnical applications. Kevin holds many US and International patents and has published numerous papers.



John Luksich is a Principal Engineer with Cargill Industrial Specialties, focusing on natural and synthetic ester dielectric liquids. Prior to Cargill, he spent 15 years as a Senior Engineer in the Dielectric Fluids group of Cooper Power Systems. In addition to dielectric fluids, his engineering career includes thin film materials development for the McDonnell Douglas Space & Physics Laboratory, and sensor development for Johnson Controls. Mr. Luksich received a B.Sc. in Chemistry in 1980 and M.Sc. in Materials Engineering in 1990, both from the University of Wisconsin. He is active in the ASTM D27 Committee on Electrical Insulating Liquids, and served as chairman of both the D27.02 Gases and Synthetic Liquids subcommittee and the Natural Ester Working Group. He is an active member of multiple Working Groups of the IEEE PES Transformer Committee. He has authored more than two dozen papers on ester dielectric fluids.



Alan Sbravati graduated from the University of Campinas, in Brazil, has an MBA in Management from FGV and a Master Degree on Project Management from ILEDE / Pittsburg Business School. He made his career starting as a mechanical designer of power transformers and in the research and development department of Siemens, being appointed as department manager and Global R&D project manager for the development of calculation routines for transformer design. Since 2004 is an active member of Brazilian Standardization Association (ABNT), holding the position of chairman of working groups, and is also a member of IEC TC14. Having participated in designs of Natural Ester filled transformers since 2006, he has been part of the technical group of Cargill since early 2013.