

SUSTAINABLE ELECTRICAL ENERGY USING NATURAL ESTER TECHNOLOGY

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ABSTRACT

This paper presents the expanding application of natural ester dielectric fluids in transformers, utilizing their thermal capabilities to develop a more sustainable equipment platform. Beyond their proven function within transformers and established environmental, fire safety, and extended insulation life values, natural esters are being utilized in higher temperature rise transformer designs, enabling smaller, more cost effective equipment.

INTRODUCTION

For more than a decade, natural esters (vegetable oils) have been applied as an alternative to mineral oil for use as a Class K dielectric liquid in transformers. Large gap tests demonstrate that natural esters are dielectrically equivalent to mineral oil in high voltage applications [1]. Over 350,000 new and retrofilled (replacing mineral oil in existing transformers) natural ester filled transformers, up to 250 kV and 240 MVA, are currently energized across the globe.

Natural esters were originally developed as a high fire point dielectric fluid produced from sustainable materials (oil from seeds). Their environmental properties provided value to environmentally conscious customers and/or sensitive locations. The sustainability of natural ester dielectric fluids is based upon two primary contributions: their environmental profile (a renewable crop that is biodegradable, non-toxic, and essentially carbon neutral), and their demonstrated ability to extend the life of the cellulose insulation system by utilizing the full thermal capability of the natural ester/Kraft paper insulation system to reduce the raw material content required to transform voltage.

Accelerated aging tests reveal that not only do natural esters function effectively with common insulation system materials, but they also improve the aging and resultant anticipated lifespan of cellulose insulating paper in normal sealed designs [2].

SUSTAINABILITY

In 1987, a UN conference defined sustainable developments as those that meet present needs without compromising the ability of future generations to meet their needs [3]. Natural ester technology enables the

transformer industry to embrace this ideology on many levels.

ECONOMIC SUSTAINABILITY

Inherently, natural esters can be classified as high temperature material. In the application of sealed transformers, they alleviate the traditional operating temperature limitations on which all current mineral oil transformer operating standards are based. The resultant smaller, lighter transformers available today continue the age-old process of using new technologies to optimize designs, thus reducing material content required for voltage transformation without negatively impacting equipment life expectancy.

Insulation System Limits

Insulating systems comprised of solid cellulose insulation and natural ester fluid as applied in current transformer designs or using traditional operational limits have a much longer thermal life when compared with mineral oil systems. This insulation life extension (longer transformer life) yields lower life cycle costs and delays asset replacement. Retro-filling existing transformers with natural ester fluid can significantly increase the load-ability of the installed base without accelerating insulation aging rate. The load-limiting factor may no longer be the insulation system, but rather may be the other temperature sensitive distribution class transformer components.

Thermal Capacity

Industry-standard thermal evaluations and accelerated aging studies show that the natural ester fluid/Kraft paper

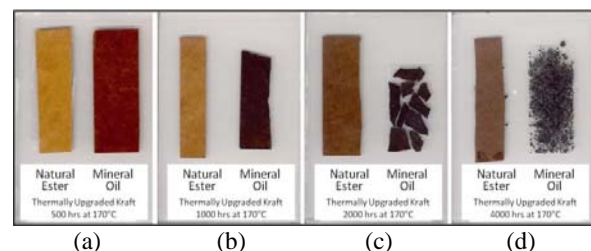


Figure 1 Relative aging of thermally upgraded paper in mineral oil and natural ester after (a) 500 hrs, (b) 1000 hrs, (c) 2000 hrs, and (d) 4000 hrs at 170°C. [3]

insulation system ages at a considerably slower rate compared to traditional mineral oil/Kraft paper insulation systems [4,5]. Fig. 1 shows examples of paper aged in mineral oil and natural ester fluid.

Natural ester fluid interacts with water produced as paper ages to chemically eliminate the water via hydrolysis [6-8]. This mechanism is the reason for the slower aging rate and extended insulation system thermal life at normal mineral oil/Kraft operating temperatures. The aging rate can be slowed in existing transformer insulation systems [9], resulting in lifespan extension for retrofilled transformers.

The thermal capability of an insulation system is typically represented by an aging curve, plotting relative aging rate versus hottest spot temperature [10]. The relative aging rate for the mineral oil/thermally upgraded (TUK) insulation system is given by Eq. 1; the relative rate for the natural ester/TUK system, derived from aging studies, is given by Eq. 2. Table 1 compares the mineral oil and natural ester relative aging rate at various temperatures.

$$V_{mo} = e^{\left(\frac{15\,000}{110+273} - \frac{15\,000}{\theta_h+273}\right)} \quad (1)$$

$$V_{ne} = e^{\left(\frac{15\,000}{130+273} - \frac{15\,000}{\theta_h+273}\right)} \quad (2)$$

Where V_{mo} = relative aging rate in mineral oil
 V_{ne} = relative aging rate in natural ester
 θ_h = hottest spot temperature (°C)

Using this approach, natural esters enable increased insulation system life as compared to mineral oil at the same hot spot temperature, or similar life at an increased hottest spot temperature, as shown in Fig. 2. The ability to run a transformer at higher temperature enables increased loading. When incorporated into equipment designs, smaller and more cost effective equipment with improved safety profiles result [11]. International high temperature insulating materials standards are beginning to recognize this technology [12].

Fire safety

The most commonly used Class K natural ester dielectric

Table 1 Relative aging rate V of thermally upgraded paper in mineral oil [10] and natural ester at hottest spot temperature θ_h .

θ_h (°C)	mineral oil V_{mo}	natural ester V_{ne}
100	0,35	0,05
105	0,60	0,09
110	1,0	0,14
115	1,66	0,24
120	2,71	0,39
125	4,38	0,63
130	6,98	1,0
135	11,0	1,58

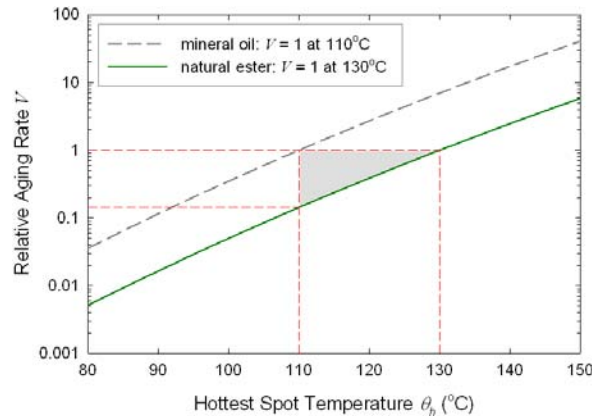


Figure 2 Relative aging rates of thermally upgraded paper in mineral oil [10] and natural ester. The shaded area represents the additional thermal capability of the natural ester/thermally upgraded paper insulation system.

fluid (Envirotemp™ FR3™ fluid) has zero incidents of transformer fires. This reduces fire mitigation requirements and associated costs. No fires means less cleanup, less downtime, and lower replacement costs.

Transformers filled with Class K natural ester fluid facilitate less costly and more efficient building interior installations, reducing or eliminating entirely the requirements of vaults and sprinklers [13]. Outdoor installations using natural ester fluid can also eliminate the need for sprinklers, fire barriers, and greatly reduce the separation distances between the transformer and building or between transformers [13].

ENVIRONMENTAL SUSTAINABILITY

Vegetable oil natural esters are agricultural products, and

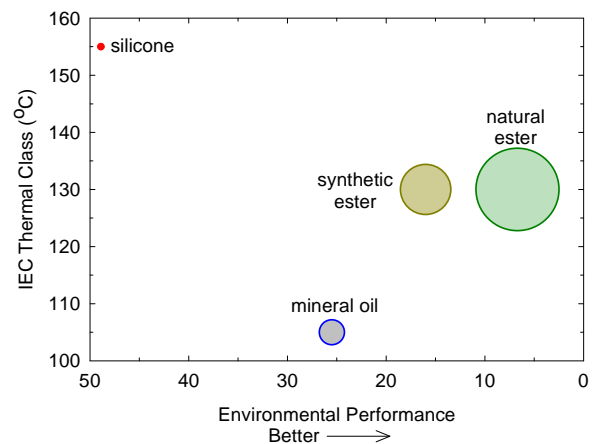


Figure 3 Environmental performance [14] versus insulating liquid thermal class (equal to the maximum recommendable operating temperature expected to give an acceptable lifetime of the liquid) [12]. Symbol diameter is proportional to percent OECD 301 ready biodegradability.

as such, are renewable resources. Natural esters can be recycled (in biodiesel, for example), and are 'readily biodegradable' in OECD tests. Because growing plants sequester carbon dioxide from the atmosphere, natural esters can be essentially carbon neutral. Depending on the additives used by the manufacturer, acute aquatic and oral toxicity tests show that natural ester fluids can be non-toxic and meet the regulatory requirements of nonhazardous materials.

The larger impact, however, is limiting the necessity of exploring, obtaining, and refining additional raw material used in the manufacturing of transformers. By optimizing transformer designs for higher temperatures, reducing material content allows current supply to be consumed in expanded applications.

SOCIAL SUSTAINABILITY

Natural ester dielectric fluids can be produced in the same region as the farmers growing the seeds, helping to support the farmers and local economy. Many governments have initiatives encouraging the use of bio-based products to reduce consumption of limited nonrenewable resources.

Using natural ester dielectric fluids as a direct replacement for transformer oil reduces (often imported) petroleum use.

GLOBAL EXPERIENCES

Many niche market transformer users specify higher temperature rated transformers. For example, wind generators have traditionally used high temperature materials to construct 'slim' type transformers, emphasizing physical size limitations that must be accommodated. Additionally, customers utilizing liquid filled transformers for indoor applications with similar room size limitations often benefit from compact transformer designs.

As natural ester technology has become better understood, the economical incentive to specify higher temperature designs is transforming the landscape. More mainstream customers are experiencing the benefits of smaller, lighter transformers, and OEMs on multiple continents are embracing higher temperature applications. These designs are less exotic and in fact are becoming the new norm.

In the USA, a growing number of utility coalitions are focusing on adopting sustainable technologies. Higher temperature rated transformers are expected to positively impact coalition members' annual transformer project costs, similar to the Asian experiences. Several OEMs are positioned to accelerate the projected savings.

New Distribution Transformers

In one significant project, an Asian utility serving a significant customer base has recently specified smaller, more compact transformers utilizing natural ester



(a) 45 kVA, 435 kg

(b) 88 kVA, 350 kg

Figure 4 Rating and weight of transformers (11400 or 13800 – 127/220 V) using the same tank: (a) standard operating temperature using mineral oil, and (b) prototype 85 K rise natural ester transformer. [11]

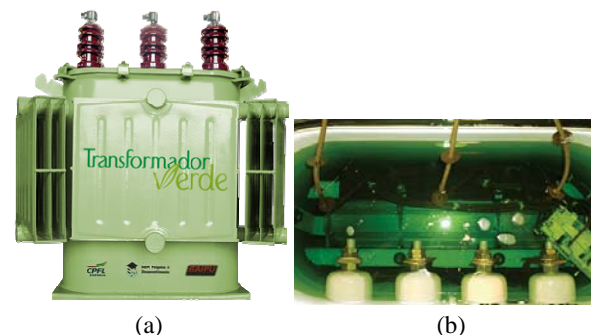
technology, anticipating saving up to 20% of their annual transformer budget.

Lowest Cost per kVA

One Brazilian project currently uses transformers designed to take full advantage of the natural ester/thermally upgraded paper insulation system. An 88 kVA, 85K rise natural ester transformer was designed to replace a 45 kVA standard design using the same transformer tank. The capacity increased 95%, yet the 88 kVA unit weighs 85 kg less than the original, reducing the effort needed for installation and maintenance as well as requiring less mounting hardware. Compared to a standard 75 kVA transformer using 102L of mineral oil, the 88 kVA natural ester transformer using 81L of natural ester fluid has lower no-load losses.

In addition, the cost per kVA was reduced by one third to €23,25/kVA from €36,75/kVA for the standard 45 kVA transformer. Fig. 4 shows the original transformer and the re-designed natural ester prototype; Fig. 5 shows the new natural ester production transformers.

Approximately 2100 transformers of this design having more than 50 million hours of operation are currently installed on the distribution network, with failure rates lower than the standard transformers now in use. The utility plans to energize an additional 900 units in 2011.



(a)

(b)

Figure 5 Example of the 88 kVA, 85 K rise natural ester transformer (11400 or 13800 – 127/220 V) currently in production: (a) external and (b) internal. [11]

Brazilian Sustainability

All materials used in the production of these transformers are produced and available for sale in Brazil, reducing transportation costs and supporting the local economy. This includes growing and crushing the seeds, refining the oil, and manufacturing the natural ester fluid. The biodegradability and non-toxic nature of vegetable oil help avoid problems of environmental contamination and minimize harm to flora and fauna. Spent natural ester fluid can be easily disposed of or recycled as biodiesel fuel. The production of natural ester fluid is essentially carbon neutral.

CONCLUSIONS

Higher temperature materials have been utilized in niche transformer markets for many years. Natural ester technology is fast becoming more applicable and affordable in the mainstream as material capabilities are better understood. Transformer insulation systems comprised of paper insulation/natural ester dielectric coolant operated at 130°C hottest spot temperature age at the same rate as paper insulation/mineral oil systems operated at 110°C hottest spot temperature. Designing with the updated standards enables a revised set of rules that minimizes the insulation system as the limiting factor. The outcome of applying this technology is smaller, more cost effective transformers possessing enhanced fire safety performance, based upon a renewable, recyclable, and non-toxic fluid having a carbon neutral footprint.

For Brazilian natural ester 85 K rise distribution transformers, the new designs have the same dimensions and external geometry with 95% greater capacity compared to the standard 45 kVA transformer. The project demonstrates the material compatibility and suitability of the chosen materials, resulting in substantial reductions in weight, fluid volume, and cost per kVA.

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