Evolution of Natural Ester Transforms Industry Norms

by **Alan Sbravati**
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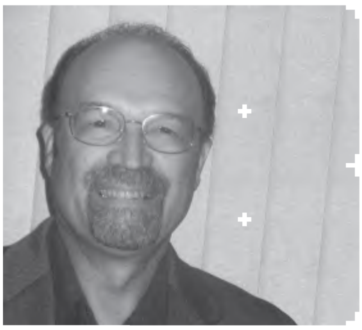
Photo: Cargill

Alan Sbravati started his career working for a transformer manufacturer, mainly developing calculation and design tools for power transformers. After almost 9.5 years in the same company, he was the R&D&E manager for power transformers in Brazil and responsible for two global R&D projects directly related to transformer design and thermal calculation. After three years in a commercial role, he moved back to a more technical position at Cargill. Over the last six years he has been working with the development and application of alternative insulating liquids, especially natural ester fluid (FR3™), holding the position of Global Technical Manager since 2018. Alan chaired the Brazilian Standards Committee from 2012 to 2016, prior to moving to USA. He participates in IEC TC 14 and Cigre working groups. Currently he is a member of IEEE Transformers Committee, and he is active in many subcommittees and task forces.



Kevin J. Rapp is the Principal Chemist for Global Dielectric Fluids of Cargill Bioindustrial. With over 40 years in the electrical industry, including 27 years in R&D where he invented Envirotemp™ FR3™ fluid and found that ester liquids enhance the life of cellulose insulation in transformers. Kevin is involved in standards as Technical Advisor/ Chairman of USNC of ANSI/IEC TC10, ASTM D27.15 and D27.91 Subcommittees. Kevin was awarded IEC 1906 Award in 2011, US-EPA Presidential Green Chemistry Award in 2013, ASTM Service Award in 2015 and installed as ASTM Fellow with Distinguished Merit Award in May 2018. He holds many patents and has published numerous papers as a member of ACS, AOCS, ASTM, CIGRE, IEC and IEEE.

Natural Ester Dielectric Liquid Development

Alternative liquids development motivation is strongly linked with the restrictions for polychlorinated biphenyls-based liquids (mostly know as PCBs) during the early 70s. The first alternative liquids the industry started using were hydrocarbons of high molecular weight, currently named as "less flammable hydrocarbons" as per ASTM nomenclature, and silicone based liquid (polydimethylsiloxane). Late in the 70s and early 80s other synthetic liquids started to be considered, with synthetic ester liquids based on pentaerythritol esters being the predominant option.

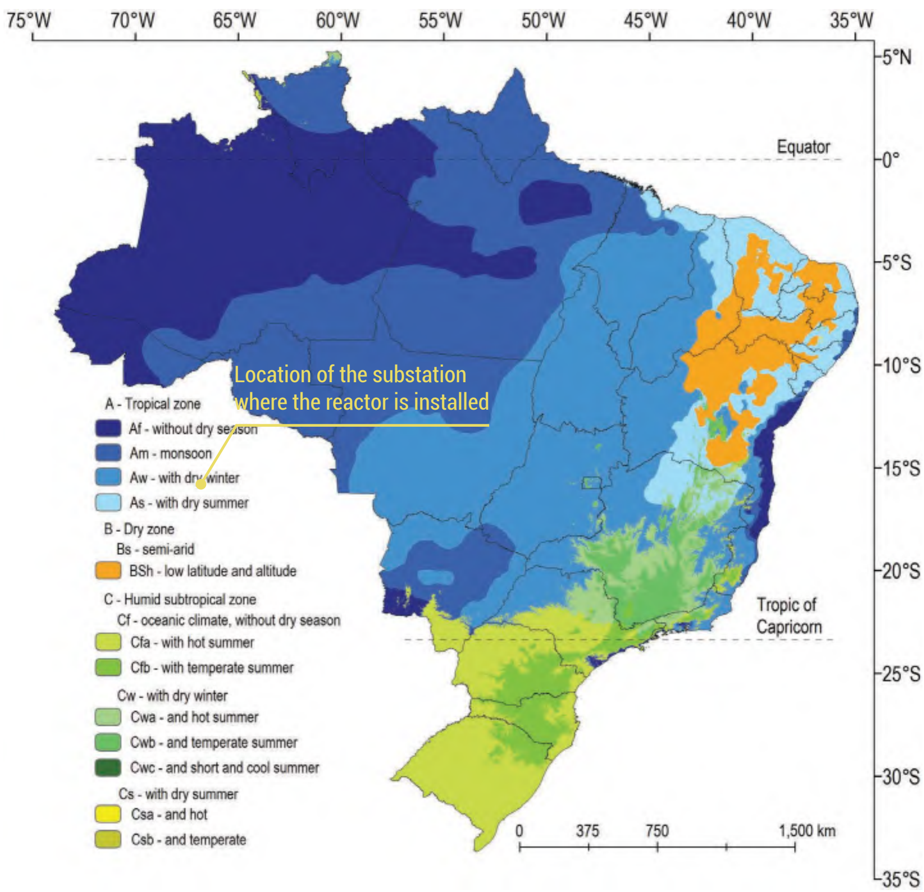
Finally, in the early 90s, researchers started developing applications based on vegetable oils, which are natural ester liquids or triglycerides. Cooper Power System got the first patent for the development of FR3 fluid in that period. Back in the early days of transformer development, around the 1890s, vegetable oils were considered for liquid immersed transformers. But just over one hundred years later the production process and proper formulation lead to a robust product, able to exceed the life expectancy of the transformer.

Although natural ester liquids were the latest development, its application overtook all the other alternative liquids, being estimated that over 2 million transformers have already been produced using FR3 fluid since the first commercial application in 1997. It is worth mentioning that this first transformer is still in service in a large amusement park in the southeast of the United States, and recent analysis of a sample confirmed that after 22 years of continuous service, most of its properties are still compliant with the requirements for "new unused natural ester liquids". Acid value and dissipation factor were expected to gradually increase along the years, while still far from the "continuous service" proposed limits.

Application of Natural Ester Filled Transformers

Transformers immersed in natural ester liquids can be found either in tropical rain forests of South America or in the streets of cold Minneapolis, MN (in the northern part of the United States), Stockholm (Sweden) and the fjords regions in Norway. Either mitigating the fire risk of a pole mounted transformer in a busy downtown area or minimizing the environmental impacts due to an accidental spill in a protected forest area, natural ester immersed transformer reliability has been proven by extensive real-life success cases.

Figure 1. Koppen climate classification [1]



An interesting example of such validations happened a few years ago in South America. A shunt reactor was installed in a remote region, at the border of the Amazon rainforest. Figures 1 and 2 show the substation location and a photo of the reactor. As later identified, the oil conservator rubber bag was not properly installed during the field assembly, keeping the reactor in a free breathing condition.

Due to the network, the reactor was continuously at nominal capacity (loading is defined by the system voltage) while the ambient temperature was rarely under 20°C (68°F) and often close to 40°C (104°F). Also, moisture was mostly very high (with no dry season), which all configured very harsh operating conditions for a free breathing unit.

After a few months in service, insulating liquid samples indicated increased moisture content. This was continuously monitored and the presence of leak point was raised. Consequently, the moisture value stabilized and acidity started to increase, followed by reduction of dissipation factor. This behavior clearly confirmed the initial suspicion of breach on the sealing system. Oxidation of the fluid was also a point of concern for the end user, but all laboratory analyses showed no reason for concern.

Seven years later, a planned outage was made possible. The natural ester viscosity had increased about 3%, indicating some oxidation was going on. The main real concern for the team was whether they were going to find excessive moisture content in the solid insulation materials, given the climatic conditions. However, the dew point measurements showed that the value was around 0.9%, which was a very good result. So, the overall conclusions were as follows:

- The moisture absorbed from the ambient was consumed by the fluid, without reaching the coils.
- Oxidation is a long-term process, taking several years to affect the fluid.
- Well formulated natural ester liquids are a very robust solution.

Dielectric Properties

While the early adopters of natural ester immersed transformers were mainly motivated by the fire safety and environmental benefits, the main driver for adoption of natural esters today is their dielectric properties. The "continuous drying" process enabled by the capacity of natural ester to absorb more water and, particularly, by the hydrolysis reaction, is the most relevant advantage of natural esters compared to all other alternative liquids.

Photo: Cargill

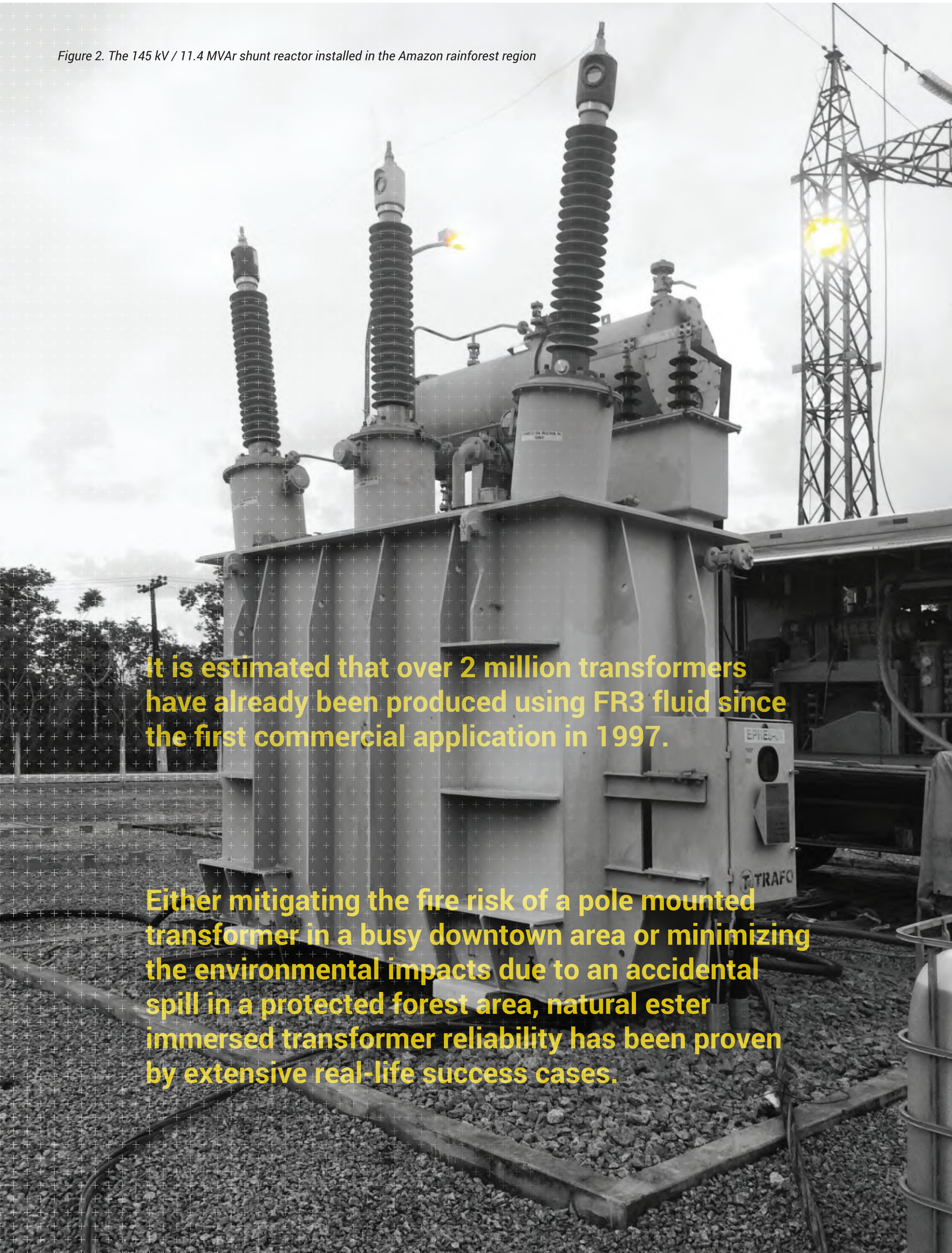


Figure 2. The 145 kV / 11.4 MVAr shunt reactor installed in the Amazon rainforest region

It is estimated that over 2 million transformers have already been produced using FR3 fluid since the first commercial application in 1997.

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Driven by moisture content and/or temperature, the reaction of the water with one of the non-hindered ester groups in the triglyceride results in the consumption of the excess moisture, generating as byproducts long chain-free fatty acids of low reactivity (mild behavior).

Moisture is one of the biggest enemies of electrical equipment. When a transformer manufacturer keeps a large core and coils inside a high-tech vapor phase oven for over a week, their main target is to reach the required dielectric capacity for the lightning impulse and other potentially destructive high voltage tests. In a mineral oil immersed transformer, in the course of the transformer life, moisture content in insulation paper tends to increase in traditional transformers. From the typical 0.5% in a new transformer, values in the range of 2% or 2.5% are not uncommon, yet highly detrimental for the dielectric withstand capacity of the insulation system. Conversely, continuous drying prevents moisture content increase in sealed FR3 fluid immersed transformers.

The continuous drying process is also key for the reduction of paper degradation rate in transformers immersed in natural ester liquids, in comparison to mineral oil and other alternative liquids. Paper degradation generates water as a byproduct, which also has a catalytic effect for further degradation, configuring a self-induced reaction. The presence of natural ester breaks this cycle – the moisture does not remain impregnated in the paper as it gets consumed by the reaction with the natural ester (hydrolysis). As a result, the thermal class of the very same thermally upgraded paper is proposed to be 20 degrees higher when it is immersed in natural ester, compared to the 120 value when immersed in mineral oil. Due to this, a superior resilience to demand fluctuations can be added to the improved long-term reliability and a reduced need for maintenance interventions to dry out the insulation system.

The capacity of natural ester to absorb more water, which enables the "continuous drying" process and reduces paper degradation rate in transformers, is the most relevant advantage of natural esters compared to all other alternative liquids.

Photo courtesy of TIRONI

The main motivation for utilities opting for natural ester immersed transformers is to reduce the frequency and duration of outages, either through the increased dielectric reliability and fewer maintenance interventions for drying processes or by mitigating the external effects caused by failures.

Case Examples

The main motivation for utilities recently converting all their new transformer purchases to natural ester immersed transformers is to reduce the frequency and duration of outages, either through the increased dielectric reliability and reduction of maintenance interventions for drying processes or by mitigating the external effects caused by failures, thus speeding up the restoration of the site.

Two utilities that adopted the use of natural ester for their transformers, one an energy distribution utility and the other an energy transmission company, applied two different approaches to explore the superior thermal performance of this liquid.

The starting point for the distribution company was the relevance of life expectancy of their transformers. The demand fluctuations that were associated with climatic conditions (heat waves) where their transformers were installed resulted in high peak demand, possibly exceeding the nameplate capacity of the transformers for short periods. Therefore, they started evaluating the use of natural ester to expand the transformers peak capacity and extend their lifespan.

A sensitivity analysis, where different values of life extension were applied to a percentage of the transformers replaced every year, confirmed that although initially costing a little more, the life extension would result in a positive net present value in comparison to traditional transformers. The quick payback of the additional investment motivated the financial department of the utility to adopt the new solution. Fire safety and environmental benefits came as additional benefits.

In the case of the transmission company, their initial motivation was the lifecycle costs, as the European normative makes them responsible for the final destination of the assets. This was quickly shaded by the possible economic savings they envisioned by exploring the higher thermal class as an alternative for avoiding increasing the number of transformers in a substation.

Their power transformers were designed for two different capacities. The rated capacity, at conventional temperature rise limits, and an additional "permanent overloading capacity", using the increased temperature rise limits. Although all guaranteed parameters were still at the rated capacity, the nominal life expectation for the insulation material would only be reached at the amplified capacity, what qualified it as a possible continuous loading condition. And they reached a 50% increment of capacity at the higher temperature rise limits.

The practical result was that, for a typical substation having 2+1 transformers (one being a spare unit), the effective capacity was equivalent to three times the rated capacity of one transformer. Should an event happen to one of the units, the other two remaining transformers would be able to keep the same loading, using their "permanent overloading capacity" of 1.5x during this period. The cost reductions associated with saving not only one transformer, but all the adjacent area and the associated electrical installations became the major benefit.

In summary, the main motivation for a customer to adopt natural ester as the insulating liquid for their transformers is to have peace of mind. Transformers immersed in natural ester liquids are safer, more sustainable and improve the system reliability and resilience of the asset.

References

[1] C. A. Alvarez, et al, "Köppen's Climate Classification Map for Brazil", *Meteorologische Zeitschrift*, Vol. 22, No. 6, 711–728, January 2014.