

In the last interview in Power System Technology 26 - "Green Energy" from February this year we mentioned that we know a lot about the FR3 Ester and its behavior in the field. We have shown some of the most important parameters and how they evolve over the years in a real everyday world of power transformers.

Let's dig a little deeper into the data we have and see how it compares to the known behavior of the mineral oil insulating fluids, which includes the GTL insulating fluids. In issue 24 of the Transformer Technology Magazine from December last year, we presented the dependencies of the mineral oil parameters in Figure 2. More on this topic can be found in IEEE Papers [1,2 and 3].

Taking a look at the FR3 data, first the data for the 'young' transformers, means less than 20 years of operation (<20). The best tool for this is the Multivariable Analysis [4], it is one of the main statistical methods used in studies with multiple inputs. We will try to provide a brief and comprehensive overview of multivariable analysis and present some of the core models that statisticians use to analyze experimental data.

One of the difficulties inherent in multivariate statistics is the problem of visualizing data that has many variables (in our environment here including age, acidity, temperature, water content, breakdown voltage, etc.) For example, a function chart showing a graph of the relationship between many of the FR3 variables is "Fig. 1".

# Multivariable Analysis

## Field behavior of Natural Esters



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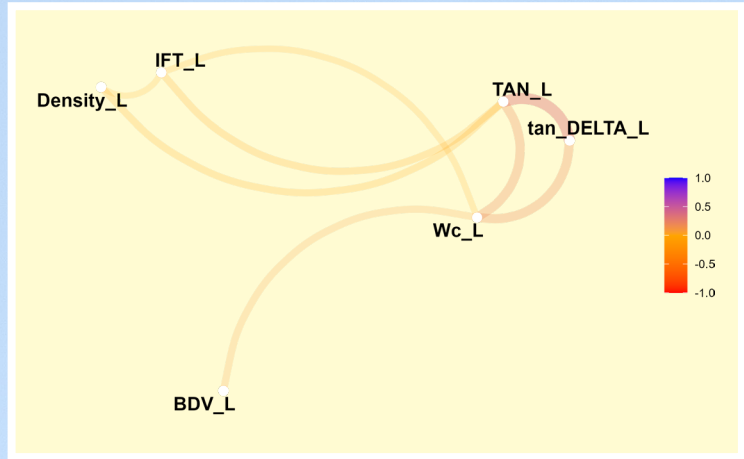
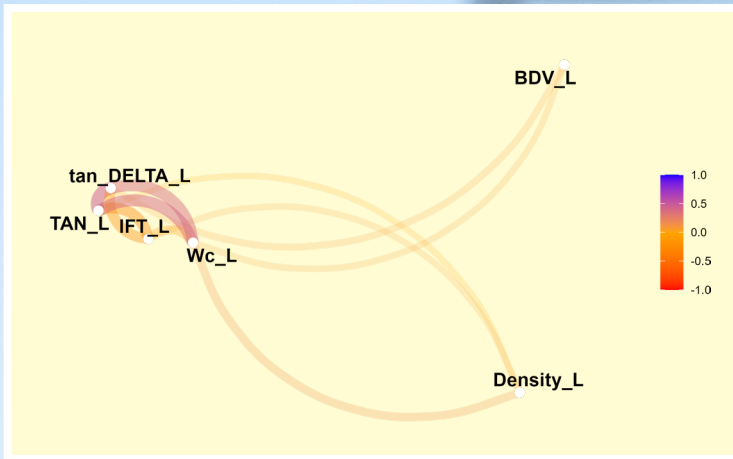
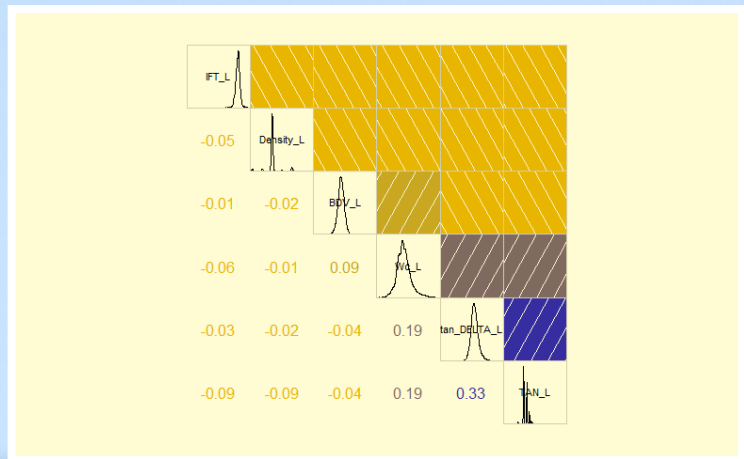


Figure 1. Function chart graph of the relationship between many of the oil's variables. The color bar shows the correlation coefficient between all the variables

Figure 2. Partial correlation between all variables is displayed numerically and as a color filed. The distribution function of individual variables is also shown - it is a different view on the same variables shown in function chart Fig.1



When we apply the same analysis to 'older' transformers, that is older than 20 years, the parameters correlate as follows:

Figure 3. Function chart graph of the relationship between many of the oil's variables in older than 20 years transformers.

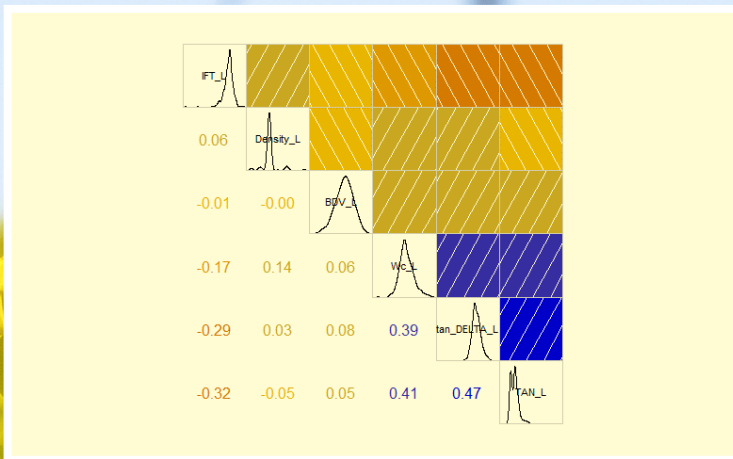
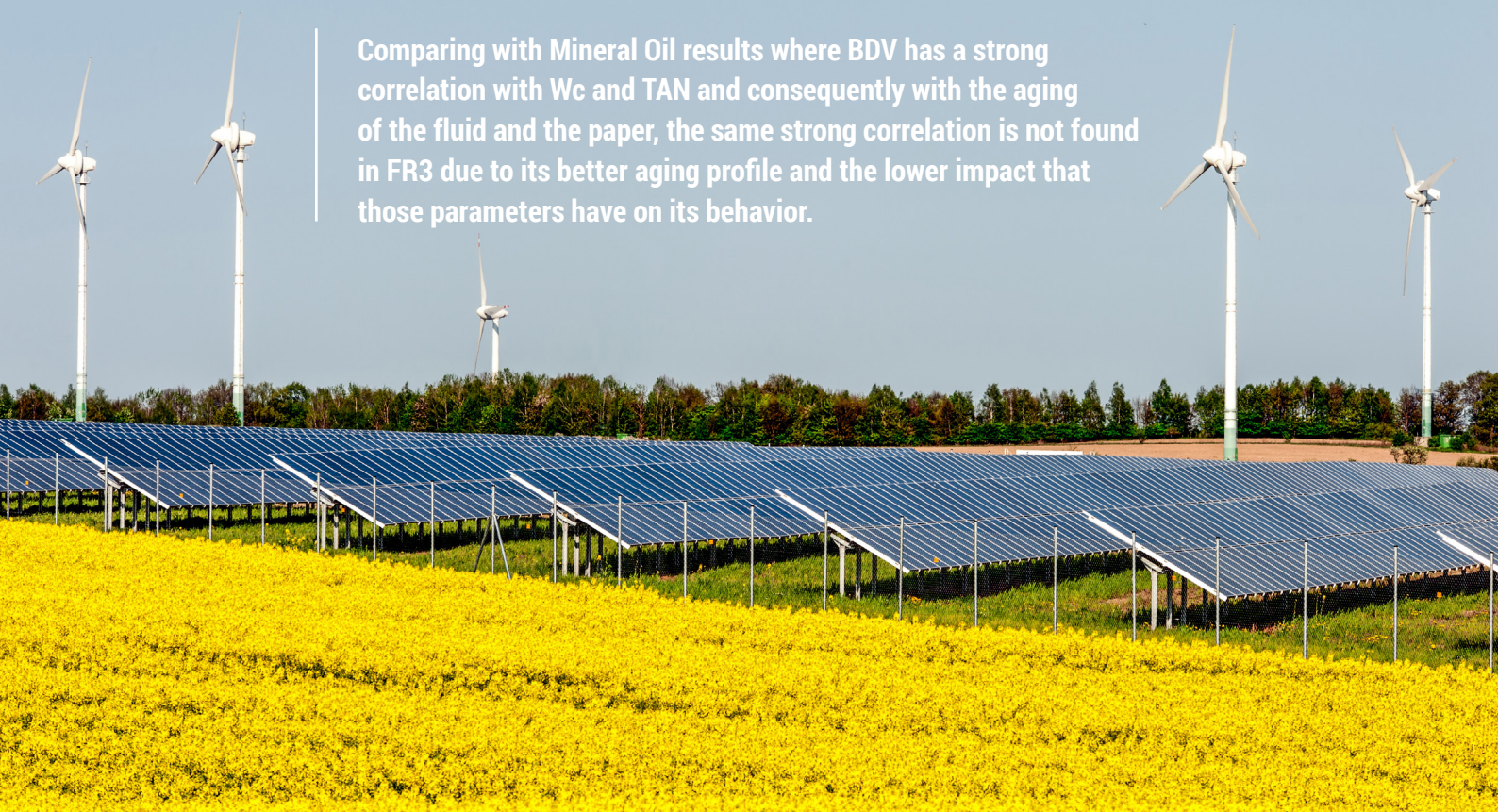


Figure 4. Partial correlation between all variables for the >20 years old transformers – analog to Fig.2

In datasets with many variables, groups of variables often move together, but as we can see the FR3 esters do not have a dominant variable. Comparing with Mineral Oil results where BDV has a strong correlation with Wc and TAN and consequently with the aging of the fluid and the paper, the same strong correlation is not found in FR3 due to its better aging profile and the lower impact that those parameters have on its behavior. This can be seen very clearly in the correlation matrix. It shows the well-known dependence of TAN, tan\_Delta, IFT and Wc (water) in all types of oils. While in FR3, the BDV seems to be very independent of other parameters, which is an excellent performance.



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As you will see in Figure 5 and especially in Figure 6, there we plot the behavior of BDV as a function of TAN vs. Wc. Even in cases where the maintenance limits of Wc and TAN have been reached, their impact on the BDV is not significant, even showing an increase under certain combinations.

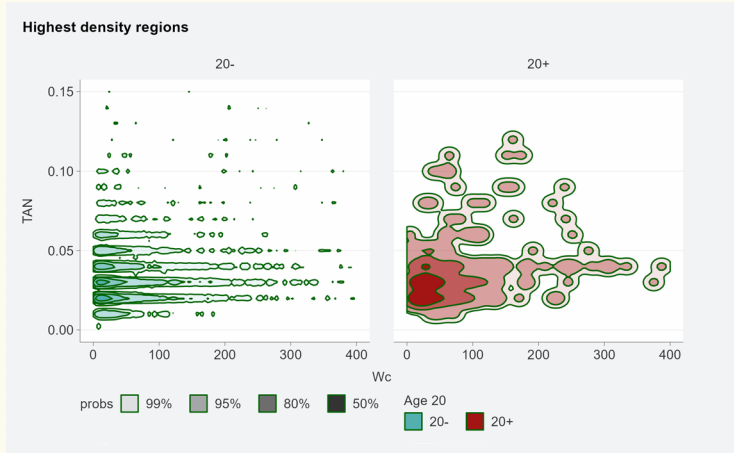
Are conventional transformers basically "ester-compatible"?

Thanks to natural ester, it is possible to load transformers in a much more varied manner or to run them at higher operating temperatures without being exposed to the risk of a transformer fire and without jeopardizing the lifespan of the units. With a few exceptions, these are transformers with a mixed insulation made of a dielectric liquid and an impregnated solid material. The solid takes over the mechanical load-bearing properties and the liquid acts not only as an insulation in coordination with the previous but also as a cooling medium. The dielectric insulating liquid is used to cool the windings, insulate the individual winding packages from one another and thus achieve optimum heat transmission performance in the smallest of spaces. In the course of changing the insulating oil, not only the properties of the insulation change, but also those of the cooling.

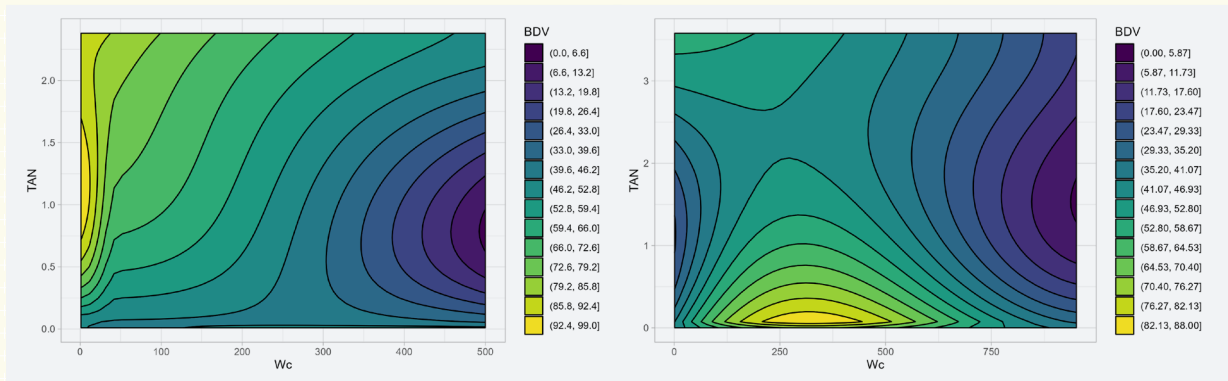
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In transformers with forced fluid cooling its flow is defined by the operating point of the pumps, so it can be adjusted to natural esters properties. But in natural flow, due to the higher viscosity of ester fluids compared to mineral oil, the flow of ester fluids through the windings, core and cooling equipment is lower than that of mineral oil. This may lead to a relative increase in the upper oil, winding and core temperature. Unlike mineral oil, heat capacity increases with temperature reducing the differences between both fluids at higher temperatures.

**Figure 5.** Depicts the development of TAN vs. Wc dependency in transformers in two age groups <= 20 and older > 20 years



**Figure 6.** shows the development of BDV as a function of TAN and Wc in young and old transformers. On the left the younger group <= 20 and on the right the older group > 20 years – The BDV values correspond to the IEC 60156 standard.



These better thermal properties can only compensate to some extent for the negative effects that occur due to the higher viscosity of ester. However, one additional benefit regarding cooling is the higher thermal class of the solid material immersed in natural ester compared with mineral oil, allowing the transformer to operate at higher temperatures [5]. This additional gap usually surpasses the negative viscosity effect as it has been shown on thousand “retrofitted” units.

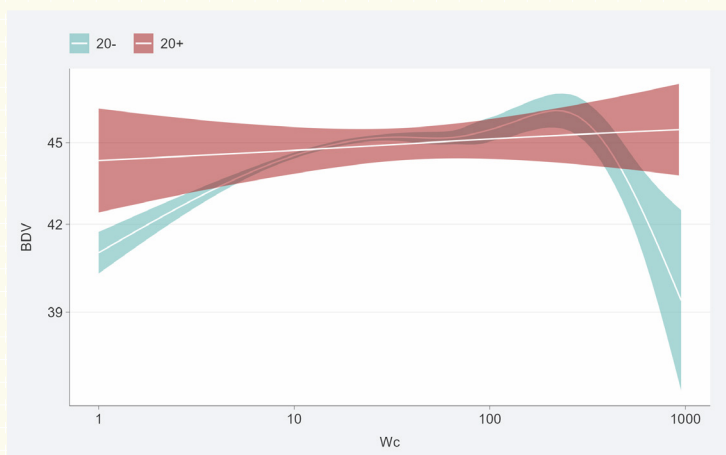
When a transformer is designed and the enhanced properties of the insulation system formed by cellulosic material and natural ester are explored, allowing higher temperature rise limits, the cooling ducts may be reduced or some of them may be removed, saving resources and reducing the total weight.

The dielectric constants of ester fluids are typically higher than mineral oil and closer to the dielectric constant of pressboard and insulating paper. Changing the insulating liquid therefore leads to less inequality in the stress distribution between solid and liquid than with mineral oil and pressboard. Except for highly inhomogeneous field distribution, the results of breakdown voltage of natural ester and mineral oil, for AC, lightning impulse (negative and positive polarity), switching impulse (negative and positive polarity), chopped wave, both in oil gap and creep indicate a very high level of equivalency between the fluids [6]. Additionally, the test results clearly indicate a higher value of PD inception voltage for natural ester liquid [7]. A different dielectric optimization or an increased safety margin when design criteria from mineral oil are applied for a “partial discharge free” transformer can be obtained.

As previously mentioned, one of the most important and fascinating findings from this analysis was the BDV in FR3 fluid increases systematically over the years of use. The fact, that the water content is controlled by the hydrolysis reaction with ester molecules and the resulting acids are soluble, mild and non-corrosive results in a slight but significant, approx. 1.5 kV/year, increase in BDV over time. FR3 seems to age just as well as fine wine!

**One of the most important and fascinating findings from this analysis was the BDV in FR3 fluid increases systematically over the years of use.**

As mentioned in one of Mr. Sinatra's songs, "It Was a Very Good Year," FR3's DNA is undeniably found in Cargill's high quality food and beverage production. This high standard makes even an insulating oil - "as vintage wine, from fine old kegs, from the brim to the dregs".



*Figure 7. shows the development of BDV as a function of Wc in young and old transformers.*

These habits of the FR3 towards water are well illustrated in Figure 7, where excellent water behavior of the "older" oil can be observed. Taking a look to the rest of parameters analyzed, we see that no correlations are found, despite the weak connection between water content, dissipation factor and breakdown voltage. The interfacial tension can be used to detect soluble polar contaminants and products of degradation qualitatively but very sensitively. The level of interfacial tension influences the decision as to whether transformer oil should be regenerated or replaced.

The degradation byproducts were also measured (Fig 1,2,3 and 4) for natural esters. Results show that interfacial tension is generally lower than with conventional mineral oil due to the higher polarity and the associated interaction with water. It also makes it less relevant to address transformer degradation by itself. Next interesting issue is the pour point. The pour point, is the point at which the oil just barely flows. One also speaks of cold flowability (media flow at temperatures below  $-30^{\circ}\text{C}$ ;  $-22^{\circ}\text{F}$ ). This is important for the starting behavior at low temperatures. The main concern for mineral oil at low temperatures is its inability to handle dissolved water. Free water can appear and create a discharge path leading to a failure. This problem is solved with Cold Start Procedures that slowly heat the unit avoiding this issue. This is not a concern for natural esters due to their higher moisture tolerance. But some cold startup procedures that are used for power transformers filled with mineral oil can be used when they are filled with natural ester fluid to deal with its higher viscosity at lower temperatures [8].

As a summary, vegetable oils are highly biodegradable (> 98%), less toxic, less flammable and have an extraordinarily high fire points (>  $350^{\circ}\text{C}$ ) when compared with mineral oil. Furthermore, they not only can increase the lifespan of the units or increase the rating power with the same size but also show a very robust long-term behavior. The moisture and acid contents, typical weak spot for mineral oil, show a low impact on the breakdown voltage of FR3 and in the overall performance of the units.

As you can see from the data, in addition to the standard DGA of hydrogen and carbon monoxide, the parameters IFT, viscosity and tan\_delta seem to be of great importance for monitoring natural ester transformers. Cargill and Passerro have been working together on such an ester sensor for a long time and are now looking for interested customers for a pilot project starting in autumn 2023. Please contact Roberto Fernandez ([roberto\\_fernandez@cargill.com](mailto:roberto_fernandez@cargill.com)) or Mirosław Wrobel ([miroslaw.wrobel@passerro.de](mailto:miroslaw.wrobel@passerro.de)) in this regard.

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**Roberto Fernández** the Technical Leader Cargill BioIndustrial-Power Systems. He is an experienced Electrical Engineer who has spent most of his career on the transformer design field and R&D activities focused on the magneto-electric and thermal design for a wide range of transformer applications. He is member of CIGRE and contributes to several IEC maintenance teams. Currently working as Technical Leader for European region at Cargill BioIndustrial.

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