# Getting the Best from Existing Transformers Through Retrofilling with Natural Ester Dielectric Fluid

*As more and more businesses seek to improve the sustainability of their operations, natural ester has, by far, been the fastest growing alternative dielectric fluid in both the utility and industrial sectors. Apart from being widely used in new installations and as a replacement for ageing and faulty transformers, increasingly, end users are also pursuing the option of retrofilling, which involves changing the dielectric fluid in operating transformers.*

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Retrofilling existing mineral oil-filled transformers not only increases the pace of transition towards the more sustainable natural ester fluid, but it also helps to extend transformer life, thereby leading to lower capital investment on new assets and reduced consumption of non-renewable materials.

As pointed out in the 2020 Sustainability Report from Meralco, the leading utility company in Philippines, natural ester dielectric fluid is considered most suitable for sustainable power generation due to its ability to enhance and improve transformer safety, environmental footprint, reliability and loading capacity all at the same time [1]. Apart from mandating the use of natural ester in their pad- and pole-mounted distribution transformer specifications, Meralco has also recently embarked on an extensive retrofilling program for their existing transformers that are deemed fit for continuous service.

As a complement to the previous review on the main incentives and benefits of retrofilling [2], this article discusses the important elements that make natural ester the ideal retrofilling fluid as a means of getting the best out of existing transformers.

## FEASIBILITY FOR ON-SITE RETROFILLING TO MEET FIRE SAFETY REQUIREMENTS

While the benefits of natural ester dielectric fluid in prolonging insulation life, improving equipment reliability and extending loading capacity are increasingly harnessed in both power grid and industrial applications, to most transformer end users, effective mitigation of fire and environmental risks remains the most important incentive for retrofilling.

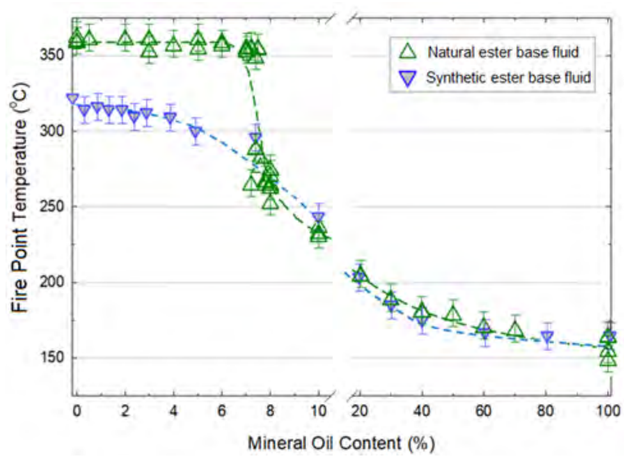


**Figure 1** *Fire points of natural and synthetic ester fluids at different residual mineral oil contents*

One of the main considerations for choosing natural ester fluid for retrofilling projects is its high tolerance to residual mineral oil in the transformers post retrofilling. As demonstrated in both laboratory and field testing, the fire point of natural ester dielectric fluid would only show a significant drop when the residual mineral oil level reaches about 7% (Figure 1), making it desirable for on-site retrofilling with proper draining and flushing [3-4]. In other candidate fluids such as synthetic ester, the fire point would drop below the 300ºC threshold for K-class less-flammable fluids (as specified in IEC 61039 [5]) at a lower residual mineral oil level, thereby necessitating a complete oil change under stringent factory environment and leading to significantly higher costs and longer down time.

In a recent prototype study involving two retrofilled distributed transformers of rated capacity at 315kVA and 400kVA [6], it was established that during the flushing process, after draining off the original fluid, natural ester should be introduced from the highest point of the conservator or from the oil level gauge port of the main tank (where there is no conservator), to maximise removal of residual mineral oil.

In the same study, the kinematic viscosity at 60ºC was found to be a suitable parameter to determine the residual mineral oil left in the natural ester fluid post retrofilling, as it shows good linear correlation against the mineral oil content in the range of 1-6% (Figure 2). Based on the kinematic viscosity results obtained from the natural ester fluid one year after retrofilling, the residual mineral oil content is estimated to be around 1.24% and 2.05% respectively, in the 315kVA and 400kVA transformer (Figure 2), which are significantly lower than what would be expected for on-site retrofilling.

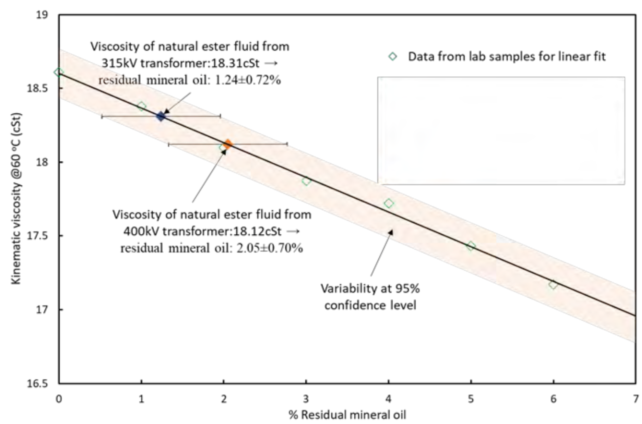


**Figure 2** *Correlation of kinematic viscosity of natural ester at 60ºC against the percentage of residual mineral oil; alongside the results obtained from fluid samples drawn from the two retrofilled transformers as described in [6]*

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As a result of the low residual mineral oil content, the corresponding fire point results at 335ºC and 338ºC were also well above the limit for K-class less flammable fluids.

With the highest fire point compared to the other dielectric fluids and a well-tested flushing protocol as described above, retrofilling with natural ester would be the most reliable solution in enhancing the fire and environmental safety of existing transformer fleets.

## REDUCED RISKS OF MOISTURE AND AIR INGRESS

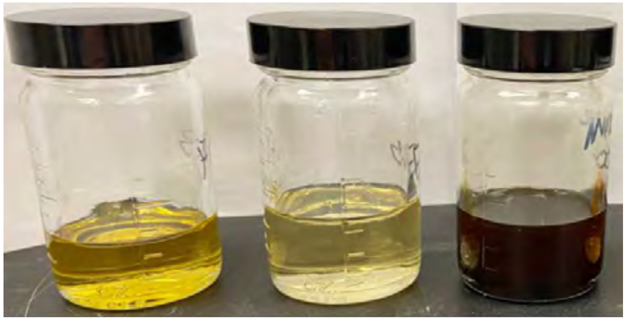
While some users might occasionally still consider oxidation stability as a constraint for retrofilling with natural ester, much of this misinformation has been rectified, thanks to the extensive studies and field experiences on this subject.

Although the oxidation stability specification in the IEC standard for natural ester dielectric fluid [7] is lower than that for mineral oil, it is now increasingly accepted that the bench test method [8] originally designed for lubricating oils does not in any way reflect the conditions in operating transformers. Based on full scale studies, including results obtained from in-service transformers, natural ester with optimised formulation has been proven to be capable of withstanding many years of operation in free breathing transformers without exceeding the critical control limits for in-service insulating liquids [9].

In a recent study aimed at evaluating the impact of oxygen and moisture ingress in the event of a breach in the sealing system of a transformer, different types of dielectric fluids were subjected to accelerated ageing at high temperatures and high humidity, respectively, under open air conditions [10]. For the high temperature ageing test, fluid samples and previously dried insulating papers were kept in open containers placed in air circulating ovens at 130ºC. For the high humidity ageing test, fluid samples in open containers were placed in water baths set at 80ºC inside an enclosed glove box with 80-100% relative humidity.

The results of the study, as summarised in Table 1, show that, except for the moisture content and breakdown voltage of the sample exposed to high humidity, none of the critical parameters of natural ester exceeded the limits for in-service fluid after the accelerated ageing tests, including increase in viscosity and total acid number that are commonly considered to be signs of oxidation. Moreover, despite having the highest relative moisture level after the accelerated ageing test at high humidity, the breakdown voltage of natural ester is still higher than synthetic ester and mineral oil.

Conversely, the mineral oil sample was found to develop heavy sludge after the high temperature accelerated ageing test (Figure 3), and its viscosity increase is also well above the control limit due to excessive evaporation loss.



Natural ester Synthetic ester Mineral oil

**Figure 3** *Appearance of the dielectric fluid samples after the high temperature accelerated ageing test (130ºC; ambient humidity; 5 weeks) under open air condition*

More significantly, the tensile strength of the insulation paper samples immersed in mineral oil and synthetic ester fluids also dropped to an alarming level after the ageing test at a high temperature (Table 1). This clearly demonstrates that ingress of air and moisture would pose an even bigger threat to the paper insulation. With natural ester the paper insulation is in fact much better preserved under such conditions due to its unique paper drying properties as reported in earlier studies [11-12].

The results from this study therefore bring home the key point that oxidation of natural ester is by no means the most critical issue when there is a breach in the sealing system of retrofilled transformers. With the resultant ingress of air and moisture, the reduction of dielectric strength and the increased degradation rate of paper insulation are clearly areas of bigger concern even before retrofilling. On the contrary, retrofilling with natural ester would help transformers to better cope with such situations before the necessary maintenance work can be carried out.

## ROBUST DIELECTRIC CAPABILITY

Apart from the high tolerance to residual mineral oil and enhanced protection against moisture and air ingress, another key factor that makes natural ester an ideal fluid for retrofilling is its robust performance in an extensive range of dielectric tests. As shown in Table 2, despite the different chemical and physical properties, the dielectric capability of natural ester is very much equivalent to, and, in some cases, better than, mineral oil [13]. While natural ester does tend to display lower dielectric strength than mineral oil under extremely divergent electric field distribution generated by the needle to plate electrode configuration, such a condition is generally unacceptable in transformer design and is therefore mostly of academic interest only.

In relation to the feasibility of retrofilling, the change of electric field distribution in the insulation system is most relevant. Since the permittivity of natural ester is about 40% higher than mineral oil, the dielectric stress will shift towards solid insulation after retrofilling. While this will increase the safety margin at the main gap between the windings due to the lower withstanding limit in the liquid insulation, it would also increase the voltage gradient and stress in the solid insulation particularly in areas where the electric field distribution might be inhomogeneous.

In practice, transformers of voltage class up to 69kV can be considered highly feasible for retrofilling and a very large number of supporting references are available for this. For voltage class up to 138kV, retrofilling is also highly feasible and supported by a large number of references, even though in some cases verification at leads and winding assembly might be required. For voltage class up to and beyond 230kV, more detailed dielectric design is normally recommended, and in

| Fluid type | Natural ester | Synthetic ester | Mineral oil |
|---|---|---|---|
| *High humidity accelerated ageing test (80ºC; 80-100% humidity; 4 weeks)* | | | |
| % Increase in viscosity @40ºC | 13% | 0% | 0% |
| Breakdown voltage (avg/max) (kV) | 20.3/26.5 | 13.4/14.4 | 18.5/22.3 |
| Moisture content (ppm/%) | 1,368/125% | 1,696/108% | 60/88% |
| Total acid number (mgKOH/g) | 0.06 | 0.05 | 0.01 |
| Dissipation factor @90ºC/50Hz | 0.012 | 0.016 | - |
| *High temperature accelerated ageing test (130ºC; ambient humidity; 5 weeks)* | | | |
| % increase in viscosity @40ºC | 20% | 0% | 245% |
| Breakdown voltage (avg/max) (kV) | 61.1/68.9 | 57.0/64.4 | - |
| Moisture content (ppm/%) | 376/35% | 94.2/6% | 46/68% |
| Total acid number (mgKOH/g) | 0.25 | 0.03 | 0.45 |
| Dissipation factor @90ºC/50Hz | 0.056 | 0.032 | 0.052 |
| Retained tensile strength of paper insulation (%) | 61.4% | 34.0% | 28.2% |

**Table 1** *Test results on natural ester, synthetic ester and mineral oil-based dielectric fluids after accelerated ageing tests under open air condition [10]*

| Fluid type | Natural ester | Mineral oil |
|---|---|---|
| *Transformer design* | | |
| Turn-to-turn | = | = |
| Coil-to-coil | = | = |
| Bushing-to-tank wall | = | = |
| Creep | = | = |
| Tap changer selector rod | = | = |
| Streaming electrification | ++ | -- |
| Bubble formation | +++ | --- |
| *Electrode geometry – oil gap* | | |
| Uniform | = | = |
| Mildly divergent | = | = |
| Strongly divergent | - | + |
| *Electrode geometry – creep* | | |
| Mildly divergent | = | = |
| Strongly divergent | - | + |

**Table 2** *Comparison of dielectric performance of natural ester and mineral oil [13]*

some cases finite element analysis of electric field distribution might be required to verify the feasibility for retrofilling.

## ROBUST DIAGNOSTIC CAPABILITY

With well-established specifications for both freshly filled and in-service transformers available for natural ester [14-15], condition monitoring capability for both fluid and equipment would not be compromised because of retrofilling, even though new threshold limits would need to be defined for some critical parameters such as power factor and insulation (Megger) resistance due to the different physical, chemical, and electrical properties of the fluid.

Being the most widely used alternative dielectric fluid, a large amount of dissolved gas analysis (DGA) data has also been collected for natural ester from a large number of in-service transformers, hence enabling robust interpretation. As shown in Table 3, due to the vast number of DGA results on record, natural ester derived from soya bean is by far the only ester based dielectric fluid with statistically reliable 90th percentile values that would allow transformer condition assessment and fault type identification to be made at a reasonable confidence level [16].

## ROBUST SOLUTION FOR RETROFILLING AND SUSTAINABLE POWER GENERATION

Thus, in consideration to the critical aspects of fire safety, maintenance, dielectric capability, and condition monitoring as described above, natural ester is clearly the most robust solution in enhancing the feasibility and benefits of retrofilling existing transformers. As the drive towards sustainable power generation intensifies, more and more utilities and industrial users will find that this well-tested solution is the one that will bring the best out of their existing transformers. T&D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| Ester fluid type | Number of records | | $H_2$ | $CH_4$ | $C_2H_6$ | $C_2H_4$ | $C_2H_2$ | CO |
|---|---|---|---|---|---|---|---|---|
| Soya bean | 4,378 | 90th percentile | 112 | 20 | 232 | 18 | 1 | 161 |
| | | 95% confidence level | (105-118) | (19-22) | (219-247) | (17-20) | (1-1) | (150-179) |
| High oleic sunflower | 476 | 90th percentile | 35 | 25 | 58 | 16 | 0 | 497 |
| | | 95% confidence level | (24-45) | (18-30) | (36-84) | (12-23) | (0-0) | (314-583) |
| Rapeseed* | ?? | 90th percentile | - | - | - | - | - | - |
| | | 95% confidence level | - | - | - | - | - | - |
| Synthetic | 157 | 90th percentile | 64 | 104 | 124 | 150 | 13 | 1344 |
| | | 95% confidence level | (52–82) | (49–135) | (105–362) | (79–215) | (0–33) | (937–1526) |

*Statistical results not available

**Table 3** *Statistical analysis of DGA results from ester based dielectric fluids as per the IEEE DGA Guide [16]*

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