

TRANSFORMER TECHNOLOGY^{MAG}

Part 2 **Bushings** Design, Maintenance and Monitoring

The Dry Type RIF® Bushing: **The New Technology in HV Bushings**


Managing Bushings: **From Statistics to Singularities - Where to Focus?**

MV Transformer Bushings: **Global Technology and Market Trends**

Ester-impregnated Bushings: One Step Closer to Sustainable Energy

by **Esseddik Ferdjallah**

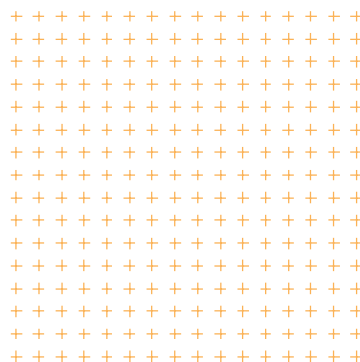
+++++



Capacitive ester-impregnated transformer bushing is an innovative, eco-friendly solution that not only helps achieve substation decarbonization but also increases the performance of high-voltage equipment.



Esseddik Ferdjallah is an electrical engineer who graduated from Ecole Polytechnique d'Alger in Algeria in 2012. He obtained his PhD from Polytech'Nantes in 2015 on the monitoring of insulation system for hydrogenators. He has been with Trench France, a Siemens subsidiary, since 2016 as an R&D engineer working on the development of new insulation technologies, topics related to monitoring, as a technical advisor for the service department, and as a technical manager in high-voltage laboratories.



Introduction

We need to ensure access to affordable, reliable, sustainable, and modern energy to drive manufacturers worldwide and support the development of environmentally friendly high-voltage equipment. One of these eco-friendly innovations is the capacitive ester-impregnated transformer bushing, an innovative solution that not only helps achieve substation decarbonization but also increases the performance of high-voltage equipment.

Motivated by feedback from site investigations and discussions with customers who are continuously looking for ways to improve service conditions and minimize costs, the first high-voltage bushing insulated with biodegradable ester fluid was introduced into the market in July 2020 (Figure 1).

The use of ester has been widely studied and promoted for power and distribution transformers over the last two decades. Ester-based dielectric fluids were found to outperform mineral oils in terms of their thermal and environmental benefits. Indeed, hundreds of ester-filled transformers are now in service and the feedback is consistently positive. The need for monitoring solutions for predictive maintenance strategies is also increasing on a global scale. Using ester-filled bushings on ester transformers expands the monitored parameters and allows dissolved-gas analysis (DGA). This type of monitoring is not possible with dry bushings.

Combining the monitoring options with the high thermal performance of synthetic ester allows ester-impregnated bushings to meet the technical requirements of high-voltage transformers, making it possible for customers to mitigate the risks of operating in overload conditions for longer periods than those allowed by international standards. The thermal aging behavior of ester-impregnated paper has been widely studied, and the results confirm an improvement in the aging resistance of paper in ester compared with standard mineral oils.



The first high-voltage bushing insulated with biodegradable ester fluid was introduced into the market in July 2020.

Why Use Ester?

Four years ago, a fundamental research was conducted on several types of esters to be used in high-voltage bushings [6]. Eventually, the company carrying out these studies chose to use a synthetic ester thanks to its high performance that offers all the benefits of ester technology in addition to its sustainability and ready biodegradability according to OECD 301 (OECD Guidelines for the Testing of Chemicals: Ready Biodegradability), which states that:

- 60 percent biodegradation occurs within 10 days after exceeding 10 percent degradation;
- 89 percent occurs by day 28 of the test.

In the first development stage, the synthetic fluid was intended for special applications in order to minimize the risk or consequences of failure: for example, wind turbines, traction, and applications near population centers. Today, due to its enhanced technical performance its use has been extended to standard applications.

Thermal Performance

One of the key advantages of using synthetic ester for bushing application is its enhanced thermal performance compared with mineral oil. The international standards organizations IEEE and IEC agreed that the thermal class of the complex kraft paper/synthetic ester is 120° (E); as opposed

to 105° (A) for the complex kraft paper/mineral oil (IEC 60076-14). For liquid-filled bushings, this is a huge improvement because they are vital components in the power system network. The increased thermal performance of bushings can positively impact transformer's condition by allowing many options for overload operation. It also offers a greater design margin than can be exploited to improve the thermal performances of transformers.

Increased Fire Safety

The risk of failure is always present in power networks. Depending on the extent of the failure, insulation liquid can cause fires that spread very quickly, resulting in extensive damage. Using synthetic ester can mitigate the fire risk. The fire-point and flash-point of synthetic esters compared with mineral oils are shown in Table 1 [1]. The synthetic ester used in the new bushing portfolio is classified according to IEC 61039 as a Class K3 fluid, which provides the following advantages:

- No fire risk in the event of a major failure: even if ester ignites, there is insufficient energy to sustain a fire, and any pools of liquid would rapidly stop burning.
- Low-density non-toxic smoke: ester is a hydrocarbon and complete combustion will yield water and carbon dioxide. Mineral oil is a mixture of multiple compounds (paraffinic, iso-paraffinic, naphthenic, aromatic, poly-aromatic, and cyclo-alkanes) that tend to have more dense, sooty combustion products.
- Lower costs for installation and maintenance of fire safety equipment.
- Lower associated insurance costs.

It has also been proven that power transformers filled with synthetic ester can be energized at -50°C [2]. For bushings, this is even more advantageous because no cooling function is required. The electrical insulation performance is ensured at such a low temperature.



Figure 1. The first capacitive ester-impregnated transformer bushing

	Natural ester-type 1	Natural ester-type 2	Synthetic ester	Mineral oil
Fire safety class	K2	K2	K3	01
Readily/fully biodegradable	✓	✓	✓	✗
Breakdown voltage kV (regular configuration)	>75	>75	>75	>70
Moisture saturation (ppm) at 20° C	1,100	1,100	2,700	55
Kinematic viscosity at 40° C	32	37	29	8.7
Relative permittivity	3.1	3.1	3.2	2.2
Pour point °C	-18	-31	-56	<-50
Flash-point °C	>315	>315	275	150
Fire point °C	>350	>350	316	170
High temperature performance	Good	Good	Excellent	Poor

Ester bushings are a result of the combination of historically proven experience with liquid-insulated bushings and the demonstrated technical performance of ester fluid.

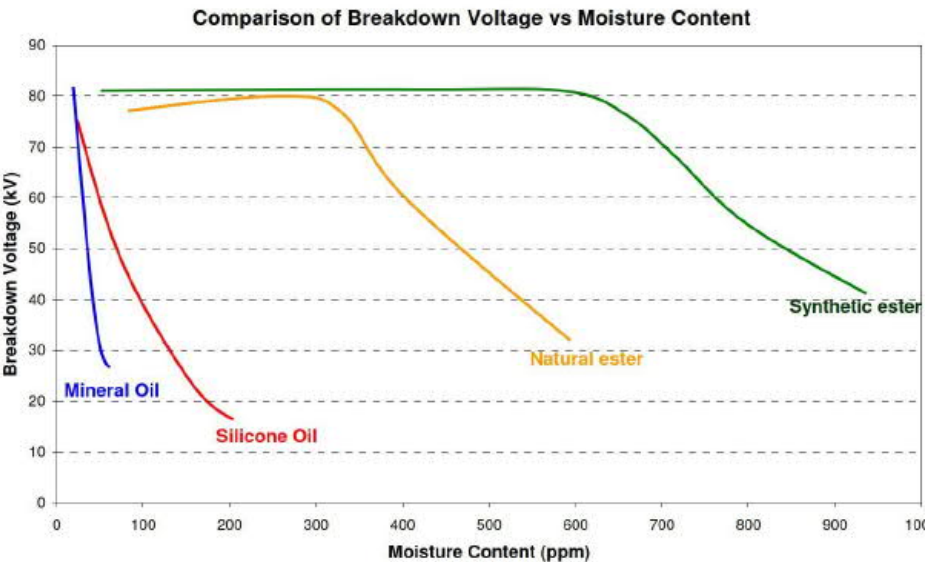


Table 1.
Basic properties of different insulation fluids

+++++

Moisture Tolerance

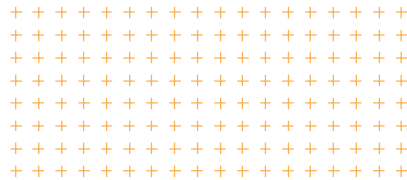
Synthetic ester has a very high moisture tolerance. This means that it maintains its electrical characteristics even with a high volume of water content (Figure 2) [5]. Its use in ester bushings prevents several known failure modes, including:

- Bubble formation during overloads: according to IEC 60076-14, the temperature for bubble creation is directly related to the moisture content of cellulose. For example, at one percent paper humidity, bubbles will form at 170°C, while, at three percent, bubbles will appear at 125°C.
- Condensation: during cyclical service conditions (solar energy), water migration between paper and liquid is contained by ester with no effect on electrical performance.
- Hydrolysis: water is one of the degradation products of paper. Unlike mineral oil, the water tolerance of synthetic ester allows more water to be trapped, which may slow down cellulose aging.
- Oxidation: the ester bushing development included a completely sealed design, and so there is no risk of cellulose oxidation.
- Corrosive sulphur: synthetic esters do not contain sulphur because they are manufactured from sulphur-free raw materials. This means that ester-filled bushings won't have corrosive sulphur problems (like reactions with the copper conductor inside the bushings).

Figure 2. Breakdown voltage dependence on moisture content with common insulating fluids



Figure 3. Active part: Winding of kraft paper on a central conductor including electrodes



Technical Challenges

The new ester-filled bushing portfolio has been developed using feedback from transformer experience and research results. Considering the vast experience and history of the company producing liquid-insulated products, the

engineers started with the established production process for conventional oil-impregnated paper (OIP) bushings and made the needed improvements. Basically, the production process for ester bushings (almost the same as for OIP technology) is divided into four main steps, as follows.

Process Improvements

1. Winding

During the winding of kraft paper on the central conductor, aluminum foil is placed in extremely precise positions to create a homogenous electrical field distribution. This operation is now completely automated to eliminate human error.

2. Drying

In this step, the active part – the result of the first step – is dried in a vacuum chamber using a well-established process to remove as much humidity from the paper as possible. The vacuum level and heating temperature are optimized to prevent premature aging of the paper. The measured polymerization temperature of the paper at the end of the drying process is higher than 1,100. When the required humidity is reached, the temperature is decreased, and the impregnation starts.

3. Impregnation

Due to the different viscosity and surface tension of synthetic esters, the impregnation process is different than with mineral oil. State-of-the-art analyses show [3] that a high temperature may reduce the viscosity to improve impregnation, but it adversely reduces the surface tension of esters. Experiments showed that a temperature of 60°C is a balance point. At this temperature, the viscosity and capillarity action of esters are similar to those of mineral oil at 20°C.

4. Assembly and filling

The impregnated active parts are then assembled (avoiding humidity recovery) and filled under vacuum with ester fluid. Obviously, the synthetic ester is filtered and degassed according to supplier recommendation to meet the international standard requirements (IEC 61200 and CIGRE recommendations) for insulation quality. Although there is no miscibility problem, new treatment, storage, impregnation, and filling installations are used for the synthetic ester that are completely separate from the installation for mineral oil.



Design Improvements

Cumulative knowledge over the last decades about ester-filled transformers has highlighted the need for design improvements – mostly due to the high viscosity of ester. However, the design of the bushings is also different, as are the stresses on the bushings. The insulating liquid in the transformer acts as electrical insulation and circulating cooler. Therefore, the higher kinematic viscosity of synthetic ester must be considered to avoid delamination. In liquid-filled bushings, no liquid flow is needed for cooling. Accordingly, no modification of this element is required.

With respect to the electrical design, a substantial amount of research has been performed to determine the fundamental behavior of esters both in laboratories and in transformers. The studies indicate that there are differences between ester-based liquid and mineral oil in terms of dielectric behavior. In fact, the difference primarily involves the ester withstand under transients with a particular shape of electrodes [4]. As for the new ester-filled bushings, the required improvements prevent these issues during service. Some research has found that these differences can be attributed to the difference in dielectric permittivity. It is an unchangeable intrinsic characteristic of liquids, but it brings advantages: the relative permittivity of synthetic ester is 3.2 as opposed to 2.2 for mineral oil. This helps to create more homogenous electrical stress inside the bushing between the liquid and the impregnated paper.



Figure 4. Bushing active parts impregnated with ester fluid

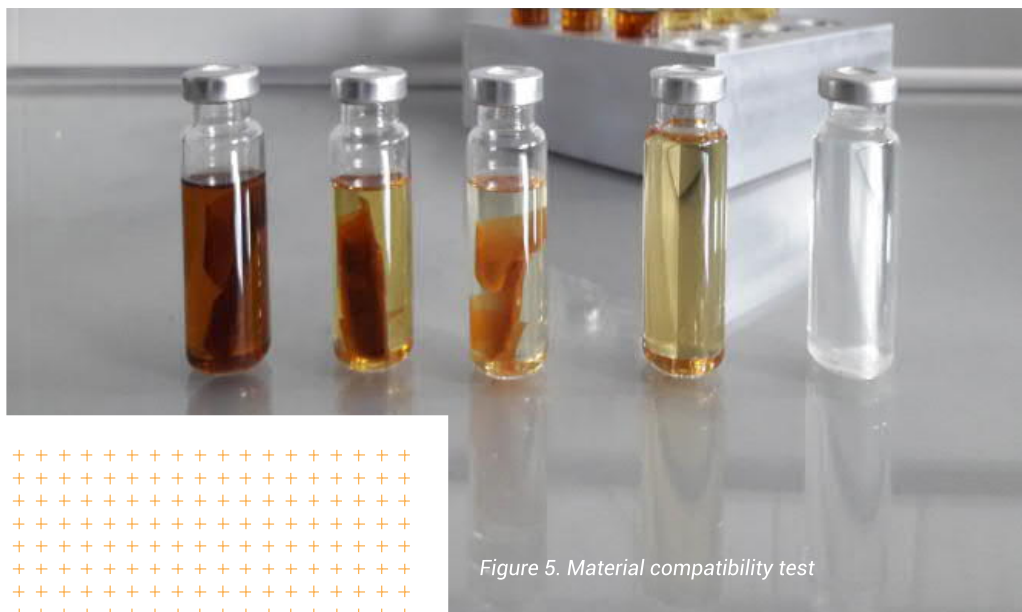


Figure 5. Material compatibility test

The use of synthetic ester as an insulating liquid ultimately improves the aging resistance of the ester bushing portfolio and can prevent several well-known failure modes of conventional OIP bushings.

New Ester-filled Bushing Portfolio: Is It Reliable?

The validation of a new insulation technology is a long and complicated process. The performance of complex kraft paper/synthetic ester has already been proven for transformer applications. However, its use in other substation

components must be evaluated and approved. To validate the new portfolio, the following validation criteria has been followed:

- Standard type tests according to IEC 60137-2017
- Qualification and special tests according to IEC 60505 and experience feedback

Rated highest voltage U_m (kV)	C_1 (pF)	$T_g \delta$ (%)	PD (pC)	Temperature of test ($^{\circ}\text{C}$)
72.5	237	0.27	<2	16
100	266	0.27	<2	17
123	198	0.25	<2	21
145	237	0.28	<2	24
170	300	0.32	<2	23
245	375	0.31	<2	24

Type Tests

Bushings for voltage levels up to $U_m = 245$ kV have been type-tested according to IEC 60137. The bottom part was immersed in ester fluid. In addition to electrical routine measurement (Table 2), each prototype was approved through:

- Long-duration withstands test (ACLD)
- Dry and wet power-frequency voltage withstand test
- Dry lightning impulse-voltage withstand test
- Dry switching impulse-voltage withstand test
- Electromagnetic compatibility test
- Temperature-rise test with current values higher than rated current to check the thermal performance of ester-filled bushings
- Cantilever load withstand test

Table 2 shows the main electrical parameters of ester-filled bushings subjected to the tests. The results are very promising: capacitance values in the same range as the values for mineral oils; very low dielectric losses, which is very important to avoid heating the bushing (direct comparison of different ester-filled products isn't possible due to temperature variations); and partial discharges lower than 2 pC, mainly due to the noise level in the test field.

Table 2.
Electrical parameters measured on ester bushings during routine tests

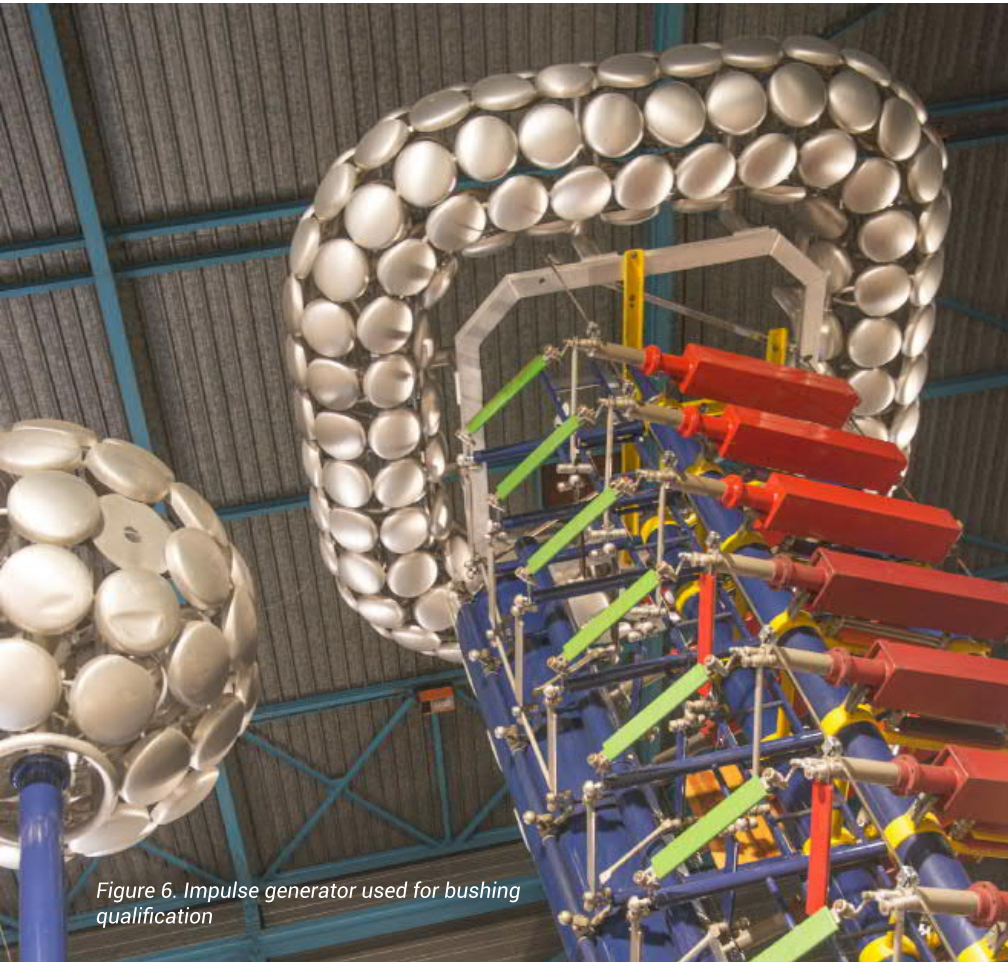


Figure 6. Impulse generator used for bushing qualification

New ester-insulated bushings have been developed to be 100 percent interchangeable with the corresponding OIP bushing, and they can be used in conventional oil transformers as well as ester transformers.

Special Tests

In parallel with the type tests, several special tests have been conducted.

- **Long-duration test (electrical aging test)**

IEC 60505 recommendations for the evaluation and the qualification of new electrical insulation systems (EIS) include conducting comparative experiments between a candidate EIS, the ester-impregnated bushing in this case, and a reference EIS, which is the consolidated OIP bushing. For this test, six bushings were produced: three prototypes for each technology (bushing design

is identical, $U_m = 72.5$ kV). The standard requires the application of three different voltages higher than the rated voltage: one voltage level for each two bushings until the bushing failure. The candidate EIS should withstand for at least as long as the reference EIS in order to be approved. Testing at 140 kV (193 percent of U_m) is complete, while the test at 110 kV is ongoing. At the end of this test, we will be able to draw the lifespan curves of synthetic ester bushing insulation using the results from the three voltages level.

- **Test of limits**

Identical bushings with ester and OIP insulation ($U_m = 145$ kV) have been tested.

