Transforming Expectations

Technologies - and their ability to deliver the new standards we expect - are developing swiftly. While choice in the transformer insulation market means no shortage of good solutions for specific applications, investment decisions increasingly pivot on whole-life cost equations. Crucial is the flexibility to integrate and maximise numerous performance criteria in unison with increasingly important factors, such as environmental impact and disposal risks. Synthetic esters are at the tipping point.

Modern transformer insulation materials must meet tough demands. Some circumstances require very specific solutions. Others are open to a range of options that can optimise costs, efficiency and operational criteria in different combinations. Fortunately, there are many robust answers. Often, the greater question is how to make the right choice?

Fire has been a historic fear, a risk closely associated with mineral oils. In consequence, as insulation materials have evolved, conscientious concern over fire control has seen cast-resin become elevated into almost the inevitable default alternative, over-ruling all other considerations where transformers are installed within, or close to, buildings.

Today, the equilibrium point has moved back strongly in favour of modern liquid-filled transformers. Diligent decision-making must now account for other pivotal cost and performance factors, including environmental impact, with knock-on socio/community applications that extend procurement beyond conventional operational and financial criteria. Legislation and regulation are also tilting the playing field. The optimum choice now has to balance a much wider set of parameters without compromising safety.

Synthetically produced ester-based, dielectric coolants have the innate flexibility to achieve this, with the advantage of being well-established in an exciting field of transformer technology excellence. Esters are bio-degradable with no adverse toxic environmental or aquatic side-effects. Importantly, they do not affect the biological treatment of activated sludge should they enter wastewater treatment plants via the sewers and are not classified as hazardous.

A new contemporary appreciation of synthetic esters means that architects, engineers and planners can once again draw on the full advantages of liquid-filled transformers within indoor environments. This has already led to diverse installations at major theme parks, steel works, Internet-hosting centres, office accommodation, public buildings, industrial plants and high-risk locations. Esters are appropriate for both very hot and cold climatic conditions. They are also suited for use in isolated renewable energy systems, such as wave or tidal energy and offshore wind farms. Fire at sea is potentially catastrophic, which is why ester-based products are winning favour in the offshore oil and gas industry, plus prestigious applications, such as cruise liners like the Queen Mary II where many lives are at stake.

Comprehensive Costings

When considering an insulating material, a true estimation of transformer investment costs has to extend from commissioning to end-of-life planning, while also including running and maintenance costs where marginal efficiency benefits amount to significant savings over a whole life time. On balance, liquid-filled transformers demonstrate better economic and performance
characteristics than dry-type units, including cast resin. Making procurement decisions on purchase costs alone would be very misleading.

**Purchase Price**
The initial price is the most obvious method of cost comparison but, as mentioned previously, it should not be used in isolation. Transformer prices vary, depending on specific requirements, the country of origin and, most recently, the availability of raw materials.

**A general range of initial transformer purchase prices**

![Graph showing initial transformer purchase prices]

**Installation**
Installation costs will vary with location, operating environment and application. Standard dry or cast resin type transformers may need separate enclosures or climate controlled rooms for outdoor and indoor applications respectively, which can also have a knock-on effect with regard to the positioning of auxiliary equipment and cable routing/termination. Liquid-filled transformers do not have such limitations but issues such as fluid containment measures have to be assessed. An important factor when considering transformer installation is noise emissions. Liquid-filled transformers run more quietly than dry or cast resin type transformers, making them more amenable for sound-sensitive areas.

**Maintenance**
The need, frequency and cost of maintenance will again largely depend on the unit’s location and application. However, the cost here is related to the robustness of a unit under operational stresses it is likely to face during working life. Its ability to withstand the spectrum of potentially damaging effects and conditions that reduce performance - its reliability - can in turn affect its life expectancy. (See failure modes later.) Due to their ‘exposed’ construction, dry/cast type are inevitably more prone to shutdowns for preventative maintenance and potential failure.

Predictive maintenance techniques, such as Dissolved Gas Analysis, allow a simple and proven method of monitoring liquid filled transformers. Equivalent methods for cast resin transformers, such as acoustic emissions for monitoring partial discharge, are possible but not widely practiced.

**Environmental**
Another increasingly important factor, is in the direct and indirect costs of environmental impact and clean-up. Transformer fluid spillages were never really acceptable. Now, their impact brings painful fines – and the potential valuable loss of reputation with influential stakeholders. A material that is intrinsically benign to the environment is clearly very desirable. Importantly, sustainable development’s inter-related financial – environmental – community goals also extend the boundaries of responsible procurement to include the implications of product manufacture, plus the immediate and long-term effects of final disposal, recycling or degradation.

**End-of-life**
A complete assessment of full-life costs today must include disposal. Recycling most dry-type and liquid-filled transformers generates an income rather than a cost, since almost all components, including fluids, have a secondary value. If re-use is not possible, then reclamation of basic materials - mainly metals - still creates a scrap value. Despite changes in design, cast resin transformers are still difficult to dismantle cost-effectively because their construction effectively locks the copper windings in the cast coils.

**Efficiency**
Besides the obvious costs, a wide range of performance factors need to be accounted for in any buying decision. In part, these are a function of efficiency. However, susceptibility to various types of failure forms the other half of the equation, including life expectancy which is an ultimate form of failure!

Even an efficiency difference of just 0.5% – a measure of energy losses – can easily exceed the original purchase price of a transformer over a life time. The innate flexibility of liquid-filled transformers offers a wider range of efficiencies and losses to match particular circumstances than is
possible with dry and cast resin transformers. This is because liquid-filled units benefit from optimised design, construction and materials which can make them much more compact. For some applications such as wind farms, such high energy efficiency associated with small transformer design has become increasingly important. The no-load (core) losses are nearly always higher for dry/cast transformers than liquid-filled units.

### Potentials for failure

Efficiency aside, the best transformers succeed when they do not draw attention to themselves through failure! There are numerous potential threats.

#### Electrical Withstand

Basic impulse levels are a measure of the ability of a transformer’s insulation system to withstand a specified minimum voltage for short-time surges with no detrimental effects. These voltage surges are commonly caused by lightning strikes on the transmission/distribution system and other voltage transients, such as the affects of switch gear.

When comparing ‘standard’ dry and liquid type transformers, DIN & IEC BIL withstand ratings are typically superior for liquid transformers.

#### Partial Discharge

Another key threat is partial discharge. This is a partial, localised dielectric breakdown between two conductors when the voltage stress exceeds a critical value. This generally occurs in voids, cracks or interfaces within the insulation system, or from sharp edges of energised materials. The major difference between dry and liquid insulation systems is that once the effects of partial discharge have damaged the insulation, there is no mechanism for dry/cast type units to recover from this damage. Liquid units, by their very nature can circulate and replace the dielectric fluid from the source of the discharge. It is also worth noting that partial discharge takes place at lower voltages in dry/cast type units than in liquid-filled transformers.

#### Harmonics Withstand

Harmonics are multiples of the fundamental power frequency of an electrical system. They can distort this frequency, which in transformers leads to unbalanced load currents that result in areas of overheating. Elements of third harmonic components are always found in transformers due to the non-linearity of the magnetic core. However, the rising use of computing equipment and power electronic drives that have non-linear power demands means that equipment prone to the effects of harmonics must have additional protection within the electrical system. Liquid-filled transformers by design are able to cope with such effects without compromising insulation integrity due to superior heat transfer characteristics and overload capacity.

In fact, the principal cause of transformer failure in both dry-type and liquid units is insulation failure. Because many transformers are now aging, the failure rate is expected to soar by 300% in the coming decade. By definition, ester-based transformers are not so old! Fluid-filled transformer insulation systems comprise solid insulation (cellulose or paper) and the liquid dielectric. Overloading, high temperature and moisture can cause cellulose degradation. Once started, cellulose, as a by-product of its degradation, creates additional water, which, unless it moves into the insulating fluid, stays in the cellulose and creates a vicious circle that accelerates degradation further. Fluids such as esters offer a unique solution to this problem in that they are highly hygroscopic when compared to mineral oils. This means that the fluid will readily form hydrogen bonds with water molecules. More importantly, esters are able to retain a good dielectric strength, even when relatively high levels of moisture are found in the fluid. Insulation failure usually causes partial discharge, mentioned above. Routine

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**More than 100 years of transformer history spanning three centuries**

Soon after transformers first appeared in the 19th century, mineral oils raised efficiency, heat dissipation, overload capacity and unit life, while reducing size. By the early 20th century, nothing much had changed in the transformer specifications required by the major electrical utilities. Mineral oil use still requires special arrangements for transport, contamination and spillage reporting, remediation and disposal. However, because of environmental and fire implications, over the century vacuum pressure impregnated (VPI) dry-type and cast-resin transformers increasingly encroached on mineral oil use near, or inside, buildings. Still a conventional choice in outdoor transformer applications, mineral oil use has fallen behind modern expectations and specifications – not least due to its low 165°C ignition point that has lead to fires and, latterly, onerous deluge-extinguishing, distancing and fire containment requirements. Thirty years ago, a step-change to fire-resistant hydrocarbon and silicone fluid use saw fire points rise to 300°C, with no fires attributed to their use since. Their fire safety advantage recognised by the insurance industry has not been matched by environmental performance where thousands of litres of fluid are involved. Esters, in contrast, not only have flash and fire points well in excess of 300°C, but the ability to readily biodegrade in accordance with OECD guidelines.
sampling and testing is straightforward on ester-based transformers, even while they are energised. The same is not true with cast resin. Yet, without early diagnosis, cast-resin transformers operation will suffer because of deteriorating insulating material in the high-tension coil. Although the effects will not be catastrophic, performance talls off sharply with heavy cost and power losses. Considerable research has gone into methods for detecting partial discharge behaviour in cast resin units as an alternative to the easy sampling in fluid units.

**Conclusion**

For the majority of transformer applications, mineral oil remains an obvious choice. However, when the risks of transformer operation are such that extra precautions are required, a more lateral approach can now be employed that brings additional welcome benefits. Specifying comparative dielectrics is relatively straightforward. Once an application’s key requirement have been identified, all suitable options can be assessed. Unfortunately, if specifiers are not in a position to consider - or even recognise - the alternatives at their disposal, it is highly likely that a key opportunity to select the optimum solution could be missed.

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