Modern power transformers for underground substations

Rob Milledge, Hitachi ABB Power Grids
Miguel Cuesto, Hitachi ABB Power grids
Mariano Berrogain, Hitachi ABB Power Grids

Introduction

Today's trend is for higher density populations in cities and urban areas. This increases the energy supply demand, together with a reduction in available space for the energy infrastructure.

A suitable and increasingly popular solution for high population densities in urban areas are underground power transformers.

Extensive research and development by Hitachi ABB Power Grids over decades into the special needs and demands of such power transformers has delivered two complementary proven technology solutions that offer non-flammable or minimal fire risk outcomes depending upon the requirement and scope. Both solutions are suitable for environmentally sensitive applications.

Hitachi ABB Power Grids has production technology integrated solutions, with current service experience ranging to 420 kV and 400 MVA, using ester filled transformers. They can be optionally combined with a TXpand™ flexible, rupture resistant tank solution delivering a truly minimal fire risk solution.

The alternative, non-flammable solution, subject to the dimensional, mass requirements, and cooling configuration requirements of the substation for the range to 145 kV, 63 MVA is to apply dry type, Hi-Dry power transformers.

Special demands for power transformers in underground substations

Beyond the normal energy transfer, safety, longevity requirements, underground power transformers must meet additional demands compared to the traditional outdoor substation including:

- Greatly improved fire safety management both within the underground substation and above ground level
- Significantly reduced risk of a breach of the transformer system tank in the unlikely event of an internal fault
- Increased environmental consideration for the control and consequence of loss of cooling / insulation media
- Suitable cooling equipment configurations for heat dissipation of transformer losses from below ground while in proximity to the local population
- Compact arrangements underground to minimize the size and cost of the underground substation transformer room.

In order to recognize the manner with which these multiple demands are met, some background understanding of the ester fluid characteristics and behavior is appropriate.

Ester fluid characteristics

Esters used in transformers are a class of organic compounds that are essentially vegetable oils. There are two basic types, natural esters, and synthetic esters. Natural esters are derived from plant-based products such as soya beans, rapeseeds, sunflower seeds, etc. Synthetic esters are synthesized by a manufacturing process that can include natural pre-cursors. Both natural esters and synthetic esters have many similar characteristics.

A summary of typical ester fluid characteristics in comparison to traditional mineral oil is given in Table 1.

A suitable and increasingly popular solution for high population densities in the urban areas is the use of power transformers within the underground substation

Table 1. Typical ester fluid characteristics

Typical data value	Unit	Natural ester	Synthetic ester	Mineral oil
Kinematic viscosity at 100 °C	mm²/s	8	5.25	3
Kinematic viscosity at 40 °C	mm²/s	33	29	12
Kinematic viscosity at 0 °C	mm²/s	190	280	76
Pour point	°C	- 21	- 50	- 60
Fire point	°C	355	315	170
Auto-ignition point	°C	401	435	178
Classification of flammability IEC 61039	-	K2	K3	O1
Breakdown voltage IEC 60159 2.5 mm	kV	73	> 75	> 70
Thermal conductivity (ASTM D2717 @ 25 °C)	W/m K	0.170	0.144	0.140

Ester fluids - Fire risk management

For any fire to occur, including the rare but significant event of a transformer failure resulting in a fire, all three of the traditional characteristics of the fire triangle must be met. That means that all three essential ingredients are needed, shown in Fig. 1.

For a transformer, these three contributory elements are:

- The fuel is the transformer fluid (mineral oil or ester fluid)
- The energy / heat source is the incoming electrical network energy feeding the fault or the already burning fluid
- The oxygen source is the air available only if there is a breach of the closed system containing the fluid, e.g., a failed and collapsed bushing leaving an opening, a tank rupture due to uncontrolled rapid internal pressure rise from an internal arc.

To minimize the fire risk, the three fire triangle aspects are addressed.

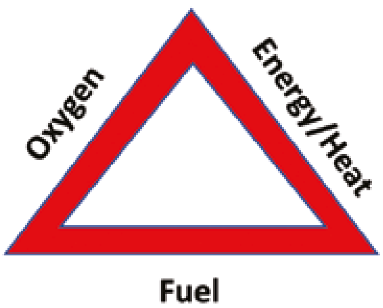


Figure 1. The fire triangle

Hitachi ABB Power Grids has production technology integrated solutions, with current service experience ranging to 420 kV and 400 MVA, using ester filled transformers

Firstly, the fluid characteristics are considered. From the fire point temperatures given in Table 1, it is apparent that the ester fluids are higher temperature fluids than mineral oil. They are much more difficult to ignite because of this. However, if an arc occurs within a power transformer, the temperature of the arc and the adjacent fluid temperature far exceed the fire point and, indeed, the auto-ignition points of these fluids. It is other characteristics of the esters that enhance their fire risk minimization performance and benefits. These characteristics include:

- Significantly lower heat release rates (low heat value)
- Much better lower limits of flammability.

When a fluid is ignited, a characteristic level of energy is released. This is classified in IEC 61039 as heat values with three gradings 1, 2, and 3 of ≥ 42 MJ / kg, < 42 MJ / kg, and < 32 MJ / kg, respectively.

Fluids with higher heat values to grade 1, such as mineral oils, burn with increasing temperature in a self-sustaining manner even when the source of energy is removed.

However, fluids with lower heat values to grade 2 and 3, such as natural esters and synthetic esters, respectively, will self-extinguish when the source of energy is removed.

This has been verified with experiments and testing and is illustrated in Fig. 2.

In practical terms, if the ester fluid is ignited, once the circuit breaker opens (the energy source is removed), then the ester self-extinguishes after a short period of time. This is unlike mineral-oil fire, which continues to increase in ferocity after the circuit breakers open and burn until all the fluid is consumed unless external intervention occurs.

It is also much more difficult to initiate the ignition of an ester fluid compared to mineral oil because the lower limit of flammability required for ignition is much higher for esters, as shown in Table 2.

In practical terms, the percentage by volume of fluid vapor to air volume before combustion can occur is fifteen times greater than for mineral oil.

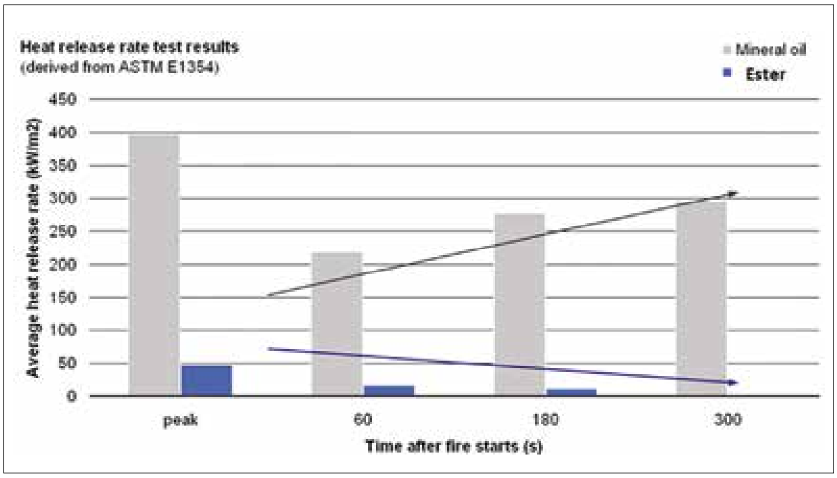


Figure 2. Heat release rates of esters and mineral oil

With esters, once the circuit breaker opens, the energy source is removed, and it will self-extinguish after a short period of time

Table 2. Flammability limits of esters and mineral oil

Explosive limits (derived from ASTM E918)	Mineral oil	Natural ester
Test temperature (°C)	200	350 - 400
Lower limit of flammability (% v)	0.6	> 9.0
Upper limit of flammability (% v)	4.8	ND

Power transformers - Fire risk management

The low flammability attributes of ester fluids have been coupled with technology domain knowledge developed within Hitachi ABB Power Grids, being the ideal combination to be applied for use in underground substations to avoid the possibility of a fire.

a) Mineral oil failure

b) Ester fluid failure

Figure 3. Internal arc test response for mineral oil and ester transformers

Practical failure testing of small transformers filled with mineral oil and esters via intentionally introduced high energy internal arcing has been conducted. These tests are relevant for both distribution and power transformers and confirmed both the low ignition probability and self-extinguishing behavior of ester filled transformers, shown in Fig. 3.

As can be seen, an explosive fireball failure with mineral oil was replaced by a relatively benign, non-explosive outcome that extinguished without detectable fire.

These results are consistent with CIGRÉ reports [1] where no reported transformer fires have occurred with less flammable fluids, such as esters.

Ester fluids - Environmental risk management

Ester fluids also deliver environmental risk improvements compared to mineral oils.

Natural esters are derived from a renewable resource in the form of plants and have a neutral carbon footprint while mineral oil is derived from a mined, limited resource.

However, to this date, the attribute of greater interest has been that both natural and synthetic esters are "readily biodegradable" while other alternatives, including mineral oil, are not. To be readily biodegradable, a fluid must breakdown into carbon dioxide, waste, and small organic molecules by more than 60 % under the action of light, water, and microbial activity during a defined period such as 21 days, 28 days, etc.

The biodegradability characteristic of the fluids is shown in Fig. 4.

Power transformers – Environmental risk management

Concern for and management of fluid spill from transformers is of particular interest for underground substations and other sensitive locations. For this reason, the ester filled transformers offer an attractive solution. While an ester-fluid spill is still undesirable, since the fluid is readily biodegradable, it is much less damaging to the environment than a mineral-oil spill.

Consequently, in many jurisdictions, the ester fluids are considered non-hazardous waste, and disposal and management of the spill are significantly simplified and easily managed, especially when compared to solutions employing silicon fluid of SF_6 gas, which are extremely unfriendly solutions for the environment.

The use of low flammable ester fluids and the technology developed by Hitachi ABB Power Grids, resulted in transformers with very low risk of fire ignition

Power transformers – General risk management

Crucial to the management of both fire and environment risks is the avoidance of breaches or unintended or uncontrolled openings in the tank enclosure system.

If the enclosure system remains intact, then fire is not possible as the oxygen component of the fire triangle, which is already explained in Fig. 1, is absent.

Similarly, if the enclosure system is intact or at least minimal fluid loss occurs, then the fluid-spill risks to the environment are manageable.

For this reason, Hitachi ABB Power Grids has developed solutions and recommends the use of a suite of further features, including dry-type bushings (including polymer exposed insulators, when applicable), TXpand™ tank designs and conservator shutoff valves. These features make a tank rupture or uncontrolled breach of the enclosure most unlikely.

Dry-type bushings

The benefits delivered by dry type bushings, which are available to system voltages up to 800 kV are:

- The internal transformer fluid system is physically separated from the air side or turret fluid side of the bushing. Damage to the containment on one side of the bushing is isolated from fluid loss on the other side.
- If the bushing itself is to fail, then it is invariably a non-explosive failure, and mechanical seals and structure of the bushing remain intact. This results in the bushing tending to act as a plug at its mounting, ensuring the transformer fluid is not lost nor exposed to the atmosphere.
- These dry type bushings are normally solid resin / polymer material to 52 kV, and resin-impregnated paper or synthetic condenser bushings for 72 kV to 800 kV.

TXpand™ flexible tank solutions

Traditionally, power transformers include resealing pressure relief valves. The valves open for a limited period of time and reseal when there is a pressure increase inside the tank. The valves protect the stiff tank from rupture and splitting due to excessive internal pressure in the event of an internal fault. This results in a limited loss of fluid rather than complete loss and fire. Unfortunately, such pressure-relief valves have a limited dynamic and size capability to sufficiently quickly release fluid and to manage the rapid tank pressure increase and avoid a tank split.

The Hitachi ABB Power Grid's approach is to enhance the capability of the system by use of a strong but flexible tank designed to suit a severe fault situation using the proprietary TXpand™ tank design.

The rapid pressure increase within the transformer tank is a function of arc energy, which in turn is related to the arc length. Longer arc lengths can occur with higher system voltages, and hence typical arc energies considered are shown in Table 3 [2].

Table 3. Arc energy levels [2]

System voltage class (kV)	Potential arc energy (MJ)
765	20
330	20
245	8
170	4
145	4
72.5	2

While the specific details are complex, the principles are relatively clear. A strong but flexible tank is required to expand in response to rapid pressure increase that results from the gas evolution associated with an arc,

i.e., $$Pressure \sim \frac{Dynamic\ Factor * Arc\ Energy * Arc\ to\ Gas\ Volume}{Tank\ Expansion\ Coefficient}$$

The effects of this are shown in Fig. 5 in comparison to a rigid tank for a 20 MJ arc.

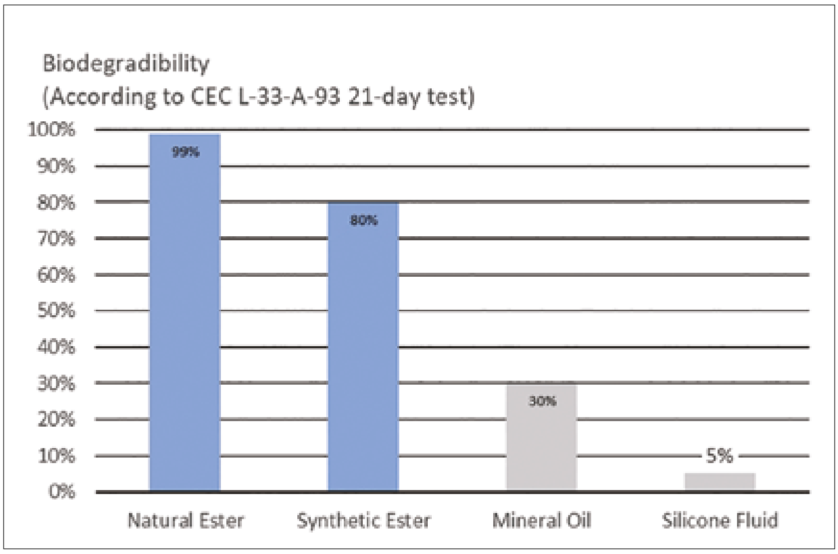
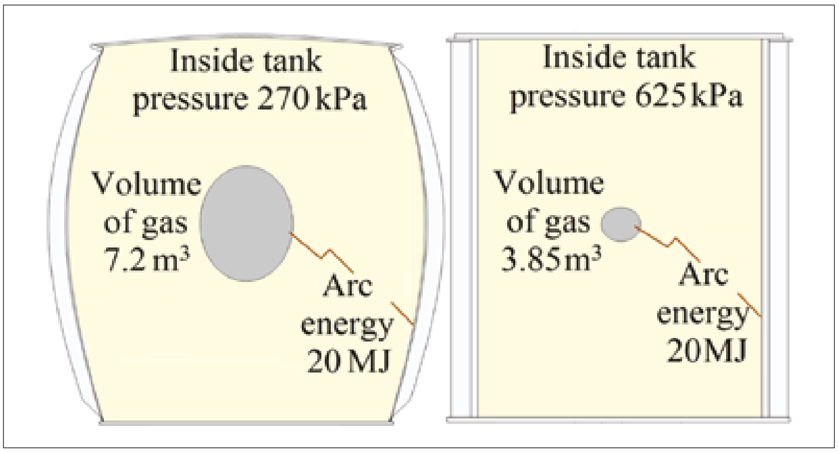


Figure 4. Biodegradability performance of fluids after 21 days

It is crucial for the management of both fire and environment risks to prevent the breaches of unintended or uncontrolled openings in the tank enclosure system

Full-scale tests have been performed simulating the 20 MJ arc and tank response, shown in Fig. 6, with the close agreement between calculated and measured results.

It was also considered and appropriate to design the TXpand™ system to have an intentional failure location in the case of arc energies far above the design requirement. This intentional failure location is normally the tank to cover interface in order to ensure, together with a conservator shutoff valve, that minimal fluid is expelled. Further full-scale tests were performed with arc energies of 30 MJ for the 20 MJ design TXpand™ tank. Again, the results and calculations showed agreement with the outcome shown in Fig. 7.



Flexible tank Rigid tank
Figure 5. TXpand™ flexible tank vs. rigid traditional tank

Initial Final
Figure 6. TXpand™ tank tests (20 MJ Arc)

Initial Final
Figure 7. TXpand™ tank testing to destruction

Power transformers – Technology demands for ester transformers

In order to design, produce, and securely deliver reliable ester filled power transformers for the underground and other substations, a strong and well-proven domain knowledge and experience are required.

This is particularly the case for power transformers, while for distribution transformers, the performance changes are less significant. Acquisition of this ester filled power transformer knowledge and understanding over decades of research and development, full-scale testing has resulted in hundreds of successful deliveries up to the range to 420 kV and 400 MVA to date.

Two significant areas requiring additional expertise for ester filled power transformers are those of dielectric performance, particularly lightning impulse and temperature rise performance. Both these considerations require a revised technology design understanding and arrangements.

Temperature rise behaviour

Reference to the ester and mineral oil characteristics in Table. 1 indicate that ester fluids have a similar thermal conductivity capability but are rather more viscous than mineral oil.

If the same design geometry is used for an ester as for mineral oil units, then one can expect that the average fluid temperature rise will be similar, but the fluid will travel rather more slowly through the windings and cooling system. Intuitively, one can expect that fluid spends more time in contact with the loss producing winding conductors and hence develops a higher top fluid temperature rise.

Additionally, it is well known that there is a non-linear inverse relationship between winding gradients to adjacent fluid and the local fluid velocity, as the convective heat transfer effect is enhanced with the velocity. With the same geometry, one can expect a greater winding gradient.

This has been verified and quantified by testing of power transformers with mineral oil and then retrofilling with ester and re-testing.

In order to fully model and understand the situation, one needs to perform computational fluid dynamic (CFD) studies to simulate and determine the flow behavior and thermal rises of an ester filled transformer.

Hitachi ABB Power Grids has performed numerous CFD studies of such kind and has been able to derive from this a thermal network model software for ester fluid power transformers. Using these tools and enhanced design software packages, the necessary design and detail winding geometry outcomes needed to optimize the thermal performance with esters can be achieved. This largely compensates for the higher viscosity characteristic of esters.

However, it has been found that thermal performance is more sensitive to variations in construction and fluid flow due to other performance demands such as dielectric withstand, etc. Consequently, it is important to determine the fluid velocity and hence the winding temperature gradient adjacent to every conductor and understand the hydraulics of the system more closely than ever.

Some comparative information for mineral oil versus ester fluid from the thermal network model of fluid velocity and winding temperature rise for every disc in a winding are shown in Fig. 8a and 8b, respectively. In this comparison, the geometry has not been re-optimized between the different liquids but illustrates the variations.

It is illustrative in the context of the sensitivity to variation to observe that the ester fluid velocities are not simply lower but include variations (troughs and peaks) not seen in the mineral oil velocity distributions. Similarly, the winding temperature rise distribution is not simply greater but has different shapes and locations for local peaks. Significantly, this includes a different location of winding hotspot.

Such information is essential to appropriately design and manufacture the ester transformer.

The thermal behavior of esters is also important for the major accessories immersed in them, such as bushings and tap changers. While often the same type of equipment as in mineral-oil transformers is used, the suppliers of such equipment should be consulted for the applicable rating and model. Typically, the bushing and tap-changer current ratings are reduced when used in ester fluids, which may result in a different model being used.

The Hitachi ABB Power Grid's approach is to use the TXpand™ tank concept to enhance the resiliency of the system by using a flexible transformer tank design prepared to suit severe fault scenarios

Dielectric, performance, and behavior

Ester fluids with power transformers differ significantly from mineral oil in the two major dielectric aspects of relative

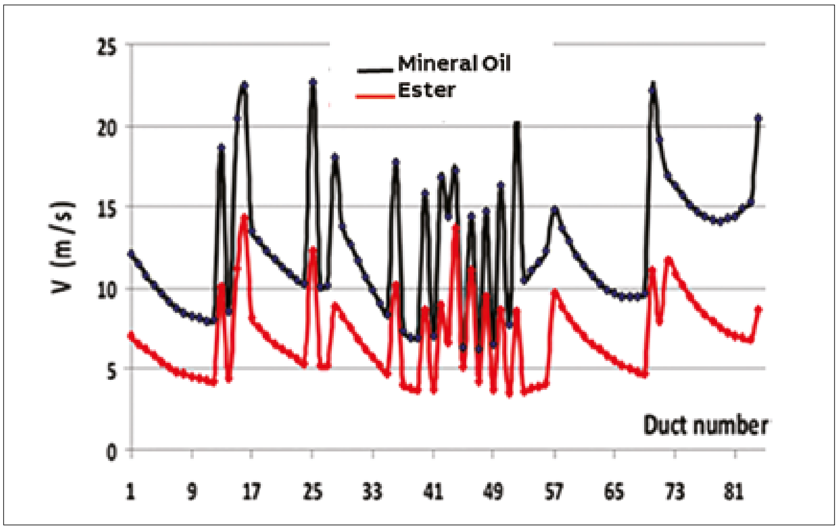


Figure 8a. Fluid velocities disc by disc

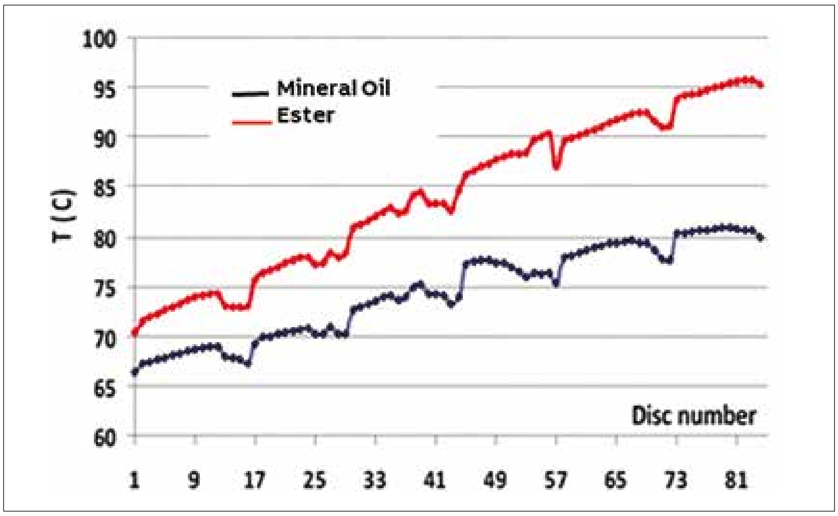


Figure 8b. Winding temperature gradients disc by disc

In order to design, produce, and securely deliver reliable ester filled power transformers for underground substations, a strong and well-proven domain knowledge and experience are required

permittivity and streamer propagation speed.

Relative permittivity

The relative permittivity, or more specifically, the ratio of relative permittivity between solid and liquid materials contributes to how the electrical is stress shared between the materials.

Higher relative permittivity values will have lower electrical stress rejecting it into other surrounding materials.

The relative permittivity of mineral oil is 2.2, and of ester fluids is 3.2. Hence for ester filled power transformers, the electrical stress is lower in the ester but greater in the solid insulation materials. This has significant implications for fluid immersed bushings, tap changers, and thick solid insulation structures inside the transformer. All will experience increased electrical stress. An interesting side consequence of this difference is reflected in the capacitances between windings and from windings to ground, also finding differences between FRA results with both fluids that should be considered when taking FRA as a footprint test.

Again, for the major accessories, the same type of equipment as mineral-oil transformers is used, but the suppliers of such equipment should be consulted for the applicable rating and model. Typically, the bushing and tap-changer dielectric rating (rated voltage) is reduced when used in ester fluids, which will result in a different model being used. The long-term performance of esters in the presence of arcing also leads to the use of vacuum on-load tap changers (where arcing occurs in the vacuum bottle) rather than the traditional diverter arcing in oil models.

Dielectric streamer propagation and lightning impulse performance

Understanding the dielectric lightning impulse behavior of ester filled transformers, which differs markedly from mineral oil, is significant since such stresses can occur in service.

This difference is characterized in Fig. 9 showing streamer speeds in a laboratory needle to plane test cell. From Fig. 9, it can be seen below a certain voltage level (stress level) that the propagation speed of a streamer has a relatively slow speed of the order of 2 km / s. However, above specific stress, the streamer has a very fast speed ten to forty times faster. It is also important to note that the threshold of slow to fast propagation speed for esters occurs much more sharply and at much lower stress levels.

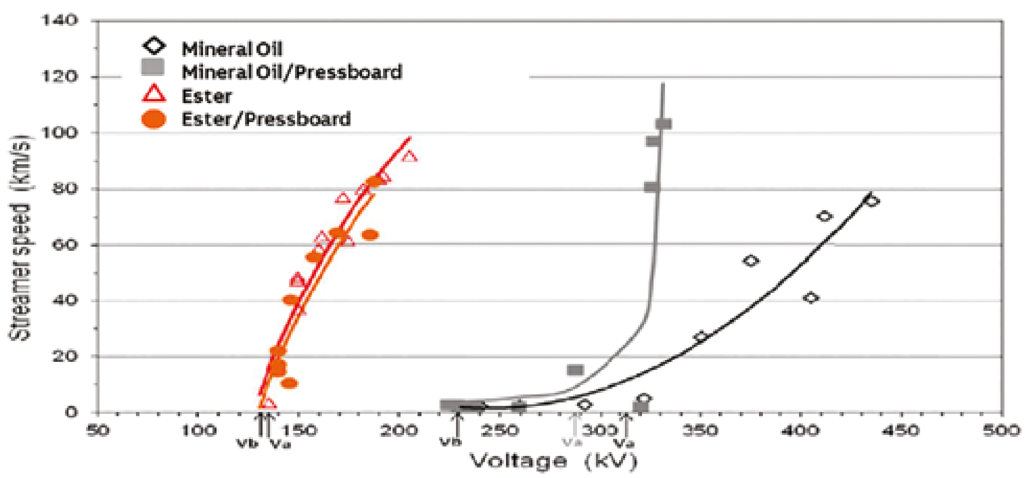
The lightning impulse stress levels used in mineral oil power transformers are typically within the range that corresponds to the slow propagation for mineral oil but fast propagation for esters. Noting that each lightning impulse stress event is a single shot, non-repeating event of duration approximately 100 µs, it means a slow propagation, 2 km / s, mineral oil streamer would travel < 200 mm during the event while the equivalent fast propagation, 40 km / s, ester fluid streamer could travel 4000 mm during the same event. If the streamer is attempting to bridge a gap between 200 to 4000 mm, then the mineral oil case would withstand the stress, but the ester fluid case would fail.

This rather simplified example derived from a laboratory test cell arrangement demonstrates that different stress levels, modified structures, and strong dielectric performance understanding is required to successfully produce ester filled transformers.

Cooling systems arrangement possibilities

Transformers that are deployed into underground substations need to have suitable external cooling equipment configurations for the site arrangement.

There are three major cooling configura-



"Considerations for the Design, Manufacture and Retro-Filling of Power Transformers with High Fire Point, Biodegradable Ester Fluids" CIGRE WG A2-203, 2012

Figure 9. Streamer speed vs. voltage stress in ester and mineral oil [3]

tions that can be used, and each delivers benefits with some constraints. These cooling configurations are:

a) External cooling equipment adjacent to the transformer, within the underground substation room. This arrangement is potentially the simplest for the transformer itself since it is not different from typical above-ground transformers.

   However, it is often more costly for the overall installation since it requires:

   - Significantly larger underground transformer room to accommodate the cooling equipment.
   - Sufficient ambient air ducting down to the substation room and back above ground to cool the full losses of the transformer.

b) Utilizing an intermediate water-cooling circuit from the underground substation room to above-ground cooling equipment. That is, adjacent to the transformer underground, a very compact ester / water heat exchanger is used with a separate intermediate water circuit piped to the above-ground where water- / air-heat exchanger is used. This water- / air-heat exchanger could be similar to a typical air-conditioning cooling tower for a high-rise building. Fig. 10 shows the typical underground ester / water cooling equipment.

   This arrangement:

   - Requires an intermediate cooling circuit and two sets of heat exchangers.

Figure 10. Typical compact ester/water heat exchanger in the underground room

Understanding the dielectric lightning impulse behavior of ester filled transformers, which differs markedly from mineral oil, is significant since such stresses can occur in service

   - Offers versatility in location and distance between the two heat exchangers.
   - Relatively minor cooling for transformer tank heat dissipation only is required for the underground transformer room.

c) The normal transformer external cooling equipment mounted above ground, some meters above the main tank. Such an arrangement is shown in Fig. 11.

   In this arrangement:

   - The vertical height between the main tank in the transformer room and the above-ground cooling bank is limited to approximately 25 m.
   - The pressure head has some impact and limits the performance of pressure relief valves and TXpand™ flexible tank arrangements.
   - Relatively minor cooling for transformer tank heat dissipation only is required for the underground transformer room.
   - The final cooler bank configuration generally cannot be tested in the transformer factory.

Dry-type (HiDry™) units

Traditionally, dry-type transformers have been limited to 36 kV. However, in recent years, resulting from a significant R&D effort, 72.5 kV system levels have been supplied. Recently developed and implemented is the world´s first 145 kV dry-type transformer. Hitachi ABB Power Grids has been leading these milestones achieving these higher voltage rating dry-type transformers using our HiDry™ technology. The history of development is shown in Fig. 12.

The main technology challenges that needed to be overcome for these higher voltage level dry-type transformers is the dielectric design of both the main insulation (e.g., between windings and between windings and ground) and the minor insulation (e.g., between parts of the same winding). Fig. 13 and Fig. 14 show examples of Hidry™ 72 kV units installed in recent years.

The current capability range of HiDry units is shown in Table 4.

The avoidance of using a large amount of mineral oil in transformers on the above-mentioned voltage ratings, which are commonly used in underground substations, can completely avoid hazardous risks to humans and the environment either by fire or spills. None of the materials in dry-type transformers have flash-points, and being in solid form eliminates the risk of fire and spills and removes the related costs for fire and spill protected installations. Dry-type materials also go one step further in the sense that they are "self-extinguishing," which means that in the event of a surrounding fire, the transformer will not propagate fire.

IEC Standard 60076-11 latest release from 2018 describes the climatic, environmental, and fire behavior classes, where these units were able to reach the levels shown in Table 5.

The main challenge of dry-type transformers, when compared to oil-filled technologies, is the weight and dimen-

Transformers that are deployed into underground substations need to have suitable external cooling equipment configurations adapted to the site arrangement

sions as dry-type transformers are typically larger and heavier than oil-filled units. This is due to the need for higher dielectric distances in air and mainly because of the lower cooling capacity. Nevertheless, there are some ongoing developments to reduce the size of the transformers, thanks to enhanced cooling [4].

Additionally, when used in underground substations, the dry type technology requires sufficient ambient air ducting down to the substation room and back above ground to cool the full losses of the transformer.

The optimised choice between the two complementary solutions of ester filled units and dry type HiDry™ units requires balancing of the relative importance, risk, and cost of:

- Application and rating of the required transformer
- Minimal flammability risk versus non-flammability
- Minimal liquid spill risk with reduced consequence versus no fluid
- Available underground space and mass allowed and associated cost
- Cooling arrangement flexibility and cost.

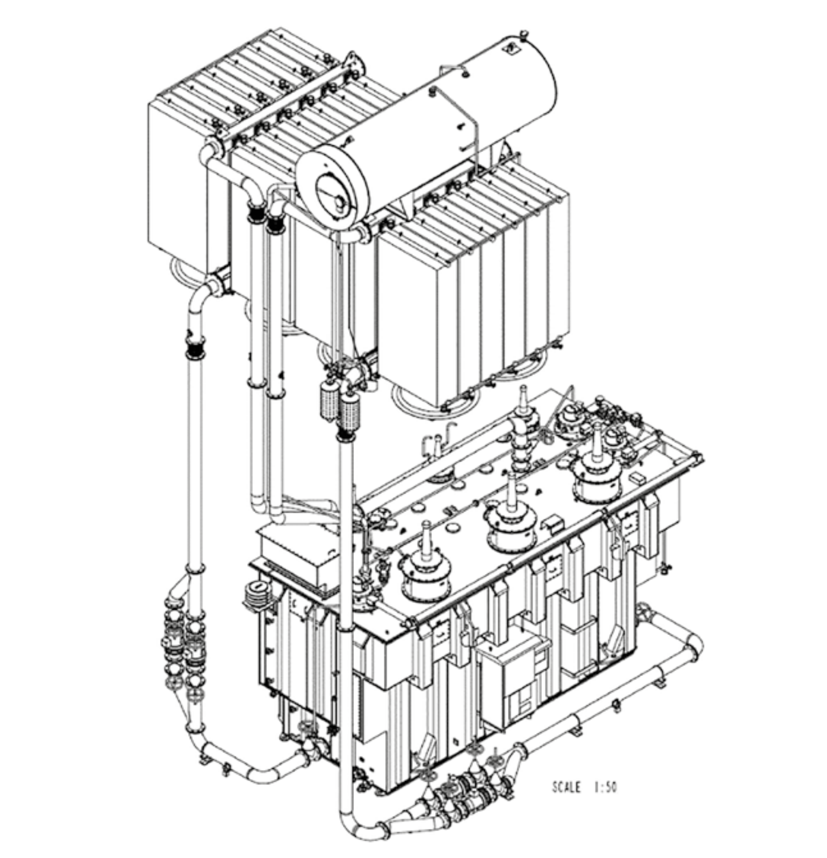


Figure 11. Transformer with cooling equipment mounted externally above ground level

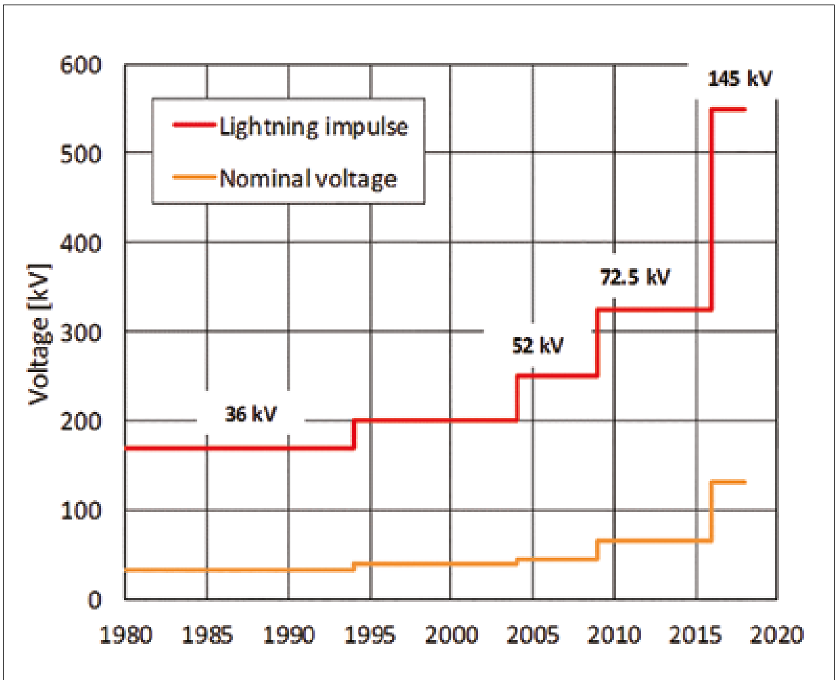


Figure 12. Evolution of the voltage level for Hitachi ABB Power Grids dry-type transformers

Conclusion

Reported global statistics for traditional power transformers are that the probability of a failure involving a major oil spill is approximately 0.6 % and of involving a prolonged fire is approximately 0.1 %.

Hitachi ABB Powergrids considered it imperative, especially combined with the increasing trend of deploying power transformers into underground substations,

Table 4. The current capability of Hitachi ABB Power Grids dry-type transformers

Rated power	up to 63 MVA
Nominal voltage	up to 132,000 V
Insulation level	up to 145 kV
Lightning impulse level	550 kV
Applied voltage	230 kV
LV insulation level	up to 36 kV
Partial discharge level	< 10 pC
Cooling	AN or AN/AF

Table 5. Climatic, environmental and fire classes of dry-type transformers based on IEC 60076-11 Standard

Environmental class	E2
Climate class	C2
Fire behavior class	F1

that power transformer solutions needed to be developed to substantially reduce or eliminate fire risk, fluid spill impacts and environmental consequence over the whole range of power transformers.

This has been achieved and is well proven via Hitachi ABB Power Grids ester filled transformers to 400 MVA and 420 kV, with further expansion to this range in the future. These transformers deliver a minimal fire risk, effectively fire safe solution. Any fluid-spill risk is also dramatically reduced by combination with the TXpand, flexible tank solution, while the environmental consequence is significantly eased due to the inherent, readily biodegradable nature of the ester fluid.

For units in the range to 63 MVA and 145 kV, either ester filled units can be supplied or Hitachi ABB Power Grids unique HiDry™ dry-type technology can be used. HiDry™ power transformers are a dry-type technology that eliminates fire risk, liquid-spill risk, and associated environmental impact completely by delivering a non-flammable, spill-proof solution into this power transformer range.

These solutions may also allow further benefits to be derived in substation size reduction and substation safety systems simplification.

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Figure 13. 72 kV dry-type transformer inside of a building (urban substation)

Figure 14. 72 kV dry-type transformer under a football stadium