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PS 2. Impact of Net Zero on the Lifetime Management of SF6 Filled Equipment

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Transformer Fire Safety in the Absence of SF6

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SUMMARY

The best-known use of SF6 in the electric power infrastructure is in switching equipment, especially circuit breakers. However, SF6 is also used in transformers across the full size range. SF6 transformers have the advantage of greater fire and explosion safety than other design concepts. They are widely used for substations in dense urban areas in the Asia-Pacific reason, and occasionally elsewhere.

As the future of SF6 is, at best, highly uncertain, there is a clear need to develop alternative technologies for transformers as well as for switching equipment. This paper considers some of the possible alternative transformer technologies, including dry-type (cast epoxy resin and cast silicone rubber) and ester-immersed (natural and synthetic). Special emphasis is placed on fire and explosion safety, but consideration is also given to other aspects.

KEYWORDS

Transformer, reactor, specification, design, construction, fire safety, SF6

1 Introduction

According to the position paper on the application of SF6 in transmission and distribution networks, published by CIGRE Study Committee B3 in June 2014 [1]:

> *SF6 is essential for the transmission and distribution equipment and switchgear, because of its excellent dielectric, arc quenching, heat transfer, and chemical recombination properties.*
>
> *This has been successfully proven since the 1960s for high-voltage equipment and since beginning of the 1980s for medium-voltage equipment. The size of equipment and switchgear had been significantly reduced since the beginning of the SF6 technology. Nowadays, SF6 technology is even more important to bring bulk power at high voltages closer to consumers as for mega cities.*

The position paper focuses mainly on use of SF6 in switching equipment. However, it mentions a number of other possible applications, including gas-insulated lines, gas-insulated instrument transformers, and gas insulated power transformers and reactors. The main focus of this paper will be on the application of SF6 to power transformers and reactors and consequences for substation design and construction.

2 Relative Benefits of SF6 Power Transformers and Reactors

SF6 insulated transformers have been in use since the 1960s. A separate international standard for gas-insulated transformers and reactors was developed in the 2000s (IEC 60076-15), and has been updated since [2]. Special consideration has also been given to SF6 insulated transformers and reactors in both the CIGRE guide to transformer maintenance (CIGRE brochure 445, [3]) and in the CIGRE Green Book on transformer and reactor procurement [4].

SF6 insulated transformers and reactors are generally considered to have the following relative benefits compared with other design concepts.

- Highest levels of fire safety
  SF6 is not flammable. SF6 insulated transformers and reactors generally only use non-flammable or low-flammable insulating and conducting materials in their construction. They therefore have the highest intrinsic level of fire safety of any transformer design concept, as acknowledged by the CIGRE guide to transformer fire safety (CIGRE brochure 537, [5]).
- Highest levels of explosion safety
  In case of a major internal dielectric fault, the internal pressure in SF6 and other gas insulated transformers and reactors increases in a predictable manner which the tank can be designed to withstand until protection systems isolate the transformer or reactor. In case of liquid immersed transformers and reactors, the liquid transmits the energy from the dielectric fault to the tank very rapidly and it is challenging to design the tank to withstand the effect of all different possible internal dielectric faults.
- Compact size
  SF6 has excellent dielectric and heat transfer properties, allowing a compact transformer or reactor design. SF6 insulated transformers and reactors are broadly similar in size to liquid insulated transformers and reactors of the same rated voltage and rated power, and more compact than dry-type transformers and reactors of the same rated voltage and rated power.
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- Low sound levels
  Vibrations for the core and winding assembly are less closely coupled with the transformer or reactor tank for SF6 and other gas insulated transformers and reactors than for other design concepts. This reduces sound levels from the core and winding assembly in operation compared with other design concepts, especially dry-type transformers and reactors.

These relative benefits have led to the widespread adoption of SF6 transformers and reactors in dense urban areas in the Asia-Pacific region. SF6 transformers and reactors are occasionally used outside the Asia-Pacific region, typically in dense urban areas or environmentally sensitive locations.

3 Need for Alternatives

According to the position paper on the application of SF6 in transmission and distribution networks, published by CIGRE Study Committee B3 in June 2014 [1]:

> *In spite of all the technical advantages of SF6 technology, SF6 is a potent greenhouse gas which is covered by the Kyoto Protocol [6]. Therefore SF6 must be managed within a closed cycle, avoiding any deliberate release to the atmosphere. During the last 20 years, as a consequence, significant effort has been undertaken to reduce SF6 emissions. The focus for manufacturers and asset owners was on finding ways of increasing the tightness of equipment and reducing handling losses.*

Since this position paper was written, public and political concern over climate change has increased. Since the position paper was written, public and political awareness of the industry's use of SF6 has also increased. As a consequence, there has been increased public and political pressure to reduce use of SF6 and especially loss of SF6. As a consequence, there has been increased research and development by the industry on alternatives to SF6.

An important recent development has been the proposal by the European Commission to update regulations on use of fluorine-containing gases [7]. These envisage the progress withdrawal of SF6-insulated switchgear from the market between 2026 and 2031. Some exemptions may be permitted where there is no suitable alternative. The proposal does not include other applications of SF6 in transmission and distribution networks. However, it seems most unlikely that use of SF6 in these other applications would continue following the withdrawal of SF6-insulated switchgear.

There is a clear need to examine alternatives to SF6, not only in switchgear but for other applications including power transformers and reactors. At the 2022 Paris session, preferential subject 2 was "Beyond the oil-immersed transformer or reactor". The main focus of the preferential subject was therefore consideration of the relative benefits of different transformer design concepts, especially new and emerging design concepts. This paper draws heavily on the papers for this preferential subject, for which the author was one of the special reporters.

4 Possible Alternative Design Concepts

In this paper, consideration is given to the following possible alternative design concepts for power transformers and reactors

- Oil-immersed
- Silicone-immersed
- Ester-immersed (natural and synthetic)
- Cast epoxy resin
- Cast silicone rubber

4.1 Oil-Immersed

The conventional oil-immersed power transformer design concept was developed shortly following the introduction of the first power transformers, and remains the most widespread type today. It is applicable across the full range of rated voltages and rated powers currently in use, and could probably be extended further if required. There are a large number of potential suppliers, which controls costs and delivery times.

The conventional oil-immersed power transformer design concept has a number of important disadvantages, which are what has led to the development of alternative concepts including the SF6-insulated transformer. A particular disadvantage is fire and explosion safety. The oil used has a sufficiently low fire point and a sufficiently high calorific value to allow self-sustaining fires to develop after a failure (see Table 1, and also Figure 1 for a comparative fire test). The oil also transmits the energy from any internal dielectric failure to the tank very rapidly and it is challenging to design the tank to withstand the effect of all different possible internal dielectric faults.

The fire and explosion safety of transformers and reactors according to the oil-immersed design concept can be improved somewhat by choice of suitable components and fittings; suitable tank design; venting of the tank; etc. There are also various explosion prevention systems, which provide rapid and safe venting in the event of an internal dielectric failure. These measures are discussed in detail in the CIGRE guide to transformer fire safety (CIGRE brochure 537, [5]). Installations can also be designed to mitigate the risks in case of explosion or fire. Conventionally this would involve increasing the distances between the transformer or reactor and other transformers or reactors or buildings (see Table 2, derived from IEC standard 61936-1 [8]). However, there are more advanced substation design methods which can be used especially in dense urban areas. These are discussed in detail in the CIGRE guide to substation fire safety (CIGRE brochure 886 [9]).

The conventional oil-immersed design concept would not therefore normally be considered to be a suitable alternative to the SF6-insulated design concept, which has intrinsically much higher levels of fire and explosion safety.

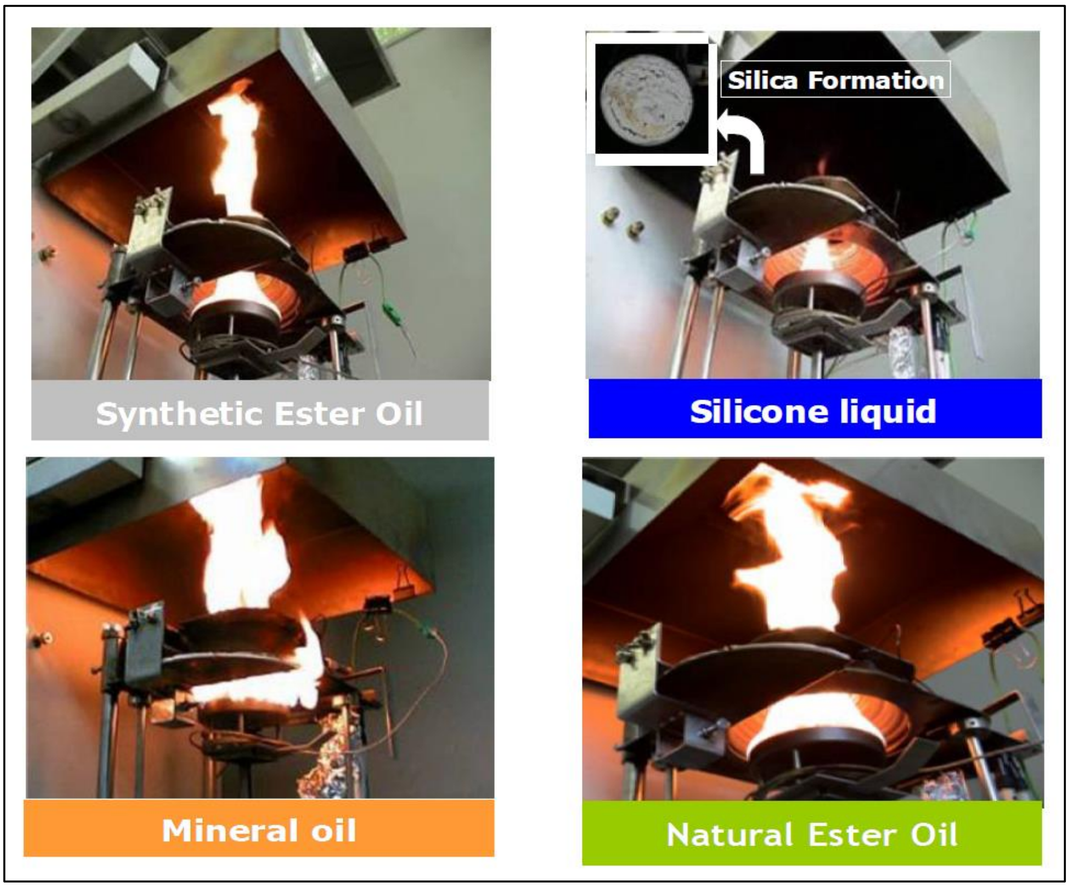
4.2 Silicone-Immersed

The silicone-immersed power transformer design concept overcomes the problem of fire safety by substituting silicone liquid for oil. It is also possible to combine use of silicone with high temperature solid insulation for a more compact design. Silicone has a sufficiently high fire point and a sufficiently low calorific value that the risk of a self-sustaining fire developing after a failure is greatly reduced (see Table 1, and also Figure 1 for a comparative fire test). However, should a fire occur, then silica is produced which is harmful to health and difficult to clean-up. The dielectric and heat transfer properties are inferior to oil, which limits the use of silicone to transformers and reactors up to and including 72.5kV class only.

Table 1
Fire Properties of Different Transformer Insulation Liquids

Liquid	Flash Point (°C)	Fire Point (°C)	Calorific Value (MJ/kg)
Oil	≥135		46
Silicone	≥300	≥350	28
Natural Ester	≥250	≥300	36.9
Synthetic Ester	≥250	≥300	31.9

Figure 1
Fire Tests on Different Transformer Insulation Liquids
(after CIGRE brochure 537 [5])



Whilst silicone remains available, improvements in other liquids have rendered it largely obsolescent. Transformers immersed in ester liquids are a more serious alternative to both the conventional oil-immersed design concept and the SF6-insulated design concept.

Table 2
Recommended Minimum Fire Clearances for Different Types of Transformer
Without Enhanced Fire Protection
(after IEC 61936-1 [8])

Immersed In	Volume (l)	Minimum Fire Clearance (m) to	
		Other transformers Building surface of combustible material	Building surface of non-combustible material
Oil	≥1000, < 2000	3	7.5
	≥2000, < 20000	5	10
	≥20000, < 45000	10	20
	≥45000	15	30
Other Liquid (ester, silicone)	≥1000, < 3800	1.5	7.5
	≥3800	4.5	15

4.3 Ester-Immersed

The silicone-immersed power transformer design concept overcomes the problem of fire safety by substituting ester liquid for oil. There are both natural and synthetic ester liquids available. Natural esters are refined plant oils, with certain additives to improve performance. Synthetic esters are engineered chemical products. Both natural and synthetic esters have sufficiently high fire points and sufficiently low calorific value that the risk of a self-sustaining fire developing after a failure is greatly reduced (see Table 1, and also Figure 1 for a comparative fire test). The dielectric properties of ester liquids are not exactly the same as oil, and the dielectric design of ester-immersed transformers and reactors is more complicated than for oil-immersed transformers and reactors. Designs have been developed up to and including 420kV class, and it seems likely that ester liquids will be applied across the full range of rated voltages in future. However, the polar nature of ester liquids seems to preclude their use in conventional HVDC transformers. The heat transfer properties of ester liquids, especially natural ester liquids, and also not the same as oil. Designs have been developed up to more than 250MVA, and it seems likely that ester liquids will be applied across the full range of rated powers in future.

The main difference between natural and synthetic esters is that synthetic esters have better chemical properties, especially better oxidation stability. Both natural and especially synthetic esters can be used at higher temperatures than oil. As with silicone, it is possible to combine synthetic esters with high temperature solid insulation for a more compact design. This design concept is widely used for traction transformers mounted on railway trains and for wind turbine transformers.

The ester-immersed design concept overcome one of the main disadvantages of the oil-immersed design concept, viz. poor fire safety. This is recognised by IEC standard 61936-1, which allows lower separation from ester-immersed designs than from oil-immersed designs (see Table 2). However, another of the main disadvantages remains. Ester liquids transmit the energy from any internal dielectric failure to the tank very rapidly just as oil does. It therefore remains challenging to design the tank to withstand the effect of all different possible internal dielectric faults, even if the risk of a fire following the tank rupture is reduced.

Use of ester-immersed transformers and reactors is increasing in many countries, and there is a substantially research and development effort to develop better designs. It is telling that out of 14 papers accepted by study committee A2 for preferential subject 2 at the 2022 Paris session, 9 concerned use of ester-immersed transformers and reactors. It is particularly telling that these 9 papers included 2 from countries in the Asia-Pacific region where use of SF6-insulated transformers and reactors is widespread.

For applications above 10MVA and 36kV class, the ester-immersed design concept would seem to be the most promising alternative design concept. The ester-immersed and SF6-insulated design concepts have similar advantages of high intrinsic fire resistance, compact size, and low sound. However, the explosion safety of the ester-immersed design concept is inferior to that of the SF6-insulated design concept. This would require some adaptations to substation design and construction, as would the need for liquid containment.

4.4 Cast Epoxy Resin

A number of different dry-type concepts have been developed for transformers and reactors. All dry-type concepts essentially use atmospheric air for both insulation and cooling. As atmospheric air does not have such good dielectric and cooling properties as the alternatives, dry type transformers and reactors are inherently less compact than those according to other design concepts of the same rated voltage and rated power.

All dry-type transformers have no intrinsic resistance to explosion in the event of a dielectric failure. In case of transformers and reactors installed in enclosures, this must be designed and constructed to provide the required resistance to explosion and also the required venting.

Vibration of the core and winding assembly in dry-type transformers and reactors is transmitted directly to the environment, rather than via another medium. Dry-type transformers and reactors have inherently higher sound levels than those according to other design concepts. This is a particular disadvantage for larger dry-type transformers, where the sound levels may be sufficient to cause significant public nuisance. The installation design needs to be suitably adapted to manage the sound levels without allowing public nuisance.

The most popular design concept uses windings which are cast into epoxy resin to provide protection against the atmosphere, moisture, and solid contamination. Reactors according to this design concept are usually do not include any magnetic circuit, and can be installed either indoors or outdoors on insulating stands. Reactors according to this design concept have been used for niche applications for many years, and have more recently been applied to replace conventional oil-immersed shunt reactors for applications up to 420kV class (see [10] for more information). It seems likely that their use can be extended to cover the full range of shunt reactor rated voltages and rated powers. Transformers according to this design concept must include a core and some structural components, which also need to be protected against the atmosphere, moisture, and solid contamination. This is more challenging than for windings, and cast epoxy resin transformers are generally suitable only for indoor applications. The need for insulation between the windings and the core also limits the maximum rated voltage. The usual maximum rated voltage is 36kV class, but special designs have been developed for up to and including 145kV class (see [11] for more information).

Epoxy resin has good intrinsic fire resistance. It does not necessarily follow that cast resin windings have good fire resistance, as this may be influenced by the use of fillers and by the use of aluminium winding conductors. It is possible to design and construct epoxy resin windings with good fire resistance, and there is a test methodology to prove fire resistance in the relevant international standard (IEC 60076-11 [12]).

A particular disadvantage of the cast epoxy resin design concept is that the windings are very challenging to recycle. Separation of the epoxy resin and the winding conductor may not be possible, and in any case the epoxy resin has intrinsically poor recyclability. Cast epoxy resin windings often have to be crushed and used as aggregates for construction, rather than recycled.

For applications up to 10MVA and 36kV class, the cast epoxy resin design concept would seem to be a promising alternative design concept. The cast epoxy resin and SF6-insulated design concepts share the advantage of high intrinsic fire resistance. The possible disadvantages of the cast epoxy resin concept in terms of explosion resistance, size, and sound level can likely be managed with some adaptations to substation design and construction. If not, then due consideration should be given to the ester-immersed design concept instead. This would also require some adaptations to substation design and construction, as set out above.

4.5 Cast Silicone Rubber

A promising new design concept for dry-type transformers was presented at the 2022 CIGRE Paris session [13]. The epoxy resin is replaced with silicone rubber, which can more easily be separated from the winding conductors to allow recycling [14]. This is an emerging technology and experience remains limited.

5 Evaluation of Possible Alternative Design Concepts

The best-known use of SF6 in the electric power infrastructure is in switching equipment, especially circuit breakers. However, SF6 is also used in transformers and reactors across the full range of rated voltages and rated powers. Compared with other design concepts, SF6-insulated transformers and reactors are considered to offer the following relative benefits:

- Highest levels of fire safety
- Highest levels of explosion safety
- Compact size
- Low sound levels

There is no available alternative technology which combines all of these benefits. For applications above 10MVA and 36kV class, the ester-immersed design concept would seem to be the most promising alternative design concept. The ester-immersed and SF6-insulated design concepts have similar advantages of high intrinsic fire resistance, compact size, and low sound. However, the explosion safety of the ester-immersed design concept is inferior to that of the SF6-insulated design concept. This would require some adaptations to substation design and construction, as would the need for liquid containment.

For applications up to and including 10MVA and 36kV class, the cast epoxy resin design concept is another promising alternative. The cast epoxy resin and SF6-insulated design concepts share the advantage of high intrinsic fire resistance. The possible disadvantages of the cast epoxy resin concept in terms of explosion resistance, size, and sound level can likely be managed with some adaptations to substation design and construction. If not, then due consideration should be given to the ester-immersed design concept instead. This would also require some adaptations to substation design and construction, as set out above.

In future, the cast silicone rubber design concept might be a more suitable alternative than the cast epoxy resin design concept, offering better recyclability.

6 Need for New Alternative Design Concepts

As there is no alternative technology which combines all of the benefits of SF6-insulated transformers and reactors, there is a need fur further work to develop new design concepts for applications where SF6-insulated transformers are essential or highly advantageous, especially in dense urban areas. The most obvious direction for future research and development would be the development of an alternative gas or gas mix. Previous work by CIGRE on alternative gases or gas mixes has focused mainly on their use in switchgear, rather than in transformers [15]. However, one paper on use of dry air or nitrogen in gas-insulated transformers was presented at the 2022 Paris session suggested that this might be a promising direction for future research and development [16].

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