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Summary

In the last seven years there has been a gradual change of strategy on the use of the SF6 gas within electrical utility companies. This is due to the arrival of new non-SF6 switchgear alternatives. Switchgear technology is now developing at a fast pace. This dynamic, both technical and commercial, brings some incertitude towards the adoption of non-SF6 switchgear.

Utilities in Australia and New Zealand are now facing the dilemma of how to best navigate through this transition to non-SF6 switchgear technology in the safest and optimum way. This conversion needs to be achieved whilst maintaining the reliability of the equipment by following optimised maintenance procedures gained with 50 years of experience with SF6 circuit breakers and remaining flexible to future options in alternative gas technologies.

This paper presents a consensus by utilities in Australia and New Zealand of the main concerns and challenges facing the shift from well proven SF6 switchgear to the new technologies. It describes the main factors to consider by Australian and New Zealand users to choose the available alternatives to SF6 HV switchgear. Finally, the strategies to introduce this new technology minimizing the risk in the operation of the grid are discussed.

Keywords

High Voltage switchgear, non-SF6 alternatives, circuit breakers, Gas Insulated Switchgear, SF6 gas

1. Introduction

During the last 50 years SF6 switchgear has been the preferred technology for HV circuit breakers above 52 kV in Australia and New Zealand, like in all the other countries around the world. During this time SF6 switchgear has improved, circuit breaker problems investigated and fixed, standards and technical guides developed, and operational procedures have evolved. As a result, SF6 switchgear has become a very mature technology and the feedback of users during this period has been very positive. The main drawback in the use of SF6, aside from hazardous in-service decomposition products, is that it is a potent greenhouse gas. Its global warming potential (GWP) is 23,500 times the GWP of the carbon dioxide (CO2). This was the reason why SF6 was included in the list of gases for global warming in the Kyoto Protocol in 1997 [4].

After the Kyoto Protocol there has been a continuous debate on the use of SF6 gas in HV switchgear. Initially the general belief was that there was no practical alternative to SF6 for use in High Voltage (HV) circuit breakers. The focus was on minimising gas leaks to atmosphere by switchgear manufacturers and utilities. Consequently, there have been no local policies forbidding or penalising the use of the gas SF6 in HV switchgear except during the brief Carbon-tax period in Australia from July 2012 to July 2014. There have been ongoing government requirements to report SF6 emissions and increased emphasis on the repair/replacement of SF6 equipment.

In the last 7 years there has been a general shift of opinion on the use of SF6 gas. This is due to the arrival of new non-SF6 switchgear alternatives. In this period several alternative gases and technologies have been developed: some well-known in the switchgear industry such as 'Clean Air' and other new synthetic gas mixtures for instance, fluoronitriles and fluoroketones. Switchgear technology is now changing very quickly, and some manufacturers have released a new non-SF6 circuit breaker with one gas only to change the same rated circuit breaker to a different gas 2 years later.

Utilities in Australia and New Zealand are now facing the dilemma of how to best navigate through this ever-changing switchgear technology in the safest and optimum way. This needs to be achieved whilst maintaining the reliability of the equipment by following optimised maintenance procedures gained with 50 years of experience with SF6 circuit breakers and remaining flexible to future changes in gas technologies.

2. Australia and New Zealand regulation on the use of SF6 in HV switchgear

2.1 Regulations in Australia

On the 1st of July 2012 the Australian Federal government introduced a carbon pricing mechanism (aka "carbon tax") starting at AU$23 per tonne of CO2-e. Australia included the use of SF6 in the "Carbon Tax" regulation. Australia was one of the first countries in the world to introduce this legislation. Companies who purchased SF6 gas had to pay a tax which was much higher than the cost of the gas. This had a very significant impact on the price of the SF6 gas: about AUS$ 500,000 per tonne of SF6 (approximately 8 - 10 bays of a 145 kV GIS). Consequently, the utilities in Australia increased their stocks of SF6 gas in advance of the introduction of the new legislation.

However, with the change of Federal government this tax was cancelled in 2014. Since then, there has not been any restriction or tax on the use of the gas SF6 in HV switchgear. What does exist is the requirement of the utilities to report the amount of gas SF6 leaked to the atmosphere.

2.2 Regulations in New Zealand

Various regulations in New Zealand cover the use and reporting of SF6 gas use, notably:

i. **The Climate Change Response Act 2002 (the CCRA)** sets the legal framework to enable New Zealand to meet its international obligations under the United Nations Framework Convention on Climate Change, the Kyoto Protocol and the Paris Agreement.

The CCRA requires Transpower:

- to target greenhouse gas emissions, including sulphur hexafluoride (SF6) gas, in a calendar year to be net zero by 1 January 2050 and for each subsequent calendar year.
- to ensure our activities to install, operate, service, modify, dismantle or dispose any electrical switchgear do not knowingly, and without lawful justification or excuse, release SF6 gas into the atmosphere.
- to follow the obligations of the emission trading scheme (ETS).

ii. **The Climate Change (Stationary Energy and Industrial Processes) Regulations 2009** require Transpower to:

- Collect, record, calculate and report on the SF6 emissions in pre-charged equipment.
- Calculate the emission of SF6 based on the formula given in Climate Change (Stationary Energy and Industrial Processes) Regulations 2009 Clause 44C.

Under the Climate Change Response Act legislation, as a major user of SF6 gas, Transpower has an upstream point of obligation and is a mandatory participant in the NZ Emission Trading Scheme (ETS). Transpower is required to submit an annual SF6 surrender of units to meet our emissions obligations.

The New Zealand Ministry for the Environment request information annually from Transpower on the use of SF6 in New Zealand. This includes the

- Total quantity of SF6 purchased for the calendar year
- Total quantity of SF6 contained in our equipment at the end of the year
- The breakdown of SF6 equipment decommissioned for the calendar year
- SF6 in our storage at the end of the year

3 SF6 alternatives available

At the time of writing this paper there were several different alternatives to SF6 HV switchgear. Most of the switchgear were only available up to 170 kV but with development plans to increase their application to higher voltages.

3.1 N2-SF6 gas mixture

This has been used for a long time in HV Circuit breakers in very cold climates as in some areas of Canada and Norway to allow for a lower dew point temperature of the gas. It has also been used in a few Gas Insulated Lines (GIL). It does not represent a valid alternative for general HV switchgear applications as it does still require an important amount of gas SF6 in the mix [1].

3.1 CO_2 + O_2 gas mixtures

The gas mixture composition is typically 90% CO2 and 10% O2. It has a GWP (Global Warming Potential) of 1 since the GWP is based on the global warming potential of CO_2, so it is 23,500 times better than SF6 from the environmental point of view. However, it is a much worse dielectric and it has worse arc-quenching capability than SF6. It is valid for installations at very low ambient temperatures. Presently it is only used for HV circuit breakers up to 145 kV.

3.2 Fluoronitriles gas mixtures

In 2014 a new synthetic gas mixture, Novec^{TM} 4710 Fluid (C_4F_7N), was developed by the company 3M. The gas mixture composition varies depending on the application and the switchgear manufacturer but typically would be around 5% C_4F_7N 13% O_2 and 82% CO_2. The dielectric strength and interruption capability are still lower than SF6 and therefore it requires a higher operating pressure. The minimum working temperature is -25C. The application today exists in HV circuit breakers, current transformers and GIS up to 145 kV [5]. There are currently development projects to increase the voltage application up to 420 kV.

3.3 Fluoroketones gas mixtures

In 2014 3M also presented a new gas mixture named Novec^{TM} 5110 Fluid ($C_5F_{10}O$). The gas mixture composition varies depending on the application and the switchgear manufacturer but typically would be around 6-12% $C_5F_{10}O$ +O_2 + CO_2. One problem of this gas mixture is its high temperature dew point which limits the minimum ambient working temperature at nominal operating pressures to -5C. As this gas mixture is an inferior dielectric and arc-quenching media than SF6, it is required to work at higher pressures and ambient temperatures which limits the application to indoor installations [6]. It was applied initially to HV GIS and there was a pilot trial of a 145 kV GIS installed in Switzerland in 2015. Later the manufacturer changed their technology towards Fluoronitriles and today the only application found is in MV indoor switchgear.

3.4 Clean Air with Vacuum Interrupter

Clean Air or Dry Air has the same composition as the air in the atmosphere (80% N_2 + 20% O_2) but without moisture and contamination. It has zero GWP. Clean Air is dielectrically significatively inferior to SF6 (45% at the same pressure). Therefore, it requires higher pressures and larger sizes compared to SF6 switchgear. Clean Air is a poor arc interruption medium, so it is necessary to use a vacuum interrupter (VI) for interruption and Clean Air at high pressure for insulation. It can be also used as low as -30C ambient temperatures. There are currently applications for HV circuit breakers and GIS up to 145 kV with development plans to increase the voltage up to 420 kV [7]. The challenge on this technology are the voltage limitations of the Clean Air as insulation and the vacuum interrupters. Vacuum interrupters are the dominant interrupter technology for medium voltage, but until recently their application was limited to 72.5 kV. The main user's experience of VI at 72.5 kV is in Japan [3].

4 Challenges facing the utilities

Utilities in Australia and New Zealand are now facing the dilemma of how to best navigate through this ever-developing switchgear technology in the safest and optimum way.

A gradual replacement of HV SF6 switchgear is already happening. The last 5 years have not seen any SF6 switchgear development. All the new HV switchgear released by the main manufacturers are non-SF6. The question for the user is when to adopt this new technology and what is the right process to implement it in the network.

One of the problems of this new technology is that it does not offer any technological advantages compared to the existing SF6 technology, and the economic benefits may be limited to reduced ETS penalties, whilst being offset by increased capital and implementation costs. Transition away from SF6 technology cannot be compared to previous transitions such as moving from bulk-oil to minimum oil and from air-blast to SF6 where there were sound technical and economic benefits. This fact does not encourage a fast implementation of non-SF6 HV switchgear. Future regulatory policy will be an important factor to speed up the implementation of non-SF6 technologies. These international regulatory policies will have a determinant influence also outside the geographic area of application. For instance, Australia and new Zealand might be affected by the F-gas and PFAS restrictions in the European Union legislation as it affects to suppliers of HV switchgear and gas. Another important issue when considering the implementation of these non-SF6 alternatives is the diversity of options currently available. There is no commonly agreed direction on which non-SF6 technology to pursue. Each manufacturer is choosing their own pathway without a congruent approach for the benefit of the end users. There is no unified international opinion on the best alternative. For instance, in recent years the Paris CIGRE conferences have included many papers discussing the benefits of each SF6 alternative. Every manufacturer has provided reasons as to why its solution was superior to others [5] [7]. It is not yet clear which will be the predominant media and when will it be universally adopted by industry.

There is also a lack of direction with specific manufacturers regarding non-SF6 technology with some manufacturers releasing a new non-SF6 breaker with one type of gas and two years later rereleasing the same breaker rating with a different gas.

This dynamic both technical and commercial brings incertitude towards the adoption of non-SF6 switchgear. It is important to bear in mind that the utility is purchasing the HV switchgear with a long-term vision of 30-50 years. As an example, there are still bulk-oil circuit breakers in operation in Australia and New Zealand. The introduction of new technology into a utility involves many stakeholders pursuing a long process of evaluation and approval, knowledge and application training and the development of internal operating procedures and maintenance plans. The risk that the new HV switchgear becomes obsolete in a few years is an important factor that must be taken into account.

Another consideration is that, due to the conservative nature of HV switchgear applications, utilities require references and proof of extensive field experience, not just laboratory certification, of the HV switchgear they install into the network. It is common practice amongst Australian and New Zealand utilities that during the HV switchgear tender process a request is made for the supplier to provide a reference list of the places where the switchgear has been sold and some contact details of customers willing to provide feed-back of their experience.

This represents a vicious circle or “catch 22”: manufacturers need field experience by utilities to sell their new non-SF6 HV switchgear and utilities need a field proven non-SF6 HV switchgear to install in their network.

Furthermore, there is not yet a common international standard or an international body of knowledge (such as the CIGRE technical brochures) to assist in the selection of the non-SF6 switchgear. Again, you need a return of experience to develop a good and useful technical standard to assist the switchgear users.

Everything makes you think that the above-mentioned obstacles will dissipate in the future as there is a confluence of the driving forces in the development of non-SF6 HV switchgear:

- **Technology:** in recent years there has been a reduction of non-SF6 alternatives proposed in HV switchgear. There is a trend to aggregate the manufacturers into just few alternatives as some manufacturers have decided to switch towards a gas used initially by just one manufacturer. From the list of non-SF6 alternatives mentioned in section 3, it is now reduced to CO_2 (used at this moment by just one manufacturer), Fluoronitrile gas mixtures and Clean Air with Vacuum Interrupter. It is very likely that this selection continues to be further reduced depending on the success of the application of these technologies at higher voltages.
- **Commercial:** there is an increased number of manufacturers offering non-SF6 alternatives and it is only a matter of time before all the manufacturers who have been manufacturing

SF6 switchgear will have a non-SF6 switchgear portfolio. An increase of competition always drives down prices. Furthermore, as the number of orders increases production costs should significantly reduce.

- **Standardisation:** there is a continuous progress to adapt switchgear standards as the IEC 62271-203 on HV Gas Insulated Switchgear [2] to the new technologies based on previous SF6 experience.
- **Field experience:** Obviously the growth of the population of non-SF6 switchgear in operation around the world will increase the return of field experience. New failure modes will be found and solved, and this will help in the development of specific maintenance plans for this new equipment.

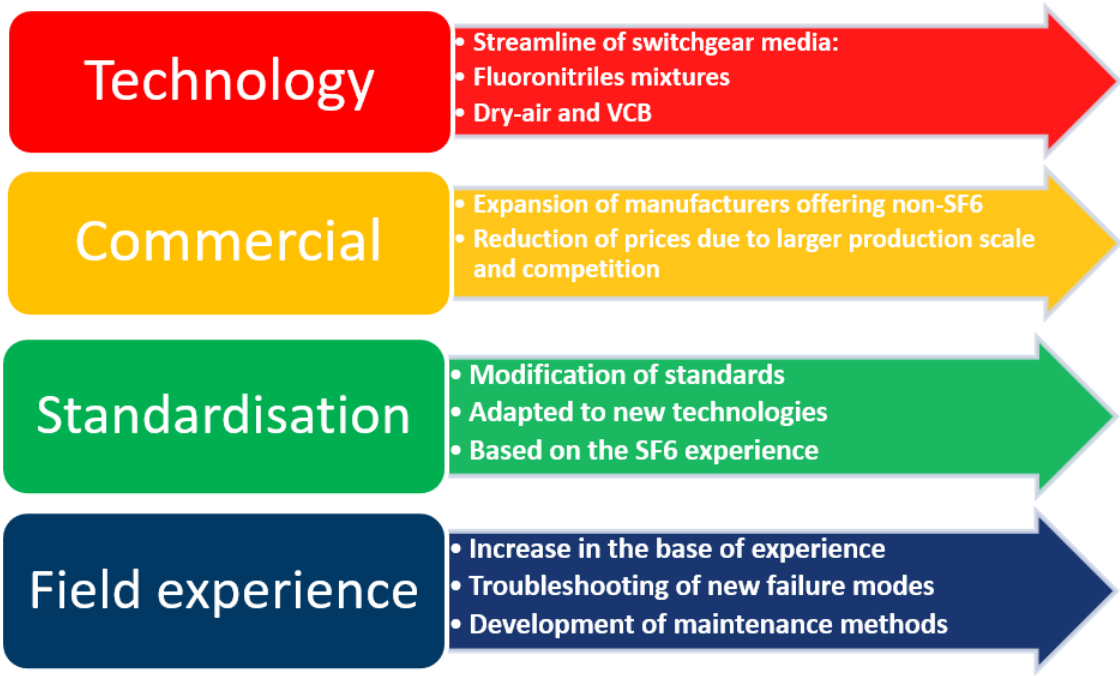

Figure 1. Confluence of the Driving Forces in the development of Non-SF6 HV switchgear

5 Strategies to implement non-SF6 switchgear

Considering all the issues previously discussed and realising that the advent of non-SF6 HV switchgear is a reality, the utility engineer is confronted to choose the best path and pace to implement it into their network with the main criteria being:

- Minimizing the risk
- Maintaining the level of reliability of the current SF6 switchgear installed
- Limiting the disruption to the network
- Leveraging of already optimised maintenance procedures gained with 50 years of SF6 experience

To comply with these requirements, the conclusion is that one cannot decide to select a specific make and model of non-SF6 HV switchgear and to exclusively install it in all new substations or for all important switchgear replacements. It is prudent to initially spread the risk and important “not to put all your eggs in one basket”.

Australian and New Zealand utilities face a greater risk when installing a new and unproven HV switchgear technology than European utilities because the HV switchgear manufacturers are in other continents and service and replacement of the equipment in case of failure usually involves longer delays.

The safest process would be the progressive implementation of non-SF6 HV switchgear. Initially with pilot trials in non-critical network locations and later in small scale refurbishment and capital projects.

It is important also to consider the technical and commercial evolution of non-SF6 options. It is expected a process of streamlining and consolidation of these alternatives will occur until only one or two options prevail and become commercially available.

Keeping abreast of these emerging technologies through technical forums such as CIGRE is essential in making the right choice over the implementation of non-SF6 switchgear.

The Australian and New Zealand SC A3 panel meets a couple of times per year and it is a perfect forum to exchange experience regarding new switchgear products.

While new SF6-free alternatives are still under development we need to reduce leakage of the existing SF6 insulated equipment. The SF6 equipment installed today will potentially leak over the next 40 years in service due to its aging, sealing system degradation and natural leakage.

We need to develop SF6 management strategy/action plans to reduce gas leakage including:

- Investigate key reasons for the SF6 leak.
- Develop SF6 leak detection flow charts for different HV equipment and highlight HV equipment design that contributes to SF6 leaks.
- Review equipment specification including improvement of equipment sealing system, reduction of SF6 point, better quality gauges, material selection and pressure relief devices as well as to improve SF6 gas monitoring system.
- Improve gas handling capability and equipment and training.
- On-line maintenance - addressing immediately potential SF6 gas leakage by repairing corrosion on SF6 gas pipes, flanges and pressure gauges and applying protective coatings on gas seals and bolts.
- SF6 gas disposal and reclamation.

6 Experiences with non-SF6 HV switchgear in Australia and New Zealand

6.1 Australian experience

An Australian distribution utility purchased and installed three 145kV vacuum dry-air live tank circuit breakers in 2022 for use at 132kV. These units are replacing three aging SF6 circuit switcher units in existing substations. As part of the procurement for the replacement project it was decided to assess the current market of 145kV live-tank circuit breakers in both SF6 and non-SF6 options. There was a motivation within the organisation to move away from SF6. The assessment in the use of non-SF6 circuit breakers was made, with factors such as having to purchase specialised non-SF6 gas handling equipment; knowledge of and long-term management of the gas mixtures used in the installed units, and direction of future non-SF6 gas mixture technology and would an orphaned non-SF6 gas technology result. The organisation's previous experience of using vacuum dry-air circuit breakers since 2012, albeit in 36kV and 72.5kV units, supported the choice of using vacuum dry-air circuit breakers as the technology for this procurement.

An Australia Transmission utility has commenced an SF6 alternatives trial project. The project has packaged the end-of-life replacement of 4 x 132kV circuit breakers (3 live head and 1 dead tank construction) and 6 x 66kV circuit breakers (3 live head and 3 dead tank construction) at a single substation for staged installation between 2023 and 2026.

The trial project will enable evaluation of implementation of at least 4 separate products. As the trial project will not be constrained to a single gas type, the installations may also provide further insight into the expected future challenge of operating multiple insulating gasses within the network.

Other key benefits of the trial implementation include:

- Accelerate Technology Risk Assessment process of non-SF6 market available equipment for general network applications.
- Perform specific technical evaluation of market available SF6 alternative switchgear against network location performance requirements.
- Determine project implementation costs to support effective cost benefit evaluation against SF6 switchgear replacement projects.
- Evaluate and confirm O&M lifecycle costs through asset procurement and in service lifecycle
- Support commercialising of SF6 alternatives through increasing customer demand and providing end user feedback to product developers.
- Review and implementation of SF6 alternative gas maintenance procedures, training, tools, materials, equipment and.
- Evaluate logistical challenges associated with operating multiple alternative gases.

6.2 New Zealand Experience with new design technology and moving to non-SF6 CBs

In 2011 Alstom engaged Transpower to conduct a trial on a new Dry air with vacuum interrupter 72.5kV, 2000 A kV livetank circuit breaker. It has proven to be reliable and is still in service, but it is an orphan as the 5-year trial period had seen Alstom head down a different technology path.

In 2012 Transpower moved to a new design/technology by adopting the 145 kV SF6 Disconnecting Circuit Breaker (DCB), currently with 98 in service and in 2019 started installing 245kV SF6 DCB's with 10 in service. During this period Transpower also procured the 145 kV SF6 Compact Switchgear Assembly (CSA) this consists of a Deadtank CB/CT with Disconnector/Earth switch on the bushing turret and option for VT.

In 2018/19 Transpower procured the first of 14 ABB/Hitachi CO_2+O_2 72.5kV, 2500A DCB Livetank Disconnecting Circuit breakers and a further four are being installed.

At present they are monitoring the progress of the 145 -245 kV alternate gas models as they become available.

Live tank circuit breakers using an insulating gas that has no global warming potential (e.g., a CO_2+O_2 mixture) appear to offer benefits compared to those using synthetic gas mixtures, including:

- The OEM has advised that no decomposition products are formed
- The gas can be vented directly to atmosphere (no requirement for gas recovery or processing)
- CO_2 and O_2 Gas is readily available
- There are no emissions reporting or ETS surrender obligations

Some trade-offs are that the gas filling pressure is much higher than for SF6 filled equipment, and this will require more robust sealing systems to avoid gas leaks that could lead to supply disruption.

Transpower has realised the importance of good change management and the process of adopting, procuring, installing, maintaining and final disposal has many challenges. Some of these aspects are summarised below.

Equipment selection:

- Apply existing knowledge of performance issues with outdoor SF6 CBs (e.g., sealing systems) to apply more robust design reviews and ongoing communications with manufacturers on the new generation non-SF6 equipment.
- Factory visits should be made to review the products prior to ordering.

Equipment ordering – trials:

- Trial orders should be considered. This needs to balance the risk of having orphans, the whole of life costs and technology obsolescence.
- Communicate with early adopters to get their operational feedback and foster sector intelligence i.e., continue dialogue with other Utilities as to their drivers for particular makes/models.

Spares/Inventory:

- Spares will need to be ordered to cover any new models and setup in inventory systems and linked to the respective new assets.

Tools and test equipment:

- Consider what new tools and test equipment be required for the non-SF6 solutions. The equipment required for different synthetic gasses is likely to be common.
- Suggested new equipment required is:

i. Filling kits, can you develop new ones based on existing SF6 kit, otherwise use standard DILO or OEM equipment.
ii. Leak detection, Transpower has procured a SF6/CO2 leak detector.
iii. Gas carts and gas testing devices (available from DILO or other suppliers)

Pressure Vessel Requirements:

- Do existing dispensations from regulatory authorities cover new technology given the increased operating pressures?

Service Specification (management) for non-SF6 gasses:

- Create an equivalent to existing SF6 management for non-SF6 gasses e.g. Transpower does not yet have a service specification for the current small fleet of CO2 CBs.
  The writing of this document will include a detailed review of published guidance in IEC/CIGRE etc.

Standard Maintenance Procedures (SMPs):

- New or modifications to existing SMP's are required for the new CB models and the new gas types.

Asset Management Systems:

- With new technology and models, they require new specification attributes, testing and condition meters to be setup.

Gas supply and cylinder management:

- New gas cylinders will be required for the new synthetic (lower GWP) gasses and empty refillable cylinders for use during maintenance.
- Establish gas sources and supply agreements for different gas types i.e., order via the equipment OEMs or direct with gas supplier(s)
- Need to establish how contaminated gas can be processed and destroyed (can air contamination be removed, where do you send badly contaminated gas for destruction)

- For the synthetic non-SF6 gasses being a blend of three components, do we need to establish how any air contamination can be dealt with.

Gas reporting:

- Will the alternate gas require reporting on usage if it does, changes will be required to SF6 reporting systems to enable the new gasses to be reported. This will include:

i. Modify the application to incorporate new gasses
ii. Modify the regulatory calculations to include different GWP for SF6 and the non-SF6 gasses

From the above the cost of this change should factor in deciding on what technology to adopt and when.

7 Conclusion

In the last eight years there has been an advent of several alternatives to SF6 for HV switchgear and fundamental operating design.
Everything indicates that SF6 will be replaced by a more environmentally friendlier media.
It is not yet clear what will be the predominant media and by when it will be universally adopted by the industry.
Utilities in Australia and New Zealand, as in the rest of the world, are facing serious challenges to implement these developing technologies, and at a time of significant network growth for the decarbonisation of the energy sector. The inherent risk that accompanies the installation of unproven HV switchgear into the network is increased by the uncertainty that the new product might become prematurely obsolete due to the current technological and commercial dynamics.
The safest strategy for utilities in Australia and New Zealand is to first investigate the available non-SF6 alternatives by utilising pilot trials and then progressively implement the new technology into the network. Keeping aware of the fast changes in the field through cooperation platforms such as CIGRE and continually reassessing available products of non-SF6 alternatives is imperative if utilities are to adequately manage the ongoing risk.

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