

## **NEXT GENERATION NETWORKS**

### **SF6 Alternatives**

**A Literature Review on SF6 Gas  
Alternatives for use on the  
Distribution Network**



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## Glossary

| Abbreviation    | Term   |
|-----------------|--|
| AIS             | Air Insulated Switchgear                       |
| AC              | Alternating Current                            |
| CO <sub>2</sub> | Carbon Dioxide                                 |
| CAS             | Chemical Abstracts Service                     |
| DNO             | Distribution Network Operator                  |
| DSO             | Distribution System Operator                   |
| EHV             | Extra High Voltage                             |
| GIL             | Gas Insulated Lines                            |
| GIS             | Gas Insulated Switchgear                       |
| GWP             | Global Warming Potential                       |
| GHG             | Greenhouse Gas                                 |
| HV              | High Voltage                                   |
| IEC             | International Electrotechnical Commission      |
| ISO             | International Organisation for Standardisation |
| kV              | Kilovolts                                      |
| LCA             | Life-cycle Assessment                          |
| MV              | Medium Voltage                                 |
| ODP             | Ozone Depletion                                |
| PPM             | Parts per Million                              |
| PFC             | Perfluorocarbon                                |
| PFN             | Perfluoronitrile                               |
| RMU             | Ring Main Unit                                 |
| RMS             | Root Mean Squared                              |
| SIS             | Solid Insulation Switchgear                    |
| SF <sub>6</sub> | Sulphur Hexafluoride                           |
| TRL             | Technology Readiness Level                     |
| TSO             | Transmission System Operator                   |
| WPD             | Western Power Distribution                     |

## 1 Executive Summary

This report summarises the available literature on SF<sub>6</sub> alternatives for the purposes of electrical insulation and arc-interruption in electrical switchgear.

SF<sub>6</sub> gas was historically used in a number of industries, including the Energy Industry, where it is commonly used to electrically insulate live equipment and quench the electrical arc generated within a circuit breaker during operation. SF<sub>6</sub> is widely used in high voltage electrical switchgear as it has a number of unique properties which make it almost perfect for this application; its high dielectric strength, self-healing and non-toxic properties are particularly useful in electrical switchgear.

In spite of its numerous advantages, SF<sub>6</sub> gas has been identified as a potent greenhouse gas and is estimated to be 23,900 times more harmful than CO<sub>2</sub> to the environment. Subsequently, regulations have been made in international policy to limit its emissions across a number of industries.

As a result, the Energy Industry has been actively seeking an alternative solution to ideally eliminate it from power network assets. Research has examined a multitude of different mediums; however it has been difficult to identify a suitable alternative which satisfies all the requirements. There are a number of candidates which have been successful in recent laboratory trials and these are currently being assessed in field tests.

From literature, there are a number of attractive alternatives to SF<sub>6</sub> including AirPlus (developed by 3M and ABB), g<sup>3</sup> (developed by 3M and GE), HFO1234zee and solid epoxy.

The identified possible interrupting alternatives to SF<sub>6</sub> are g<sup>3</sup> and vacuum interruption.

Pending engagement with manufacturers, it is anticipated that these mediums will be retro-fit into existing switchgear and tested to support possible integration into business as usual, on the basis of positive outcomes from laboratory tests.

## 2 Introduction

### 2.1 Overview

Sulphur Hexafluoride (SF<sub>6</sub>)<sup>1</sup> gas is widely used in high-voltage<sup>2</sup> (HV) switchgear as an insulating and current-breaking medium. SF<sub>6</sub> has excellent insulating and arc-quenching capabilities which deliver reliable performance in relatively compact designs<sup>3</sup>. It is therefore well suited to power system applications where equipment is often located in areas with a small available footprint such as densely-populated urban environments, offshore platforms or wind power installations [1].



Figure 2-1: 36kV Indoor MV Switchgear comparison (AIS on left, SF<sub>6</sub> on right) [1]

In recent years, SF<sub>6</sub> has been widely recognised as a potent global warming gas, or greenhouse gas (GHG), with a Global Warming Potential (GWP) of 23,900 [2] [3] over a 100 year time period and lifetime of 3,200 years [4].

As a result, SF<sub>6</sub> was included in the 1997 Kyoto Protocol [5] which has led to government taking action to reduce emissions and the consumption of SF<sub>6</sub> and specific regulations have now been put in place across industries. For the energy industry, this means that companies must operate and maintain SF<sub>6</sub> switchgear in a responsible manner. This includes managing switchgear on a closed cycle to avoid deliberate gas release into the atmosphere and monitoring any emissions during operation.

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<sup>1</sup> SF<sub>6</sub> will refer to the compound in its gaseous form, unless otherwise stated.

<sup>2</sup> >1kV

<sup>3</sup> In comparison to alternative mediums such as air or mineral oil.

In the UK, EC Regulation No. 517/2014 enforces regular monitoring of any emission from equipment that contains significant quantities of GWP gases; this includes bi-annual or quarterly checks depending on the installed gas mass. An amendment to this regulation was introduced that requires any equipment containing more than 22kg of SF<sub>6</sub> to have an automatic leak detection system fitted [6] [7]. The vast majority of installed switchgear contains quantities much lower than 22kg; however it is anticipated that these regulations will become more stringent in the future where SF<sub>6</sub> switchgear will require inbuilt leak detection technology.

The concerns over the environmental impact of SF<sub>6</sub>, as well as increasingly strict regulations, have led industry and academia to actively seek alternative solutions in an effort to eliminate the emissions of SF<sub>6</sub> gas from HV electrical equipment. In 2016/2017 alone, approximately 554kg of SF<sub>6</sub> gas was leaked into the atmosphere from electrical switchgear on the UK distribution system; the equivalent of burning over 6.2 million kilograms of coal [8]. UK Distribution Network Operators (DNOs) are very aware of the impact that the energy industry has by using SF<sub>6</sub> gas, and are proactively searching for an alternative solution which meets the network requirements and is environmentally sustainable. There has been progress in developing alternative mediums for use in electrical switchgear from a number of manufacturers which are at a differing technology readiness levels (TRLs) [9].

The SF<sub>6</sub> Alternatives project seeks to identify a viable substitute for SF<sub>6</sub> to be used in distribution switchgear. The project shall explore potential retrofit solutions as well as trialling new commercially available products.

The project will comprise of three main stages:

1. Identifying suitable alternative mediums from current literature;
2. Developing a methodology to test the findings on equipment procured from WPD's licence area; and
3. A comprehensive factory and field testing program to support integration into current practices.

The purpose of this report is to provide a comprehensive literature review of SF<sub>6</sub> alternatives and previous trials conducted to test or demonstrate their capabilities. It is anticipated that this approach will provide sufficient information to identify key mediums to be considered for testing within HV switchgear for insulation and arc interruption.

The report is structured as follows:

- A background to SF<sub>6</sub> switchgear and other existing technology is presented to provide context for the discussion regarding the alternative mediums;
- Each identified alternative medium is presented, including its properties, current TRL, and associate trials; and
- The commercially available SF<sub>6</sub> free electrical switchgears products are discussed.

It is also anticipated that the outcomes of these deliverables may contribute to a possible reduction in the volume of SF<sub>6</sub> required in switchgear yielding an environmental saving among other benefits. Furthermore, it is predicted that positive results and learning outcomes will also provide support to manufacturers and developers to continue to develop alternative solutions in a competitive environment.

### 3 Background

SF<sub>6</sub> has been used in a number of applications beyond the energy industry including electrical insulation in medical equipment (such as X-ray machines), laser etching, tracer compounds, insulating glazed windows, and die casting. The advantageous properties of this unique gas have led to widespread use across a number of industries.

However, with the introduction of regulation EU 517/2014 and its predecessors, the use of SF<sub>6</sub> has been banned in most industries, with remaining industries<sup>4</sup> being obligated to follow strict leakage monitoring procedures which is discussed further in Section 3.1. The energy industry is able to continue with the use SF<sub>6</sub> subject to strict compliance with the regulations.

#### 3.1 Environmental Concerns Regarding SF<sub>6</sub>

Greenhouse gases can be defined as atmospheric gases which absorb infrared radiation emitted from the earth and subsequently radiate it back to earth, rather than allowing it to escape into space. This absorption of infrared rays and re-radiating them back to earth contributes to an average increase in the earth surface temperature. This increase in temperature has been found to disrupt the current ecosystem, inflicting what is known as 'Climate change' or 'Global Warming' with effects such as glacial retreat, rising sea levels, and ocean acidification being seen across the world [10] [11] [12].

The stability of the SF<sub>6</sub> molecule means that it is a potent greenhouse gas as it is able to absorb infrared radiation and it is largely resilient to chemical or photochemical breakdown. It subsequently has an atmospheric lifespan of 3200 years [3] [13]. This lifespan effectively makes any atmospheric release irreversible. It is for this reason that SF<sub>6</sub> is so environmentally damaging.

In comparison to other greenhouse gases, the atmospheric concentration of SF<sub>6</sub> is extremely low. In 1993<sup>5</sup>, it was estimated that the contribution of SF<sub>6</sub> to non-natural global warming was between 0.01% and 0.07%. The main concern with SF<sub>6</sub> is that its long atmospheric life time means that even small excursions of SF<sub>6</sub> will have a cumulative and permanent environmental impact [14].

The impact of SF<sub>6</sub> on the trend of Global Warming can be quantified by Global Warming Potential (GWP); a comparative measure which evaluates the impact of a particular gas against CO<sub>2</sub>. Specifically, it compares how much radiation energy can be absorbed by 1 tonne of a gas, relative to 1 tonne of CO<sub>2</sub> over 100 years [15]. Table 3-1 shows the GWP that SF<sub>6</sub> possesses, relative to a selection of some of the main greenhouse gases used in industry; some of these gases have since been banned from industry as more environmentally alternatives have been sourced.

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<sup>4</sup> Where no suitable alternatives yet exist to replace SF<sub>6</sub>

<sup>5</sup> The 1990s were at the peak of emission levels, which current legislation uses as a benchmark for emission reductions.

Table 3-1: Greenhouse Gases Global Warming Potential [3]

| Gas                               | Common Source or Application   | GWP    |
|-----------------------------------|--|--------|
| Carbon Dioxide (CO <sub>2</sub> ) | Fire suppression, carbonated beverages, by-product of fossil fuel consumption                  | 1      |
| Methane (CH <sub>4</sub> )        | Consumed as fuel (also known as Natural Gas)   | 21     |
| HFC <sup>6</sup> -152a            | Refrigerant, aerosol spray propellant  | 140    |
| Nitrous Oxide (N <sub>2</sub> O)  | Known as 'Laughing Gases, pain relief in dental procedures, car performance, and preservative. | 310    |
| HFC-32                            | Refrigerant  | 650    |
| HFC-134a                          | Refrigerant, SF <sub>6</sub> Alternative in Magnesium melt protection                          | 1,300  |
| HFC-4310mee                       | Solvent for cleaning process   | 1,300  |
| HFC-125                           | Used as a fire suppression agent   | 2,800  |
| HFC-227ea                         | Used as a fire suppression agent   | 2,900  |
| HFC-143a                          | Refrigerant, aerosol spray propellant  | 3,800  |
| HFC-236fa                         | Used as a fire suppression agent, refrigerant  | 6,300  |
| CF <sub>4</sub>                   | Refrigerant, electronics fabrication   | 6,500  |
| C <sub>4</sub> F <sub>10</sub>    | Fire suppressant, ultrasonic contrast  | 7,000  |
| C <sub>2</sub> F <sub>6</sub>     | Semiconductor fabrication  | 9,200  |
| Fluoroform (HFC-23)               | Semiconductor fabrication, fire suppressant  | 11,700 |
| SF <sub>6</sub>                   | Electrical Switchgear  | 23,900 |

As can be seen from Table 3-1, SF<sub>6</sub> has an extremely high GWP of 23,900 [2] [3]. Subsequently, it was identified in the Kyoto protocol as a greenhouse gas, with measures being taken to eliminate atmospheric emissions and reduce its use in industry [4].

This has included EC Regulation No 517/2014 [27], which came into force in January 2015 with the aim of reducing fluorinated greenhouse gases (F-Gases), which includes SF<sub>6</sub>. The enforced policy hopes to see an 80% reduction in emissions from F-Gases by 2035 [16], which will be achieved through:

- Decreasing allowances for F-gas producers and importers to influence the amount of F-gases that can be placed on the market through;
- Bans on certain F-gases in particular applications; and
- Tightening obligations on leak checks, repairs, recovery, and training.

The aforementioned regulations have led to bans on using SF<sub>6</sub> in industries such as magnesium die-casting and others where suitable alternatives exist including refrigeration, air-conditioning and fire protection applications. However, applications where the use of alternative equipment i.e. equipment that does not contain SF<sub>6</sub> would comprise technical, safety or significantly inflate costs are subject to some exemptions [7]. Electrical switchgear is granted such an exemption due to the lack of commercially available alternatives that would not incur unreasonable compromise.

<sup>6</sup> HFC is an abbreviation for Hydrofluorocarbon

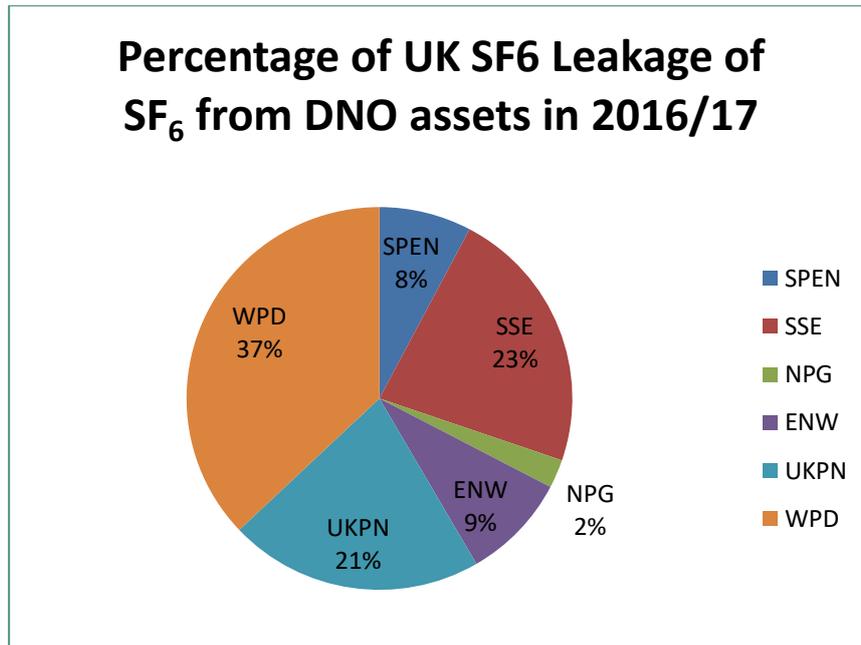


Figure 3-1: SF<sub>6</sub> leaked in 2016/17 from UK DNO Assets by DNO

Currently, UK DNOs are required to strictly monitor and report on the SF<sub>6</sub> mass leaked from distribution and transmission network assets. Figure 3-1 **Error! Reference source not found.** shows the distributed network asset SF<sub>6</sub> emissions for the year 2016/17, which are publically available through each DNOs RIIO-ED1 RIGs Environment and Innovation Commentary. The total mass leaked in this year was 554 kg.

By the 1<sup>st</sup> of July 2020, the European Commission will publish a report assessing the viability of replacing GHG gas medium-voltage switchgear. Until this time, SF<sub>6</sub> switchgear is subject to stringent leakage checks and monitoring of any GHG emissions.

This regulation was reviewed and amended in January 2017 to introduce further measures requiring leak detection systems to be fitted to any electrical switchgear containing 22kg of SF<sub>6</sub> or greater. The stipulation is that the equipment shall be routinely checked either bi-annually for switchgear containing more than 6kg, or quarterly if the mass is greater than 22kg of SF<sub>6</sub> [28].

It should be noted that SF<sub>6</sub> GWP alone is not adequate to measure the environmental impact of electric power equipment using SF<sub>6</sub> technology. The environmental impact of any specific application should be evaluated using the Life Cycle Assessment (LCA) approach, as regulated by ISO 14040:2006 – Life Cycle Assessment Principles and Framework [8]. Therefore, any proposed alternative should be assessed using the same measure for environmental impact.

The project will specifically focus upon Ring Main Units (RMUs). There is currently a high volume of SF<sub>6</sub> filled 11kV RMUs within most UK DNO networks which contribute to the SF<sub>6</sub> emissions from the DNO distribution assets. Therefore, the following sections and discussion will focus upon this type of switchgear.

### 3.2 The Utilisation of SF<sub>6</sub> in the Energy Industry

Of the 8000 tonnes of SF<sub>6</sub> produced annually, approximately 80% of this is consumed by the energy industry for use in switchgear. Switchgear is a broad term to cover a range of equipment which can switch and interrupt currents in an electrical power system during normal and abnormal (fault) conditions, for power system protection and control [17]. Typical examples of switchgear include circuit breakers, fuses, and isolators.

For the purposes of this report, only switchgear which uses SF<sub>6</sub> as an insulating or interrupting medium and are rated above 1kV will be discussed; hybrid technology such as SF<sub>6</sub> gas-insulating, vacuum-interrupting units are also included.

HV SF<sub>6</sub> switchgear is popular as it offers significant benefits in comparison to other switchgear types including [1]:

- High operational reliability;
- Less susceptible to environmental conditions;
- Reduced maintenance;
- Local personnel safety; and
- Reduced space requirements.

As discussed previously, the application of SF<sub>6</sub> to switchgear can have two distinct roles; to insulate the live components from earth and to interrupt the arc drawn upon opening circuit breaker contacts.

The main types of HV switchgear that use SF<sub>6</sub> either as an insulating or interrupting medium are:

- GIS (Gas Insulated Switchgear for high voltage in indoor and outdoor applications);
- Gas Insulated Transformers;
- Gas Insulated Substations; and
- Assemblies of HV devices and GIL (Gas insulated lines).

For the purposes of this report, only GIS have been discussed. Gas Insulated substations and GILs have been discussed in Appendix B: SF<sub>6</sub> applied in various gas-insulated electrical equipment as background information.

#### 3.2.1 SF<sub>6</sub> as an Insulating Medium

An electrical insulator prohibits electric current to flow through it, meaning the movement of internal electric charges is inhibited thus prohibiting current flow. This can be required in electrical equipment in order to control the current path and prevent harm to both personnel and network assets.

Typically in insulating materials or mediums, there will be an electrical limit to the insulating properties above which it will begin to degrade as a result of excessive voltage. This is known as the 'dielectric strength' of a medium, an important characteristic in electrical switchgear design.

Due to its molecular composition, SF<sub>6</sub> is extremely stable giving it a high dielectric strength. In comparison to other common insulating mediums SF<sub>6</sub> has approximately 2.5 times the dielectric strength of air at atmospheric pressure, and 5 times the density, making it a

superior insulating medium [18]. Furthermore, there is a proportional relationship between gas pressure and dielectric strength. At 3 kg/cm<sup>2</sup> (2.94 bar), SF<sub>6</sub> has a higher dielectric strength when compared with insulating oil. This high dielectric strength is advantageous in electrical equipment design as it allows more compact equipment design with smaller clearance gaps.

In addition, SF<sub>6</sub> possesses a volumetric specific heat (the ability to store heat internally before a phase change) which is 3.7 times greater than air, preventing heat being transferred to electrical equipment which in turn limits the potential damage caused through heat exposure [19].

In electrical utility applications, common electrical insulation mediums are air or SF<sub>6</sub>, with some legacy switchgear being mineral oil filled. However, this legacy equipment has inherent fire and explosion risks, in the event of failure, and are no longer favoured for use on the modern UK network. This is outlined in Figure 3-2.

Air insulated devices are typically large and sensitive to environmental conditions such as pollution or humidity, as examples [20]. Air insulated switchgear is available as a competitive product; however there would be issues in retro-fitting sites which currently use SF<sub>6</sub> as the medium due to the physical size difference and sensitivity.

In some cases hybrid solutions are developed, including vacuum-interrupting, solid insulation and vacuum-interrupting, SF<sub>6</sub>-insulating switchgear [21]. This alternative solution has been investigated as part of this literature review and is discussed in Section 4.2.3.

Overall, SF<sub>6</sub> is a superior insulator to current available mediums, such as air and oil, as it can provide compact switchgear solutions and has an unparalleled dielectric strength which allows it to be deployed more readily at Extra High Voltage (EHV).

### 3.2.2 SF<sub>6</sub> as an Interrupting Medium

When used as an interrupting medium, SF<sub>6</sub> is able to quickly quench the arc generated when the electrical contacts are separated.

SF<sub>6</sub> is an electronegative gas. This allows gas molecules to capture free electrons, produced by an arc event, and combine these with the existing gas molecules to produce large, heavy and slow moving ions. The absorption of the free moving electrons and low mobility of the combined ions further improves the dielectric strength of the gas, relative to air and other gases [22].

While SF<sub>6</sub> is thermally stable up to 500°C, the temperature at an arc-core can reach up to 20,000°C meaning SF<sub>6</sub> molecules will disassociate into multiple gasses. However, SF<sub>6</sub> is known as a 'self-healing' dielectric. As temperature falls the molecules will recombine enabling the dielectric strength to recover [23].

This ability to recombine after the arc, with very little gas being consumed during the process, is very valuable. Most of the stable by-products do not degrade the dielectric strength meaning no by-products leave conductive deposits and can be removed through filtering [10]. The time taken for this dielectric recovery is known as the 'Arc-Time constant' and for SF<sub>6</sub>, this happens within microseconds allowing multiple short –interval interruptions if necessary [19].

During disassociation the molecules absorb heat which is subsequently released as the molecules reform into SF<sub>6</sub> at the arc edge, thus transferring the heat very efficiently and cooling the gas [24]. During the arc extinction process, the gas is blown across the arc, removing the heat through both natural and forced convection. The high density and low viscosity further improves the efficiency of this process [25].

Further information on circuit breaker operation and interruption fault current can be found in Appendix A.

An interrupting medium is required in switching equipment designs to control and extinguish the arc as quickly as possible and then to ensure that the joining contacts are electrically isolated once the contacts are opened. Circuit breakers are one switching element type, designed to be able to interrupt fault currents as well as switch live circuits in and out of operation. This report specifically discusses circuit breakers when discussing SF<sub>6</sub> as an interrupting medium and vacuum interruption, as a known alternative.

### 3.2.3 Circuit Breakers

Over the 20<sup>th</sup> century, many different mediums have been employed to disperse an electrical arc; in addition, developments in circuit breaker design have played a significant role to improve interruption and heat dissipation. Figure 3-2 shows an approximate time line of the different mediums deployed in switchgear as an interrupting medium.

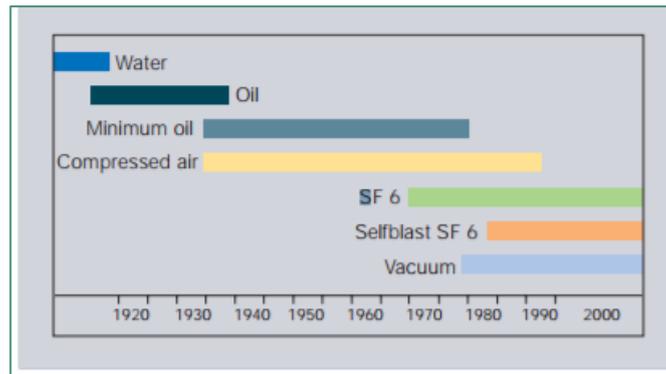


Figure 3-2: Circuit Breaker Interrupting Mediums over the 20th century [26]

Circuit breakers are designed to ‘break’ or ‘interrupt’ the circuit current flow; the purpose for this operation is to protect and control the transmission and distribution system in the event of a fault. This function is crucial to switch circuits into service, carry load, and take circuits out of service either through manual or automatic control.

A closed circuit breaker will carry electrical load, and an open breaker break electrical currents and will support other assets such as isolators to provide circuit isolation. Ideally, breakers will change between these operating conditions on an occasional basis, utilising their full capacity to interrupt short-circuit conditions on rare occasions [27]. Short-circuit interruptions are the most arduous for the circuit breaker due to the electrical and thermal stresses of breaking an electrical arc.

For the purposes of this report, circuit breakers have been distinguished by their interrupting medium in the following sections.

### 3.2.3.1 Sulphur Hexafluoride Circuit Breakers

SF<sub>6</sub> breaker designs were first successfully manufactured by Westinghouse in 1957. By the 1970’s, SF<sub>6</sub> HV switchgear was popular, with an increasing demand for gas leading to large scale production of SF<sub>6</sub> for this purpose. At this time, other industries were identifying other applications of SF<sub>6</sub> gas, supporting the large scale production.

Initial designs used a double pressure system, which was superseded in the 1970s by a single-pressure puffer type design. The double pressure type system worked on a very similar basis to the air blast design, modified to make a closed loop system for the exhaust gases. After the arc was quenched, gases in a low pressure reservoir were filtered, compressed and then stored in the high pressure reservoir for further use. Heaters were also fitted to ensure the gas did not become a liquid in low temperatures, which would make the medium unusable as an interrupter [23].

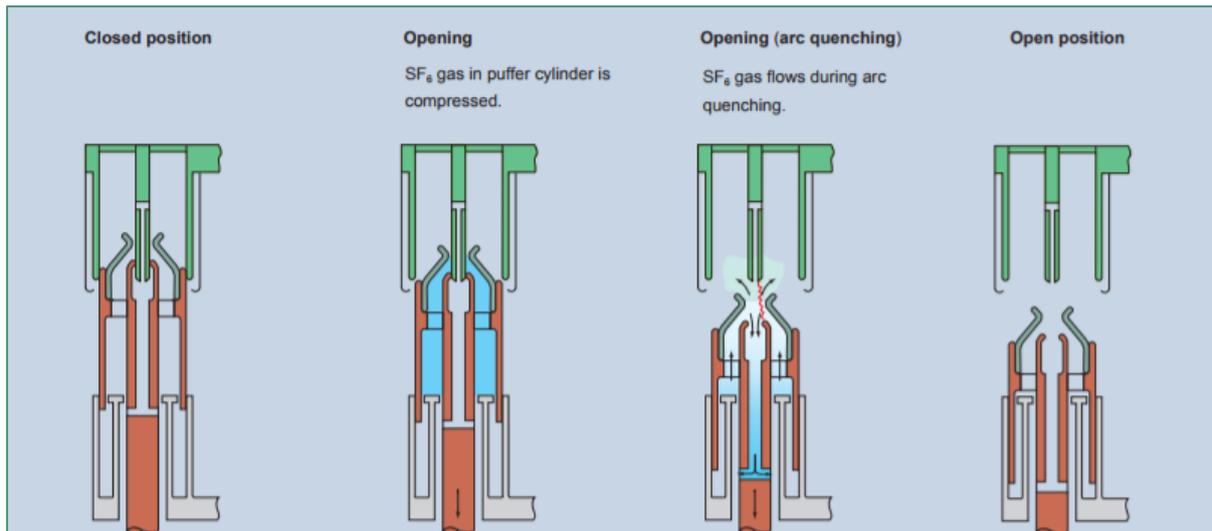


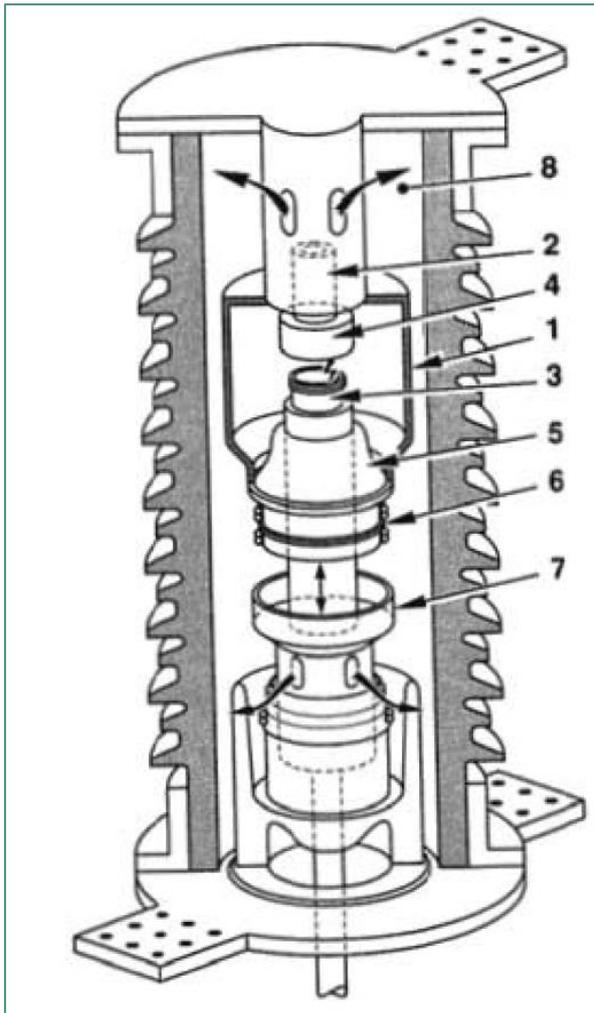
Figure 3-3: Single-Pressure Puffer Type Interrupter [28]

Single-pressure puffer type interrupters took advantage of the relative movement of the contacts to compress the SF<sub>6</sub>; the pressurised gas is then blown across the arc. This concept is demonstrated in Figure 3-3, with the gas flow being blown axially across the arc. Axial flow is regarded in literature as the most efficient method of arc-quenching through the turbulence created by the gas flow. Relative to the double pressure design, axial flow reduces the energy consumed by the device during operation to clear the arc.

This configuration is also known as a 'Self-Blast' type breaker as the operation is achieved without external gas compressors. However, there is a distinction between 'Puffer' and 'Self-Blast' breakers. In puffer type configurations, the gas is compressed mechanically whereas self-blast mechanisms use the heat generated from the arc to increase the gas pressure [29]. In self-blast circuit breakers, an arc is drawn across the contacts inside the interruption chamber and the gas is released into the arc's presence as the moving contact is removed from the arcing chamber.

Improved designs can use a puffer assist, to enhance the interruption capabilities, or a magnetic coil, to rotate the arc around the gas which provides additional cooling. A coil also improves the arc contact lifetime by reducing the rate of mechanical erosion [29].

SF<sub>6</sub> switchgear is typically designed as 'sealed pressure system' for medium voltages (<52kV), which are sealed for life and thus unopened during service lifetime. For voltages exceeding 52kV, 'closed pressure systems' are used and losses due to leakages are replenished and equipment is opened during periodic maintenance.



1. Expansion Cylinder
2. Fixed Arcing Contact
3. Moving Arcing Contact
4. Coil
5. Insulating Spacer
6. Fixed main contact
7. Moving main contact
8. Exhaust volume

Figure 3-4: 'Self-Blast' Circuit Breaker Outline [29]

Due to the circuit breaker mechanisms used in SF<sub>6</sub> switchgear, there will always be a source of SF<sub>6</sub> leakage regardless of the arc-quenching method used.

The concern surrounding SF<sub>6</sub> leakage is the driver for the current regulation which stipulates that switchgear containing significant volumes of SF<sub>6</sub> must be monitored and leakage rates must be reported. Recently, improvements in designs have seen leakage rates which are less than 0.1% per year. However, older units are currently still deployed in the field which have higher leakage rates.

### 3.2.3.2 Vacuum Circuit Breakers

Vacuum interrupters work differently to other interrupters as the arc is diffused, as opposed to the surrounding medium absorbing the energy.

The arc is sustained by the electrons and ions emitted from the circuit breaker contacts as ionised metal vapour, therefore to interrupt the current (at current zero) if the ions and electron emission can be stopped quickly enough, the electrons in the contact gap are removed. Metal vapour condensing shields may be used to support the removal of ions within the contact gap.

In essence, the interruption process is dependent on preventing an arc column and electrode spots being formed; the cathode surface normally has many micro-projections as opposed to being a perfectly smooth surface. When the contacts separate, the current will collect at these raised points as they are the last points of contact between the cathode and anode [23] [17].

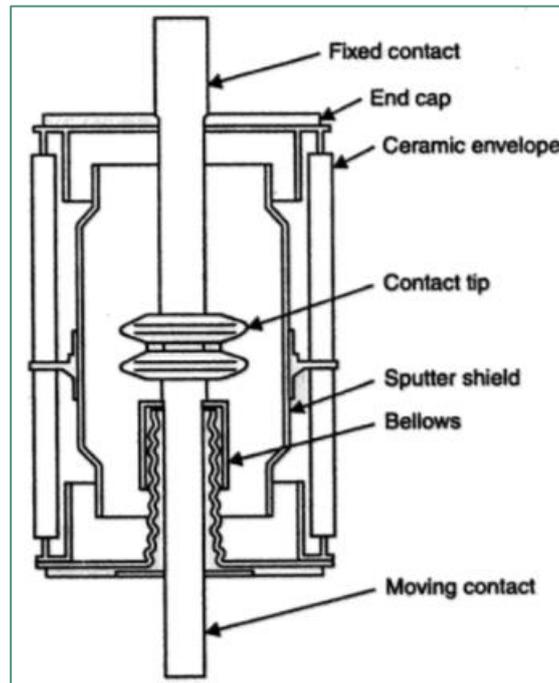


Figure 3-5: Vacuum circuit breaker cross-section [11]

Vacuum contacts are typically designed to manipulate the magnetic field from the current flowing through the contact or a magnetic coil to support the arc disruption. An example of this design is Figure 3-6, where the grooves and material composition are designed to interrupt the arc as efficiently as possible. Another design component is to rotate the anode and cathode contacts in order to lengthen the arc and allow it to be interrupted more efficiently.

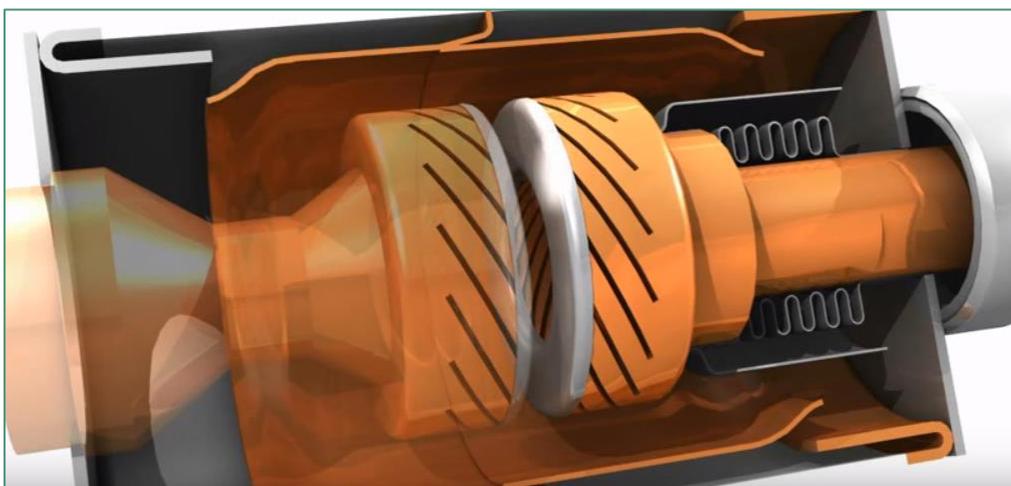


Figure 3-6: Vacuum Circuit Breaker Contact Illustration [30]

The capabilities of vacuum interrupters depend on contact size and material. While vacuum technology is deployed at lower voltage levels, as the voltage rating increases, this creates significant technical and economic demands on the switchgear design. Current designs can interrupt for rated voltages up to approximately 72.5kV with new designs extending this to 145kV [31]. Due to the significant energy required to operate the breaking mechanisms, extending the voltage operating range beyond this may require multi-break systems.

While the interrupting technology does not provide a clear indication of the physical size difference between SF<sub>6</sub> and vacuum switchgear, the insulation requirements for higher voltages and multi-break designs will be significant and may impact the overall dimensions of such switchgear.

### **3.2.4 Further SF<sub>6</sub> Properties**

Other properties of SF<sub>6</sub> are that it is non-flammable, non-explosive, colourless, odourless, and non-toxic [10] [32]. These properties are important when considering other mediums used in the energy industry, such as oil circuit breakers which have an inherent risk of flammability and explosion. However, whilst SF<sub>6</sub> is non-toxic, it does not support life and can cause suffocation [33].

SF<sub>6</sub> is chemically inert and will not react with metallic components or contacts. Such components will not get oxidized or corroded as a result, meaning there is reduced equipment maintenance.

### **3.2.5 Summary of Key Properties**

The key benefits of using SF<sub>6</sub> gas within utility applications are described in Table 3-2. In addition, SF<sub>6</sub> is well-established with wide market availability which is also easy to handle by site personnel during maintenance.

From Table 3-2, it can be shown that any alternative has multiple characteristics to fulfil in order to provide an uncompromised alternative gas which can deliver the same benefits as SF<sub>6</sub>. Section 4 presents the alternative mediums identified in literature and outlines where they meet or fall short of the given characteristics.

Table 3-2: SF<sub>6</sub> key properties for utility applications

| Key Benefits of using SF <sub>6</sub> as an Electrical Insulator | Key Benefits of using SF <sub>6</sub> as an Electrical Interrupter |
|--|--|
| High Dielectric Strength   | Electronegative gas  |
| High Thermal Stability   | High Thermal Stability   |
| High Density   | 'Self-Healing' Gas   |
| Low Heat Transfer  | Negligible interruption by-products                                |
| Non-Toxic  | Non-Flammable  |
| Chemically Inert   | Non-Toxic  |
| Reduced switchgear footprint                                     | Chemically Inert   |
|  | Fast arc-quenching   |
|  | Low Arc Time Constant  |

### 3.3 Policy & Standards

#### Environmental Policy

As discussed previously, EC Regulation No 517/2014 [27], which came into force in January 2015, has the aim of reducing fluorinated greenhouse gases (F-Gases), which includes SF<sub>6</sub>. The enforced policy hopes to see an 80% reduction in emissions from F-Gases by 2035. This long term aim indicates that there could be more stringent policy or amendments in the future which will impose more restrictions on the use and emissions of SF<sub>6</sub>.

#### Switchgear Testing Policy

Given that a number of alternative mediums to SF<sub>6</sub> are still in their developmental phase, there is no standardised material for implementation, operation and testing of these technologies. The best course of action may be to use any available SF<sub>6</sub> standards and apply them as appropriate; this includes the IEC 62271 family of standards.

#### Switchgear Maintenance Policy

Several policies exist which guide the user in all stages of using SF<sub>6</sub> for electrical switchgear. This includes procuring, transporting, handling, maintaining, 'topping-up', and disposing (or re-using) of SF<sub>6</sub> and switchgear.

The applicable standards have been tabulated in Table 3-3.

Table 3-3: Applicable Technical Standards for working with SF<sub>6</sub> gas

| Reference                         | Standard  |
|-----------------------------------|---|
| ENA ER G69                        | Guidance on working with Sulphur Hexafluoride   |
| ENA ER S38                        | Reporting of SF <sub>6</sub> Banks, Emissions and Recoveries  |
| IEC 62271                         | High voltage switchgear and control gear. (The family of standards will be useful, specifically Part 303:Use and handling of Sulphur Hexafluoride (SF <sub>6</sub> )) |
| BS EN 60376:2005                  | Specification of technical grade Sulphur hexafluoride (SF <sub>6</sub> ) for use in electrical equipment  |
| CIGRE Technical Brochure 234:2003 | SF <sub>6</sub> Recycling Guide   |
| CIGRE Technical Brochure 276:2005 | Practical SF <sub>6</sub> handling instructions   |
| CIGRE Technical Brochure 430:2010 | SF <sub>6</sub> tightness guide   |
| BS EN 60480:2004                  | Guidelines for the checking and treatment of sulphur hexafluoride (SF <sub>6</sub> ) taken from electrical equipment and specification for its re-use                 |

### 3.4 SF<sub>6</sub> Switchgear Monitoring, Maintenance and Hazards

#### 3.4.1 Monitoring and Maintaining SF<sub>6</sub> Switchgear

SF<sub>6</sub> is monitored to ensure the gas is at a sufficient pressure in order to maintain the dielectric strength needed to provide electrical clearance. Furthermore, the amount of SF<sub>6</sub> leaked to atmosphere must be monitored and recorded.

There are two main methods in order to detect gas leakage from equipment:

1. Taking separate readings for gas and temperature; and
2. Measuring gas density through natural frequency readings using a true-gas density monitor.

As environmental temperature will impact readings, both of the above methods seek to remove the impact of temperature on measurements.

Furthermore, SF<sub>6</sub> insulated switchgear can have a number of different alarms and sensors:

- Pressure gauge with high and low pressure alarms configured;
- Gas density sensor; and
- Moisture detection.

Typically SF<sub>6</sub> switchgear will have pressure or density gauges fitted to the insulated compartments. There will typically be a value for minimum operating pressure, at below which the operating functionality of the circuit breaker is compromised; some devices may trip and 'lock-out' if the pressure falls below this value. In distribution systems, SF<sub>6</sub> and GIS is operated at relatively low pressures; between 0.1 bar and 0.9 bar.

Some equipment may also have a high pressure alarm, indicating a rise in pressure. This may occur if the seal between adjacent compartments has failed and the compartments operate at different pressures. Furthermore, additional SF<sub>6</sub> density sensors can be placed within the enclosed compound to monitor the amount of gas present in the local

compartment. To ensure the quality of the SF<sub>6</sub> is satisfactory, there is typically a compressor which can provide a gas sample to be assessed.

Moisture is also a primary issue in SF<sub>6</sub> switchgear in the event of toxic by-products being released; some solid compounds can become more hazardous when it comes into contact with moisture. GIS designs will typically design moisture removal into the products, but these schemes will have a limit and so moisture detection equipment and alarms can be used to warn operators of a possible break in the seal.

Some switchgear can be topped up with additional SF<sub>6</sub> in closed pressure systems, if the internal pressure has been identified as lower than the rated pressure. The medium is usually delivered as a liquid at a low temperature. Topping up is only carried out by trained specialist personnel due to the risks of spilling, overfilling, and adjusting the amount of gas required based upon the gas temperature and the local atmospheric temperature. Overfilling can result in rupturing the equipment and causing a complete release of gas.

### 3.4.2 Hazards

Heavy duty switching operations can generate harmful by-products from decomposition. During typical sealed operation, these by-products will recombine into SF<sub>6</sub>. However, during arcs or in the event of switchgear failure, SF<sub>6</sub> and its by-products can be released into the environment.

SF<sub>6</sub> by-products can be produced due to partial discharge from insulation defects, switching arcs, sparks during switching operations or failure arc. Different by-products are formed through different electrical discharges.

While SF<sub>6</sub> in its pure form is non-toxic, it does not support life and can therefore become a breathing hazard if it has collected. As it is heavier than air, it can typically collect close to the ground, in cable trenches or drainage systems, for example. Therefore, site personnel are instructed to take care in such environments [2] [33]. Handling procedures have been developed to advise how to remove solid by-products and dispose them responsibly.

Gaseous by-products can affect the purity of SF<sub>6</sub> gas (which must comply with IEC 60736), which will also impact any handling of used SF<sub>6</sub>, as the mixture can have toxic effects.

Exposure to solid by-products, if inhaled, include irritation to exposed skin and eyes, the nose, throat, and lungs; further symptoms can occur if sufficient volume reaches the gastrointestinal tract [34]. The key by-products of SF<sub>6</sub> are listed in Table 3-4, prioritised based upon toxicity and risk.

Table 3-4: SF<sub>6</sub> Gas and By-product hazard description [34]

| Chemical Formula                                  | Chemical Name                            | Permissible Exposure Limit (over 1 working day) (ppm) <sup>7</sup> | Experimental Concentration (percent by volume)** |
|---|--|--|--|
| HF  | Hydrogen fluoride                        | 1.8ppm [35]  | 1  |
| SOF <sub>2</sub> (SF <sub>4</sub> ) <sup>8</sup>  | Thionyl sulphide (sulphur tetrafluoride) | 0.1 ppm [36]   | 0.5  |
| SOF <sub>4</sub>                                  | Sulphur tetrafluoride oxide              | 0.1 ppm [36]   | 0.085  |
| SiF <sub>4</sub>                                  | Silicon tetrafluoride                    | 0.5 ppm [37]   | 0.085  |
| S <sub>2</sub> F <sub>10</sub> (SF <sub>5</sub> ) | Disulphur decafluoride                   | 0.01 ppm [36]  | 0.025  |
| SO <sub>2</sub> F <sub>2</sub>                    | Sulphuryl fluoride                       | 5ppm [35]  | 0.006  |
| SO <sub>2</sub>                                   | Sulphur dioxide                          | 2ppm [35]  | 0.002  |

Furthermore, additional by-products can be formed as a result of electrical discharge or arcing; these include SF<sub>2</sub>, SOF<sub>10</sub>, S<sub>2</sub>O<sub>2</sub>F<sub>10</sub>, and H<sub>2</sub>S. In addition, some metal fluorides compounds can form including copper fluoride (CuF<sub>2</sub>), aluminium fluoride (AlF<sub>3</sub>) and tungsten compounds (such as WF<sub>6</sub> and WO<sub>3</sub>) [34].

Of these by-products, S<sub>2</sub>F<sub>10</sub> is recognised as having a relatively high toxicity and is recognised as causing the greatest concern for personnel safety.

The products can be found in two forms; as gases or as a solid power. Specific guidance is given on how to recognise the presence of such product through:

1. A strong 'rotten egg' odour at low concentrations;
2. Eye, nose, throat, and lung irritation at high concentrations; and
3. Presence of residue powders (white, tan, or grey).

However, such indicators are not recommended to be used as precautionary safety method as S<sub>2</sub>F<sub>10</sub> is odourless in a pure form.

Engineering recommendation G69 provides clear advice on how to mitigate risks and hazards when working with SF<sub>6</sub> switchgear.

The investigation of any alternatives should look beyond the technical characteristics and ensure that it is assessed holistically. Paper 0819 from CIRED 2017 has presented the key variables outside technical capabilities which impact the viability of a compound being used as an SF<sub>6</sub> alternative for switchgear. These factors included safety, reliability, long term stability, environmental impact and health. The summary of their output can be seen in Figure 3-7 [38].

<sup>7</sup> PPM stands for parts per million. This can also be expressed as milligrams per litre (mg/l)

<sup>8</sup> SF<sub>4</sub> is readily hydrolysed (broken down by chemical reaction with water) to SOF<sub>2</sub>

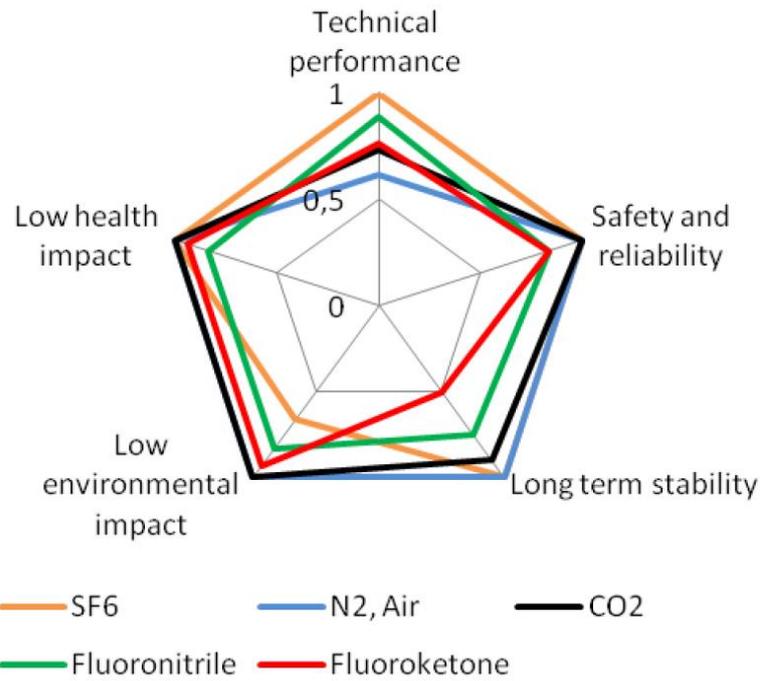


Figure 3-7: Outcome of holistic assessment of SF6 alternative mediums [38]

## 4 SF<sub>6</sub> Alternatives

### 4.1 Requirements

Whilst the environmental impact of SF<sub>6</sub> has been known and quantified for decades, there has been significant difficulty in finding an alternative medium which not only matches the technical performance of SF<sub>6</sub>, but also can provide the same compact solution to serve current applications.

Any potential alternative must have a low GWP and also be compliant with the strict criteria that current switchgear must meet [21] [39]. These specifications include:

- High dielectric strength;
- High heat dissipation;
- Low boiling point;
- Low toxicity;
- Fast arc-quenching capability;
- No Ozone Depletion (ODP);
- Non-flammability;
- Compatible with switchgear materials (Non-Corrosive);
- Chemically inert;
- Similar footprint to SF<sub>6</sub> units;
- High stability;
- Market availability; and
- Easy to handle during maintenance work.

Some of these properties have been expanded to explain why it is necessary to include these in the technical requirements for a SF<sub>6</sub> alternative:

#### 4.1.1 Low boiling point

To avoid condensing within typical temperature ranges, any interrupting alternative should have a suitable boiling point; this will ensure the medium remains gaseous. SF<sub>6</sub> has a boiling point of -63.8°C [32]. Manufacturers note that their customers require a minimum operating temperature of between -15°C and -25°C [40].

#### 4.1.2 No Ozone Depletion (ODP)

While SF<sub>6</sub> currently only impacts the environment by being a GHG, any alternative must not increase the overall environmental impact. This includes ozone depletion and global warming.

#### 4.1.3 Compatible with switchgear materials (Non-Corrosive)

Any alternative shall not corrode the switchgear unit thereby diminishing its serviceable lifetime beyond that of currently deployed units.

#### 4.1.4 Similar footprint to SF<sub>6</sub> units

From a DNOs perspective, increasing the footprint of GIS would result in other issues such as renting or purchasing new land. In urban areas, where land prices are at a premium, this

can result in a significant proportion of the total capital expenditure; if physical size was not a constraint then AIS or CO<sub>2</sub> breakers could be an acceptable solution.

#### **4.1.5 Market availability**

Ideally, the alternative medium would be widely available from multiple sources to facilitate market competition. Furthermore, the cost to transport the medium shall not be excessive.

#### **4.1.6 Easy to handle during maintenance work**

The medium should have minimal toxicity, to the degree where it can be handled safely and short-term exposure is not harmful. SF<sub>6</sub> by-products are known to be harmful to varying degrees; however there are a number of policies indicated in Section 3.3 to support maintenance workers in identifying and protecting themselves from these compounds.

The gas should have a method of safely transporting and maintaining filled switchgear. If the switchgear requires 'topping up' this shall be stated by the manufacturer in their product manual.

Thousands of gas compositions have been researched and tested using computation screening [41]; however it has been difficult to identify substitutes which possess all of the above mentioned characteristics in the current equipment configuration.

Prior holistic research has also been made on key alternative mediums investigating areas such as toxicity, tightness, medium compatibility, flammability and GWP. The outcomes of the study noted that no medium fully met all of the criteria, with some producing very toxic by-products, others having strong reactions with other materials, and others being flammable [40].

The available literature regarding the possible alternatives to SF<sub>6</sub> is not as comprehensive as the data detailing SF<sub>6</sub> characteristics. Industry recognises that such investigations are still early and further work is required [42].

## **4.2 Insulating Alternatives**

The solutions presented in this discussion have been previously assessed as only suitable for insulation purposes as they have been found to have poor arc-quenching capabilities.

### **4.2.1 Past Solutions & Investigations**

#### **4.2.1.1 SF<sub>6</sub>/N<sub>2</sub> mixtures**

Initial work to reduce the SF<sub>6</sub> volume within switchgear was to mix pure Nitrogen (N<sub>2</sub>) [43] or Carbon Dioxide (CO<sub>2</sub>) [44].

Mixtures containing N<sub>2</sub> have already been in use within GIL, where large gas volumes are required. It was found that a mixture of N<sub>2</sub> with 10-20% of SF<sub>6</sub> showed a significant improvement in dielectric strength, however, the volume of SF<sub>6</sub> meant the mixture still possessed a high GWP.

In previous case studies, it was found that a mixture of SF<sub>6</sub> and N<sub>2</sub> in a 10/90 volume ratio yielded a dielectric strength of 59% , relative to pure SF<sub>6</sub>, but the GWP is 8650 (38% of pure SF<sub>6</sub>). This GWP is still relatively high in comparison to the greenhouse gases outlined in Table 3-1 and therefore cannot be said to have a low environmental impact [21]. Also, such

mixtures require a higher pressure to match the dielectric strength of SF<sub>6</sub> and can still potentially emit SF<sub>6</sub> to the atmosphere. The conclusion to the use of such mixtures was that they could serve as an intermediate step in the process to identify an alternative which would eliminate the contribution of SF<sub>6</sub> [43] [45], but not as a true alternative due to multiple compromises.

#### 4.2.1.2 Fluorinated Gases

Fluorinated gases were identified in the early stages of the search for a SF<sub>6</sub> alternative due to the high dielectric strength associated with such compounds. Initial concerns arose concerning the high boiling points; it is typical for pure gases to scale dielectric strength with boiling point. This is an issue for deploying such gases in switchgear; however the conventional solution is to reduce the boiling point by introducing a buffer gas [39].

Initial investigations into alternative gases are typically assessed against basic criteria including toxicity, corrosivity, flammability, low GWP, and low ODP. From the initial assessment of available gases, gases from the following families were concluded to have the greatest potential:

- **Hydrofluoroolefins (HFO1234ze and HFO1234yf);**
  - Testing showed that these compounds had a low GWP (less than 10) and a dielectric strength 80% of SF<sub>6</sub>, but were deemed unsuitable for switchgear applications due to their flammability and that they would leave carbon residue during gas decomposition [46].
- **Fluoroketones (including C<sub>5</sub>FK and C<sub>6</sub>FK);**
  - Multiple compounds have been tested specifically for HV GIS applications. Studies have shown greater dielectric strength and low GWP when compared to SF<sub>6</sub>. However, the products have high boiling points and would require mixing with buffer products to maintain a gaseous state at operating temperatures [21]. Moreover, some products had high toxicity and vapour pressure which created an industrial handling hazard and were rejected.
- **Fluoronitriles (iC<sub>4</sub>F<sub>7</sub>N);**
  - Studies have shown promising results, with a high dielectric strength (approximately twice that of SF<sub>6</sub>), a reduced GWP of 2300, and a low boiling point. It has been developed into compounds which are currently being tested in multiple field trials.
- **Perfluorocarbons;**
  - While research into perfluorocarbons (PFCs) showed promising dielectric strength, the overall GWP was still in the range of 5000 – 12000. Table 4-1 outlines the dielectric strength and GWP of a selection of PFCs [21].
- **Fluorooxiranes;**
  - This family was found to have some compounds which responded similarly to fluoroketones. However, the molecular composition is different which results in a more stable compound under solar radiation (with a lifetime of 38 years and a subsequent GWP of 4100).
  - Studies focused on C<sub>4</sub>F<sub>8</sub>O, due to its low boiling point (0°C), low toxicity, and superior dielectric strength (relative to SF<sub>6</sub>), however the conclusions were the GWP was too high compared to the technical benefits.

Fluoroethers and Hydrochlorofluoroolefins have also been investigated. Some of these gases were also being utilised as replacement gases for refrigeration and fire suppressant applications; these were other industries which had previously been using mediums with a high GWP or ODP, and subsequently had to find alternatives to comply with government regulations however the gases were not determined as suitable alternatives for the energy industry for various reasons [40].

Table 4-1: PFC relative dielectric strength (when compared to SF<sub>6</sub>) [21]

| PFC                            | Dielectric Strength (% of SF <sub>6</sub> ) | GWP   |
|--------------------------------|---|-------|
| CF <sub>4</sub>                | 40%   | 7390  |
| C <sub>3</sub> F <sub>8</sub>  | 88%   | 8830  |
| C <sub>4</sub> F <sub>10</sub> | 120%-130%                                   | 8860  |
| C <sub>4</sub> F <sub>8</sub>  | 125%  | 10300 |
| C <sub>2</sub> F <sub>6</sub>  | 78%   | 12200 |

Two key chemicals have shown great benefits in multiple testing stages; fluoroketones and fluoronitriles. 3M has recently produced mediums specifically designed to replace SF<sub>6</sub> within the energy industry [47] as both an insulator and interrupter. These products are two dielectric fluids, Novec 5110 (a fluoroketone) [48] and Novec 4710 (a fluoronitrile) [49]. As both are fluids at typical operating temperatures, they must be vaporised and mixed with other gases (typically air or CO<sub>2</sub>) to produce a gas which can be used within switchgear. This is discussed in further detail in Section 5 of this report.

#### 4.2.1.3 Other Investigations

Cyanoketene (OCCHCN) has been theoretically studied as a potential alternative insulation gas for SF<sub>6</sub>, using computational methods. Furthermore, the paper has identified different criterion for identifying alternative solutions for SF<sub>6</sub> [50]. However, there as yet is no evidence of the gas being tested to confirm the findings from the report. Therefore the TRL of this gas, for the application as an insulation medium within switchgear, can be estimated as 1 based on available literature and is too low for the purposes of this project.

Previously, in 2010, Honeywell submitted a US patent for gaseous dielectrics with low global warming potentials, low boiling points and reasonable toxicity levels which registered numerous gases as having the potential characteristics to be used as an insulation medium in electrical equipment. This included Hydrofluorocarbons such as HFC-134a as detailed in Table 3-1 [46]. However, no literature has suggested that further work has been undertaken to produce an alternative medium to SF<sub>6</sub> for switchgear applications on the basis of this patent.

### 4.2.2 Solutions under Investigation

#### 4.2.2.1 HFO1234zee

HFO1234zee, a hydrofluoroolefin, was presented at CIRED 2017 as a possible SF<sub>6</sub> alternative for MV switchgear as an insulation medium.

Paper 0389 [51] presents the findings from the investigations into multiple technical characteristics required for this application with the conclusion that, based on these outcomes, HFO1234zee is a feasible alternative to SF<sub>6</sub> for electrically insulating MV

switchgear. Having said this, additional testing may be required to bring it to a similar TRL to the other alternatives proposed.

It has been noted that the medium is not suitable for current interruption due to its flammability however it has been recommended to be used with a vacuum interrupter to present an SF<sub>6</sub> free solution.

#### **4.2.2.2 Synthetic Air**

While previous sections in this report have outlined why SF<sub>6</sub> is a superior insulating medium in comparison to air, Nuventura, a newly established company in Germany, have recently put forward a design concept which uses synthetic air alone as the electrical insulator without compromising the compactness of the design. This product is discussed further in Section 6.

### **4.2.3 Commercially Available Solutions**

#### **4.2.3.1 Solid Insulation Switchgear (SIS)**

Manufacturers and developers have investigated other routes to identify alternative mediums; companies such as Eaton [52], Meiden [53], Hitachi [54], Schneider [55], Toshiba [56], and others [57] have investigated or developed solid-insulation, vacuum-interrupting solutions which are capable of interrupting currents up to 145kV.

These designs have the live equipment moulded with epoxy resin and then covered with an earthed conductive layer. It presents advantages over AIS by protecting the equipment from environmental damage or third party interference. Manufacturers present this technology as possessing high reliability and reduced routine maintenance requirements. Furthermore, the design reduces the risk of a phase to phase fault.

Proposals have also been submitted for the use of hybrid insulation GIL systems combining gaseous insulation using dry air, N<sub>2</sub>, or CO<sub>2</sub> together with solid insulation. As an example, the solid insulation can cover the live parts in a resin of epoxy or analogous type, providing a steep electric gradient thus reducing the electric field around the live equipment with a gas providing the insulation between the epoxy and the sheath.

However, the insulation from these sources may not be equivalent to that provided by SF<sub>6</sub>, and such technology may require an increased physical footprint compared to that made possible when using SF<sub>6</sub> insulation. Therefore, any technology being evaluated to replace existing SF<sub>6</sub> assets should carefully assess this criterion.

#### 4.2.3.2 Fluoroketones

Novec 5110 (CF<sub>3</sub>C(O)CF(CF<sub>3</sub>)) has been developed as an alternative to SF<sub>6</sub> gas, intended for use as an insulating medium with:

- A GWP of less than 1;
- A boiling point of 26.9°C;
- A dielectric strength 1.4 times greater than SF<sub>6</sub>;
- Non-flammable; and
- Non ODP.

In addition, the manufacturer notes that it is compatible with a wide range of equipment components. It is noted that there can be issues in components found in lubricating greases and elastomers used in gaskets and O-rings. However, the boiling point is too high for operating as a pure gas and requires mixing.

ABB have collaborated with 3M to produce a gas mixture branded '*AirPlus*' which is a mixture of Novec 5110 and dry air. This product has been made commercially available within a specific product portfolio including indoor HV RMUs. These have been in field testing since November 2015 and have provided consistent results with the behaviour expected from previous work [58].

The technical specification has been summarised in Section 5.1.

### 4.3 Interrupting Alternatives

The solutions detailed in this section have both the capability to insulate switchgear and interrupt fault current.

#### 4.3.1 Past Investigations

Previously, proposals have been made to replace SF<sub>6</sub> with trifluoroiodomethane (CF<sub>3</sub>I) [59]. The superior dielectric strength of CF<sub>3</sub>I, GWP of 5 and an atmospheric life time in the order of a few days appeared to show positive benefits. It was considered one of the first serious candidates as an alternative, demonstrating positive behaviour when mixed with CO<sub>2</sub> or N<sub>2</sub>, with the possibility of being used in both insulating and interrupting applications.

Despite these positive outcomes, it was concluded there are two key issues in using the compound for these applications [21] [42]:

- CF<sub>3</sub>I was classified as a category 3 carcinogenic, mutagenic, and reprotoxic (CMR) substance. This meant it was incompatible on an industrial scale; and
- The presence of Iodine (I) caused oxidation and corrosion.

#### 4.3.2 Commercially Available Products

##### 4.3.2.1 CO<sub>2</sub> pure gas

While CO<sub>2</sub> has been seen as the most promising arc-quenching alternative gas [60] [61] ( which can be further enhanced by adding other compounds [62]), when studying the

performance of naturally occurring gases, the gases switching and dielectric properties are below those of SF<sub>6</sub> [1] [63].

CO<sub>2</sub> has been previously investigated as both an insulating and interrupting medium. To enhance the arc-quenching ability of CO<sub>2</sub> without introducing corrosivity or flammability, an 85% CO<sub>2</sub>/ 15% O<sub>2</sub> mixture was introduced to improve the decay rate of the post-arc current. The tests were carried out using the 'self-blast' technique using the arc heat; this design used a tank which was 1.7 times the size of an equivalent SF<sub>6</sub> rated unit [44].

However, it has been noted in literature that common gases such as CO<sub>2</sub> and N<sub>2</sub>, have significantly inferior interrupting capabilities compared to gas mixtures using SF<sub>6</sub> at similar pressures. To use such mediums for interrupting purposes has led to larger interrupter designs, typically using a multi-break system, with high gas pressures to meet the same technical specification. Such devices will require a large driving force to operate the interrupting mechanism which can result in a higher environmental impact [1].

Commercially available products using pure CO<sub>2</sub> as a replacement for SF<sub>6</sub> have been developed, however they are much larger than SF<sub>6</sub> equivalent units [64].

#### 4.3.2.2 Fluoronitrile

Novec 4710 has been developed as an alternative to SF<sub>6</sub> gas, intended for use as both an interrupting and insulating medium with:

- A GWP of 2100;
- A boiling point of -4.7°C;
- A dielectric strength 2 times greater than SF<sub>6</sub>;
- Non-flammable; and
- Non ODP.

In addition, the manufacturer notes that it is compatible with a wide range of equipment components. It is noted that there can be issues in components found in lubricating greases and elastomers used in gaskets and O-rings. However, the boiling point is too high for operating as a pure gas and requires mixing.

GE has collaborated with 3M to produce g<sup>3</sup>, a mixture of Novec 4710 and CO<sub>2</sub>. Laboratory tests have been conducted to identify the technical characteristics of g<sup>3</sup> for the purposes of HV switchgear, which have yielded positive results [65]. Currently, products are being tested with GIS and GIL in multiple sites, as well as instrument transformers, across nine utilities [66].

The technical specification has been summarised in Section 5.2.

#### 4.4 Considerations for Testing and Validating SF<sub>6</sub> Alternatives

When an alternative medium to SF<sub>6</sub> has been proposed, it must undergo testing to verify performance and the required criteria. This testing must not only assess the switchgear unit and the medium, but also how they will interact at all stages in the switchgear units lifetime. This will include installation, handling, monitoring, operation, and decommissioning. By doing this, industry can build confidence in the proposal and the TRL can be raised.

Any alternative solution can only be considered as acceptable by industry by meeting the requirements of IEC and ISO regulations. These include the IEC 62271 family of standards and ISO 9001.

In addition, any alternative medium will have to be similarly tested and specified, just as SF<sub>6</sub> gas is in:

- IEC 62271-303 – High-voltage switchgear and control gear: Use and handling of SF<sub>6</sub>;
- IEC 60376 - Specification of technical grade sulphur hexafluoride for use in electrical equipment; and
- IEC 60480 – Guidelines for checking and treatment of sulphur hexafluoride taken from electrical equipment and specification for its re-use.

Any testing program prepared to study alternative mediums and their performance in existing switchgear must assess not only the technical characteristics associated with the switchgear, but also the risks associated in using the medium, including any by-products which may be generated through partial discharge, arcing, or other electrical phenomena. Whilst the alternatives are being tested to replace SF<sub>6</sub>, this does not mean that they will necessarily react in the same manner under different testing conditions. For example, some mediums have shown a decrease in dielectric strength in lower temperatures [40].

Research in alternative mediums is still on-going, with further work required. Exhaustive studies on decomposition products after current switching and their level of toxicity are still required for different operating conditions [42]. Furthermore, it should be considered how the switchgear lifetime will be affected by new medium or gas mixture. How the medium ages and reacts with surrounding materials shall also be analysed carefully through accelerated ageing tests and operating the equipment under different environmental conditions.

Finally, an effort should be made to identify and document any issues in using the alternative medium including handling, mixing, maintaining constant mixture composition, recycling, and the associated equipment design changes that may be required.

Overall, it is clear that there are challenges in not only developing an alternative product which will be accepted by the market, but also in developing a switchgear product using the proposed mediums or in integrating them into an industry which has been focused on SF<sub>6</sub> switchgear for a significant period of time.

#### **4.5 Summary of Identified Alternatives**

Section 4 has outlined the key alternative solutions to SF<sub>6</sub> which have been identified in literature, as well as outlining mediums which were previously considered and subsequently concluded as unsuitable. Work has been done to pure mediums to enhance their properties and make them more suitable for deployment in switchgear applications.

Table 4-2 summarises key technical characteristics of the gases shortlisted in literature, at the time of writing.

Table 4-2: Properties of pure mediums considered for alternatives to SF<sub>6</sub>[39]

| Mediums  | SF <sub>6</sub>     | CO <sub>2</sub> | C5-PFK    | C4-PFN     | HFO1234zee     |
|--|---------------------|-----------------|-----------|------------|----------------|
| CAS Number   | 2551-62-4           | 124-38-9        | 756-12-7  | 42532-60-5 | 1645-83-6      |
| Boiling Point (°C)                                 | -64                 | -78.5           | 26.5      | -4.7       | -19            |
| GWP  | 23900               | 1               | < 1       | 2100       | 6              |
| ODP  | None                | None            | None      | None       | None           |
| Flammability                                       | None                | None            | None      | None       | Yes            |
| Dielectric Strength (relative to SF <sub>6</sub> ) | 1                   | 0.3             | 1.4       | 2          | 0.8-0.9        |
| Toxicity (ppm)                                     | 1000                | 5000            | 225       | 65         | 800            |
| Potential Insulator                                | -                   | ✓               | ✓         | ✓          | ✓              |
| Potential Interrupter                              | -                   | ✓               | ✗         | ✓          | ✗              |
| TRL  | 9                   | 8-9             | 7         | 6          | 3              |
| References   | [10] [25] [42] [67] | [44] [68]       | [48] [69] | [40] [49]  | [40] [51] [70] |

As outlined in section 4.3.2, the pure mediums developed by 3M have been blended with common gases such as air, nitrogen and carbon dioxide to reduce the boiling point of the pure products to make them suitable for switchgear applications as an interrupting medium; however this has reduced the dielectric strength.

Also, pure CO<sub>2</sub> has been discounted as a viable alternative for the purposes of this study, due to the increase in switchgear physical dimensions, relative to a similarly rated SF<sub>6</sub> unit. However, CO<sub>2</sub> mixtures make up some of the gas mixtures which have been trialled previously by developers.

## 5 Available Technology

Some of the compounds presented in Table 4-2 have been adjusted and produced as commercial solutions to replacing SF<sub>6</sub> for energy industry applications. These have been outlined below. Furthermore, the current status on the availability of vacuum technology has also been noted.

### 5.1 ABB - AirPlus

AirPlus, developed in collaboration between 3M and ABB, is a fluoroketone (C5-PFK) compound<sup>9</sup>. As with other pure gases, the addition of fluorine increases the dielectric strength at the cost of increasing the boiling point. Subsequently, it required a buffer compound to lower the boiling point.

For MV design, Novec 5110 is blended with dry air. At HV levels, CO<sub>2</sub> and dry air are both added to improve the gas electrical properties.

ABB have developed, and commercially advertised SafeRing AirPlus as a medium voltage gas-insulated indoor RMU, which can operate at 24kV with a 630 A rating. This product uses AirPlus as an insulating medium for live components and vacuum interruption [71]. In addition, ABB have also developed SafeRing Air which uses dry air insulation up to 11kV. Both products have the same physical dimensions as SafeRing, ABB's SF<sub>6</sub> insulating RMU design.

SafeRing AirPlus is currently deployed as a field test in Flevoland, in the Netherlands. Four units were integrated into an existing wind farm grid, and will be monitored for a three year period from 2015 to 2018.

The monitoring is measured by the amount of a specific decomposition gas (Heptafluoropropane, C<sub>3</sub>HF<sub>7</sub>) to indicate the gas condition. Furthermore, gas pressure and temperature were monitored. The outcomes from the field trial have indicated that the gas has performed as expected and that AirPlus insulation gas will not impact the lifetime of MV switchgear [71].

### 5.2 GE - g<sup>3</sup>

The compound g<sup>3</sup>, was developed in collaboration by GE and 3M and has been fully type-tested and is commercially available.

Similar to AirPlus, it required a buffer compound to lower the boiling point. For MV design, Novec 4710<sup>10</sup> (a C4-PFN) is blended with Nitrogen. At HV levels, CO<sub>2</sub> is blended to improve the gas electrical properties.

Technically, g<sup>3</sup> has been found to have similar performance characteristics to SF<sub>6</sub> For instance, it is able to deliver the same dielectric strength as SF<sub>6</sub> under ambient conditions.

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<sup>9</sup> Referring to section 4.2.3.2

<sup>10</sup> Referring to section 4.3.2.2

Furthermore, g<sup>3</sup> has been tested for breaking capability and has been proved up to 420kV with similar dimensions and operating energy to SF<sub>6</sub> equipment.

Practically, GE has gas handling systems in place including bespoke supply, handling and monitoring solutions. Moreover, there are specific measurement devices to monitor gas ratio, moisture, tightness and detect leakage available.

Currently, g<sup>3</sup> is being used in HV GIL and gas insulated substations by multiple Transmission System Operators (TSO):

- National Grid (UK) is replacing a 420kV gas-insulated busbar at their Sellindge substation, near Folkestone in England as a pilot test for g<sup>3</sup>. The project was commissioned in 2016;
- Scottish Power Energy Networks (Transmission) has awarded GE with a contract to supply a GIL with g<sup>3</sup> in Kilmarnock South Substation in the South West of Scotland; this project alone is estimated to save 1.7 tonnes of SF<sub>6</sub>; and
- Axpo, a TSO in Switzerland, is being supplied with a 145kV gas-insulated substation only using g<sup>3</sup> in all components.

Further results from these trials will be expected in due course. However, GE currently have no known product available for MV switchgear and so no direct comparison can be made with current products.

### 5.3 Nuventura – Synthetic Air

Nuventura have outlined their product which uses synthetic air as an insulator without compromising on the compactness offered by SF<sub>6</sub> switchgear, matching the typical width of SF<sub>6</sub> solutions. Furthermore, they have suggested that the capital and operational expenditure is lower when compared to SF<sub>6</sub> switchgear, by 7-10%, due to the lack of need for gas handling procedures or gas regulations.

Their product currently works for 12-36kV, with a rating of up to 1250A.

Their product is currently being pilot tested by an unnamed Distribution System Operator (DSO) in Germany, and they are currently engaging with other TSOs/DSOs to conduct further pilot testing. There will be articles expected later in 2018 to discuss the work performed to date.

### 5.4 Solid Insulation

Multiple manufacturers have put forward traditional vacuum interrupting technology as an alternative interrupting medium to SF<sub>6</sub> gas, which has been available for several years. Companies such as Eaton, Schneider, ABB and Lucy all have commercially available products which are capable of interrupting MV fault currents.

While some products still use SF<sub>6</sub> as an insulating medium, others such as Eaton and Schneider have developed SF<sub>6</sub>-free products by deploying solid insulation. Such technology may have additional hurdles to overcome such as alternative components placement within the switchgear which may conflict with current installation procedures.

## 5.5 Considerations in Adapting or Using Commercially Available SF<sub>6</sub> Alternatives

As outlined, there are multiple technologies arising which have the potential to replace SF<sub>6</sub> to some extent in the near future. These technologies have a broad spectrum of TRLs and are being applied in different formats (different voltage levels and different switchgear). In addition, some companies have developed these technologies into commercially available alternatives. There are also additional technologies, such as g<sup>3</sup>, which do not have any literature demonstrating any switchgear at MV levels.

As this project is specifically looking to retro-fit SF<sub>6</sub> switchgear at a MV level, it is important to identify:

- Which current SF<sub>6</sub> technology is deployed in industry and what its purpose is;
- Which current switchgear can be retro-fitted; and
- The variation in width and length of alternative products, as a significant increase in these dimensions could mean extensive cost and labour to accommodate it on site.

Specifically, the physical dimensions of the unit and the interface to the surrounding connections should ideally be as similar to current switchgear as possible to limit the cost of wide-scale retrofitting; however it is accepted that this may not be possible due to the nature of some solutions and the differentiation between utility practices.

Furthermore, current technology may have different applications; for example the ABB SafePlus units are all designed to be indoor RMUs whereas the current project is investigating the viability of retro-fitting outdoor RMUs. These issues should be clarified with the manufacturers to confirm the viability of retro-fitting switchgear using particular alternative mediums.

In addition, SF<sub>6</sub> alternative technology is being deployed in other forms of switchgear in the Energy Industry. This includes circuit breakers such as the Schneider Premset, which uses solid insulation and vacuum interruption, but is not fitted within RMUs. Deploying such technology may require further labour and cost.

## 6 Further work

While this report outlines the proposals which are currently available, further work is required to allow the project to progress towards trialling key mediums in the suggested switchgear to identify the viability of a retro-fit SF<sub>6</sub> alternative solution.

In order to refine a list of suitable switchgear through analysis of technical information such as typical field lifetime of switchgear, common failure modes, key components and/or materials which affect lifetime and compatibility of proposed alternative mediums all require input from manufacturers to provide a clear picture of what trials are possible. These discussions will help to hone the design of any proposed retro-fit.

Furthermore, the economic feasibility of alternative proposals should be addressed also; however it will be difficult to compare the cost of installing a business as usual product (SF<sub>6</sub> based) with field trial costs. However, as trialling continues, these costs should become more apparent. The feasibility could be identified through comparing economic indicators such as capital and operational expenditure.

In addition, key personnel within utilities should be interviewed to identify what designs will conflict with current business as usual practices and what compromises could be possible in the future. It is possible that multiple utilities may need to be surveyed in order to identify common themes of acceptable design and practice.

The maintenance regime will need to be assessed for any alternative proposed. As current products are advertised as either maintenance free or low maintenance, it would be ideal to develop a product with the same intention. However, new products will require much more testing and product validation before enough market trust has been developed.

## 7 Conclusion

The purpose of this report is to provide a literature review of SF<sub>6</sub> alternatives and any previous trials conducted to test or demonstrate their capabilities, thus providing sufficient information to identify key mediums which should be considered for testing within HV switchgear as a potential solution for insulation and arc interruption.

Research has shown that there are alternative solutions currently available for replacing SF<sub>6</sub> within a circuit breaker. AirPlus and g<sup>3</sup> are both currently under test in live networks, and have been tested according to IEC specifications. Furthermore, vacuum interrupting technology has been well researched with multiple companies offering commercial products using different insulating mediums; the alternatives to SF<sub>6</sub> have included solid epoxy and common naturally occurring gases. HFC1234zee has also been investigated as a possible insulation alternative. Finally, Nuventura have proposed technology which uses dry air in relatively compact solutions.

Therefore, the insulating alternatives to SF<sub>6</sub> gas which could be considered for retro-fitting into existing switchgear under laboratory conditions are AirPlus, g<sup>3</sup>, HFC1234zee and solid epoxy. In addition, Nuventura's technology could be considered for UK field testing.

The interrupting alternatives to SF<sub>6</sub> gas which could be considered for retro-fitting into existing switchgear under laboratory conditions are g<sup>3</sup> and vacuum technology.

Table 7-1: Summary of Considered SF<sub>6</sub> Alternatives

| Description          | GWP        | Suitable for Insulation | Suitable for Interruption | Comments  |
|----------------------|------------|-------------------------|---------------------------|---|
| Pure CO <sub>2</sub> | 1          | ✗                       | ✗                         | Not compact enough for SF <sub>6</sub> retro-fit [44] [68]  |
| HFO1234zee           | <10        | ✓                       | ✗                         | Too flammable for interruption [46] [72]  |
| Perfluorocarbons     | 5000-12000 | ✗                       | ✗                         | GWP too high [21]   |
| C5-PFK               | 1          | ✓                       | ✗                         | Possible insulator; 'AirPlus' is a commercial product using this technology [48] [69]                         |
| C4-PFN               | 2100       | ✓                       | ✓                         | Possible insulator and interrupter; 'g <sup>3</sup> ' is a commercial product using this technology [40] [49] |
| CF <sub>3</sub> I    | 5          | ✓                       | ✓                         | Category 3 CMR Substance [21] [42]  |

These recommendations have been made on available existing literature. The suitability of the alternative mediums will also require manufacturer engagement and a feasibility study

of adapting the medium for specific existing switchgear. Furthermore, this area of research is very much active and it is possible that other alternatives may be developed which have not been discussed in this document.

Furthermore, WPD's needs should be considered in any retro-fit design. Current asset deployment will be focused on current equipment and radical alterations to existing equipment may require extensive labour and high costs, making any derived solution uneconomical.

## Bibliography

- [1] S. S. J.-M. B. F. M. M. D. P. R. K. T. S. K. U. P. P. H. I. E. K. A. J. R. S. D. D. Peter Glaubitz, "CIGRE Position Paper on the Application of SF6 in Transmission and Distribution Networks," CIGRE, 2014.
- [2] Energy Networks Association, "Engineering Recommendation G69: Guidance on working with Sulphur Hexafluoride," Energy Networks Association, London, 2013, Issue 3.
- [3] Environmental Protection Agency, "Global Mitigation of Non-CO2 Greenhouse Gases: 2010 - 2030," Environmental Protection Agency, Washington, DC, 2013.
- [4] P. V. R. P. A. T. B. R. B. D. F. J. H. J. L. D. L. G. M. J. N. R. P. G. R. M. S. a. R. V. D. Forster, "Chapter 2: Changes in Atmospheric Constituents and in Radiative Forcing," in *The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge, UK & New York, USA, Cambridge University Press, 2007, pp. Pg 212-213.
- [5] United Nations, "Kyoto Protocol to the United Nations Framework Convention on Climate Change," United Nations, Kyoto, Japan, 1998.
- [6] Environment Agency, "F Gas: Guidance for Users, Producers and Traders," UK Government, 31 12 2014. [Online]. Available: <https://www.gov.uk/government/collections/eu-f-gas-regulation-guidance-for-users-producers-and-traders>. [Accessed 17 10 2017].
- [7] European Parliament and Council, "Regulation (EU) No 517/2014 of the European Parliament and of the Council of 16 April 2014 on fluorinated greenhouse gases and repealing Regulation (EC) No 842/2006," European Union Law, 20 05 2014. [Online]. Available: [http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L\\_.2014.150.01.0195.01.ENG](http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2014.150.01.0195.01.ENG). [Accessed 13 11 2017].
- [8] Environmental Protection Agency, "Greenhouse Emissions Calculator," Environmental Protection Agency, 24 01 2017. [Online]. Available: <https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator>. [Accessed 2017 12 01].
- [9] Ofgem, "The Electricity System Operator Innovation Roll Out Mechanism: Guidance," in *SO-IRM Guidance Document*, Ofgem, 2017.
- [10] L. G. Christophorou, J. K. Olthoff and D. S. Green, "Gases for Electrical Insulation and Arc Interruption: Possible Present and Future Alternatives to Pure SF6," USA Department of Commerce, 1997.
- [11] IPCC, "Climate Change 2014 Synthesis Report Summary for Policymakers," IPCC, 2014.
- [12] NASA, "Climate Change: How do we know?," NASA, 24 10 2017. [Online]. Available: <https://climate.nasa.gov/evidence/>. [Accessed 2017 10 26].

- [13] Columbia Climate Center, "Mitigating SF6 Emissions: GNCS Factsheet," Columbia Climate Center, Columbia, 2012.
- [14] W. M. Ravindra Arora, "3.5.7 SF6 Gas and Environment," in *High Voltage and Electrical Insulation Engineering*, Hoboken, New Jersey, Wiley, 2011, p. 210.
- [15] G. D. S. F.-M. B. W. C. J. F. J. H. D. K. J.-F. L. D. L. B. M. T. N. A. R. G. S. T. T. a. H. Z. Myhre, "Chapter 8: Anthropogenic and Natural Radiative Forcing," in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge, Cambridge University Press, 2013, p. 733.
- [16] E. Agency, "Explanatory Memorandum to the Fluorinated Greenhouse Gases Regulations 2015 No.310," Department for Environment, Food and Rural Affairs, 2015.
- [17] R. Rajput, *Power System Engineering*, New Dehli: Laxmi Publications, 2006.
- [18] CIGRE Task Force B3.02.01, "Guide for the preparation of customised "Practical SF6 Handling Instructions"," CIGRE, Paris, 2005.
- [19] Siemens, "Techtopics: Use of SF6 Gas in Medium Voltage Switchgear," Siemens, Raleigh, 2005.
- [20] A. B. H. Okubo, "Recent Trend and Future Perspectives in Electrical Insulation Techniques in Relation to Sulfur Hexafluoride (SF6) Substitutes for High Voltage Electric," *IEEE Electrical Insulation Magazine*, pp. 33 - 41, May 2011.
- [21] A. G. F. B. P. P. J. O. M. C. M. B. R. V. S. K. W. Y. KIEFFEL, "SF6 Alternative Development for High Voltage Switchgears," Cigre, Paris, 2014.
- [22] Z. J. J. S. J. O.-S. Władysław Opydo, "Sulphur hexafluoride as a high-voltage insulation - Selected Problems," Poznań University of Technology, Poznan, Poland, 2014.
- [23] H. M. Ryan, "8.1.2 Sulphur Hexafluoride," in *High Voltage Engineering & Testing*, IET, 2013, p. 305.
- [24] Schneider Electric, "SF6 Properties and use in MV and HV Switchgear," Schneider Electric, 2003.
- [25] European Fluorocarbons Technical Committee, "Main Applications of SF6 Gas," European Fluorocarbons Technical Committee, 2017. [Online]. Available: <https://www.fluorocarbons.org/products-applications-sulphur-hexafluoride-sf6/>. [Accessed 24 10 2017].
- [26] D. Koch, "SF6 properties and use in MV and HV switchgear (Cahiers Techniques No. 188)," Schneider Electric Technical Collection, 2003.
- [27] C. H. Flurscheim, "The function of Circuit Breakers," in *Power Circuit Breaker Theory and Design*, London, IEE Power Engineering Series 1, 1985, pp. 1-17.
- [28] Fuji Electric, "Three Phase Encapsulated Type SF6 GIS (Type SDF for 170kV)," Fuji

- Electric, Osaki, Japan, 2013.
- [29] R. D. Garzon, *High Voltage Circuit Breakers*, New York: Marcel Dekker, 1997.
- [30] *Gas-insulated switchgear: safe operation*. [Film]. Siemens, 2015.
- [31] Siemens, "High-Voltage Circuit Breakers," Siemens, Berlin, Germany, 2012.
- [32] PubChem Compound Database, "Sulphur Hexafluoride Compound Summary," National Center for Biotechnology Information, [Online]. Available: <https://pubchem.ncbi.nlm.nih.gov/compound/17358>. [Accessed 24 10 2017].
- [33] Western Power Distribution, "Standard Technique SP2LB/3 - Relating to the use of SF6 gas in switchgear," Western Power Distribution, 2016.
- [34] ICF Consulting, "Byproducts of Sulfur Hexafluoride (SF6): Use in the Electric Power Industry," U.S. Environmental Protection Agency, Washington, DC, 2002.
- [35] Health and Safety Executive, EH40/2005 Workplace Exposure Limits, HSE, 2013.
- [36] Centers for Disease Control and Prevention, "The National Institute for Occupational Safety and Health," CDC, 11 04 2016. [Online]. Available: <https://www.cdc.gov/niosh/npg/npgd0580.html>. [Accessed 01 12 2017].
- [37] Cameo Chemicals, "Silicon Tetrafluoride," Cameo Chemicals, 2016. [Online]. Available: <https://cameochemicals.noaa.gov/chemical/1449>. [Accessed 01 12 2017].
- [38] S. Kosse, P. G. Nikolic and G. Kachelriess, "Holistic evaluation of the performance of today's SF6 alternative proposals," in *CIREN 24th International Conference on Electricity Distribution*, Glasgow, 2017.
- [39] r. R. S. J. Y. H. I. M. C. E. D. C. M. F. F. G. W. H. Y. K. S. J. G. J. J. M. S. P. M. R. P. R.-J. H. S. J. S. T. U. X. L. a. S. Y. M. Seeger, "Recent development of alternative gases to SF6 for switching applications," *Cigre Electra*, Paris, 2017.
- [40] C. Preve, D. Piccoz and R. Maladen, "Validation Methods of SF6 Alternative Gas," in *CIREN - 23rd International Conference on Electricity Distribution*, Lyon, France, 2015.
- [41] M. Rabie and C. M. Franck, "Computational screening of new high voltage insulation gases with low global warming potential," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 22, no. 1, pp. 296-302, 2015.
- [42] C. Preve, R. Maladen, G. Lahaye, T. Penelon, M. Richaud and S. Galas, "Hazard Study of MV Switchgear with SF6 Alternative Gas in Electrical Room," in *CIREN 24th International Conference on Electricity Distribution*, Glasgow, 2017.
- [43] Task Force D1.03.10 for Working Group D1.03, "N2/SF6 Mixtures for Gas Insulated Systems," Cigre, Paris, 2004.
- [44] H. Y. M. T. K. H. N. T. M. H. Uchii T., "Investigations on SF6-Free Gas Circuit Breaker Adopting CO2 Gas as an Alternative Arc-Quenching and Insulating Medium," in

- Gaseous Dielectrics X*, Boston, Springer, 2004, p. 205.
- [45] A. B. a. A. (. Haddad, "Recent Advances in the Quest for a New Insulation Gas with a Low Impact on the Environment to Replace Sulfur Hexafluoride (SF<sub>6</sub>) Gas in High-Voltage Power Network Applications," *Energies*, 2017.
- [46] M. H. Luly and R. G. Richard, "Gaseous Dielectrics with Low Global Warming Potentials". US Patent US 7,807,704 B2, 05 10 2010.
- [47] 3M, "Powering a sustainable future: 3M Novec Insulating Gases," 2017. [Online]. Available: <http://multimedia.3m.com/mws/media/14086000/3m-novec-insulating-gases-brochure.pdf#>. [Accessed 23 11 2017].
- [48] 3M, "3M™ Novec™ 5110 Insulating Gas Data Sheet," 2017. [Online]. Available: <https://multimedia.3m.com/mws/media/11321230/3m-novec-5110-insulating-gas.pdf>. [Accessed 23 11 2017].
- [49] 3M, "3M™ Novec™ 4710 Insulating Gas Data Sheet," 2017. [Online]. Available: <https://multimedia.3m.com/mws/media/11321240/3m-novec-4710-insulating-gas.pdf>. [Accessed 23 11 2017].
- [50] H. Z. Y. S. Q. C. B. H. Z. L. Zhiguo Chen, "Theoretical Study of OCCHCN as a potential alternative insulation gas for SF<sub>6</sub>," *AIP Advances*, vol. 7, no. 10, 2017.
- [51] D. P. R. M. Christophe Preve, "Application of HFO1234zee in MV Switchgear as SF<sub>6</sub> Alternative Gas," in *CIREN - 24th International Conference on Electricity Distribution*, Glasgow, UK, 2017.
- [52] D. B. Durocher, L. T. Connor, D. M. Haim and J. d. Jong, "Safety by Design: Solid Insulated Technologies challenge the use of SF<sub>6</sub> in MV Switchgear," 03 2015. [Online]. Available: <file:///C:/Users/michael.eves/Downloads/Safetybydesign-solidinsulatedtechnologieschallengetheuseofSF6inmediumvoltageswitchgear.pdf>. [Accessed 30 11 2017].
- [53] Meiden, "Solid Insulated Switchgear," Meiden, 2017. [Online]. Available: [http://www.meidensha.com/products/energy/prod\\_01/prod\\_01\\_04/prod\\_01\\_04\\_01/index.html](http://www.meidensha.com/products/energy/prod_01/prod_01_04/prod_01_04_01/index.html). [Accessed 30 11 2017].
- [54] K. Tsuchiya, K. Nagano, A. Morita and T. Hirao, "Development of Medium-voltage Switchgear for Reducing Environmental Impact and Space-saving," 2014. [Online]. Available: [http://www.hitachi.com/rev/pdf/2014/r2014\\_04\\_102.pdf](http://www.hitachi.com/rev/pdf/2014/r2014_04_102.pdf). [Accessed 30 11 2017].
- [55] Schneider, "Premset 15 kV Switchgear," 22 11 2017. [Online]. Available: [http://download.schneider-electric.com/files?p\\_Reference=6045CT1601&p\\_EnDocType=Catalog&p\\_File\\_Id=8463649230&p\\_File\\_Name=6045CT1601.pdf](http://download.schneider-electric.com/files?p_Reference=6045CT1601&p_EnDocType=Catalog&p_File_Id=8463649230&p_File_Name=6045CT1601.pdf). [Accessed 30 11 2017].
- [56] Toshiba, "Solid Insulated Switchgear," 07 2015. [Online]. Available: <http://www.toshiba.co.jp/sis/railwaysystem/en/products/catalog/pdf/c1SolidInsulated>

- Switchgear.pdf. [Accessed 30 11 2017].
- [57] M. Zheng, J. H. Ma, L. Yu, S. W. Lee and Y. G. Kim, "Development of Solid Insulated Switchgear for Medium Voltages," in *CIGRE - 21st International Conference on Electricity Distribution*, Frankfurt, Germany, 2011.
- [58] M. K. e. al, "RMU with Eco-Efficient Gas Mixtures: Field Experience," in *CIGRE 24th International Conference on Electricity Distribution*, Glasgow, 2017.
- [59] H. K. e. al, "Investigation of the performance of CF3I gas as a possible substitute for SF6," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 15, no. 6, 2006.
- [60] T. U. e. al, "Fundamental Research on SF6-Free Gas Insulated Switchgear, adopting CO2 Gas and its Mixtures," in *International Symposium on Eco Topia Science*, 2007.
- [61] P. S. e. al, "CO2 as an Arc Interruption Medium in Gas Circuit Breakers," *IEEE Trans Plasma Science*, vol. 41, no. 8, p. 2359, 2013.
- [62] T. U. e. al, "Thermal Interruption Capabilities of C)2 Gas and CO2 Gas Mixtures," in *XVIII International Conference on Gas Discharges and their Applications*, Greifswald, Germany, 2010.
- [63] K. J. e. al, "High Pressure N2, N2/CO2 and CO2 Gas Insulation in comparison to SF6 in GIS applications (Paper C-01)," in *14th International Symposium High Voltage Engineering*, 2005.
- [64] ABB, "CO2 High voltage circuit breakers: Enhancing eco-efficiency with LTA LTB-LTA 72 D1 and DCB-LTA 72 D1," ABB, Sweden, 2012.
- [65] F. K. e. al, "Characteristics of g3 - An alternative to SF6," in *CIGRE - 24th International Conference on Electricity Distribution*, Glasgow, 2017.
- [66] GE, "g3 Technology: The Alternative to SF6 for High Voltage Applications," 2016. [Online]. Available: [https://www.gegridsolutions.com/products/brochures/AlstomEnergy/itr/164696\\_182570\\_Grid-ACS-L3-g3-1001-2016\\_08-EN\\_lo.pdf](https://www.gegridsolutions.com/products/brochures/AlstomEnergy/itr/164696_182570_Grid-ACS-L3-g3-1001-2016_08-EN_lo.pdf). [Accessed 23 11 2017].
- [67] Y. &. I. T. &. P. P. &. O. J. Kieffel, "Green Gas to Replace SF6 in Electrical Grids," *IEEE Power and Energy Magazine*, 2016.
- [68] J. K. O. a. D. S. G. L. G. Christophorou, "Gases for Electrical Insulation and Arc Interruption: Possible Present and Future Alternatives to Pure SF6," United States Department of Commerce Technology Administration, 1997.
- [69] N. G. e. a. ] J. D. Mantilla, "Investigation of the Insulation Performance of A New Gas Mixture with Extremely Low GWP," *Electrical Insulation Conference*, Philadelphia, USA, 2014.
- [70] J.-L. Bessede, *Eco-Design in Electrical Engineering: Eco-friendly Methodologies, Solutions, and Example for Application to Electrical Engineering*, Springer, 2017.

- [71] ABB, "Gas-insulated ring main unit SafeRing AirPlus," 2018. [Online]. Available: <http://new.abb.com/medium-voltage/switchgear/gas-insulated-switchgear/iec-gis-rmu-for-secondary-distribution/iec-gas-insulated-ring-main-unit-safering-airplus>. [Accessed 26 01 2018].
- [72] C. Preve, D. Piccoz and R. Maladen, "Application of HFO1234zee in MV Switchgear as SF6 Alternative Gas," CIRED 2017, Glasgow, 2017.
- [73] Siemens, "Switchgear Type 8DJH for Secondary Distribution Systems up to 24kV (GIS)," Siemens, Munich, Germany, 2014.
- [74] H. Koch, "Gas Insulated Transmission Lines - GIL," IEEE, Tampa, FL, USA, 2007.
- [75] Siemens, "Gas Insulated Lines," Siemens, 2017. [Online]. Available: <https://www.siemens.com/global/en/home/products/energy/high-voltage/power-transmission-lines/gas-insulated-lines.html>. [Accessed 09 11 2017].
- [76] C. T. D. & P. Vassiliou, "Sulfur Hexafluoride (SF6): Global Environmental Effects and Toxic Byproduct Formation," *Journal of Air & Waste Management Association*, vol. 50, no. 1, pp. 137-141, 2000.
- [77] K. Smythe, "Trends in SF6 and End-Use Applications: 1961–2003," in *Conference on SF6 and the Environment*, Scottsdale, Arizona, 2004.
- [78] R. S. D. K. T.G. Hughes, "Stored Chemical Energy Propulsion System for Underwater Applications," *Journal of Energy*, vol. 7, no. 2, pp. p 128-133, 1983.
- [79] M.S. Naidu, "Gas insulated substations," I.K.International publishing house Pvt.Ltd., 2008.
- [80] H. Koch, "Gas-Insulated Lines," Wiley, West Sussex, 2012.
- [81] F. Pinnekamp, "The Circuit Breaker: A Showcase of Industrial Product Development," ABB, 2007.
- [82] Department for Environment, Food and Rural Affairs, "Fluorinated greenhouse gases (F gases)," UK GOV, 2014.
- [83] Intergovernmental Panel on Climate Change, "Global Warming Potential," Intergovernmental Panel on Climate Change, 2017. [Online]. Available: <http://www.ipcc.ch/ipccreports/sres/aviation/index.php?idp=71>. [Accessed 2017 10 17].
- [84] EurElectric, "SF6 and Alternative Technologies for Electrical Switchgear," EurElectric, 2015.
- [85] Siemens: TechTopics, "Use of SF6 Gas in Medium Voltage Switchgear," 03 06 2005. [Online]. Available: <https://www.energy.siemens.com/us/pool/us/services/power-transmission-distribution/medium-voltage-product-services/tech-topics-application-notes/techttopics53rev0.pdf>. [Accessed 23 10 2017].

- [86] C. Dodds, "SF6 Gas Detection For HV GIS Switchgear - Crowcon F-Gas Detector," 08 03 2016. [Online]. Available: <https://www.cablejoints.co.uk/blog/article/sf6-gas-detector-crowcon-fgas>. [Accessed 23 10 2017].
- [87] Schneider Electric SA, "Circuit Breakers: SF6 Switchgear (1 to 40.5kV)," Schneider Electric SA, 1998.
- [88] D. Nyberg, "SF6 Alternatives for Power Utilities," 3M, 2017.
- [89] United States Environmental Protection Agency, "Understanding Global Warming Potentials," United States Environmental Protection Agency, 14 02 2017. [Online]. Available: <https://www.epa.gov/ghgemissions/understanding-global-warming-potentials>. [Accessed 2017 10 26].
- [90] Environment Agency, "How to operate or service high voltage switchgear containing SF6," Department for Environment, Food & Rural Affairs, 01 01 2017. [Online]. Available: <https://www.gov.uk/guidance/how-to-operate-or-service-high-voltage-switchgear-containing-sf6>. [Accessed 26 10 2017].
- [91] W. KD, "Gis Versus Non-Gis — A Value Based Comparison," in *Gaseous Dielectrics IX*, Boston, MA, Springer, 2001.
- [92] Environmental Protection Agency, "Global Mitigation of Non-CO2 Greenhouse Gases: 2010 - 2030," Environmental Protection Agency, Washington, DC, 2013.
- [93] ABB, "Gas-insulated Switchgear Type ELK-14; The modular system for GIS, 300kV," ABB, Zurich, Switzerland, 2011.
- [94] Siemens, Techtopics No.3 - SF6 vs Vacuum, Wendell, NC: Siemens, 2012.
- [95] S. Blázquez, M. Antiñolo, O. J. Nielsen, J. Albaladejo and E. Jiménez, "Reaction kinetics of (CF3)2CFCN with OH radicals as a function of temperature (278–358 K): A good replacement for greenhouse SF6?," *Chemical Physics Letters*, vol. 687, no. 1, pp. 297-302, 2017.

## 8 Appendices

### 8.1 Appendix A: Principle of Arc Interruption

In switchgear interruption, two key parameters exist; making capacity and breaking capacity.

Breaking capacity is the RMS value ( $\sqrt{2}I_K$ ) of the short-circuit current that the device can interrupt at its rated voltage.

Making capacity considers the highest possible short-circuit current that a unit can close onto (closing the circuit) without failing. This will be the peak asymmetrical value (coloured red in Figure 8-1), as opposed to the RMS.

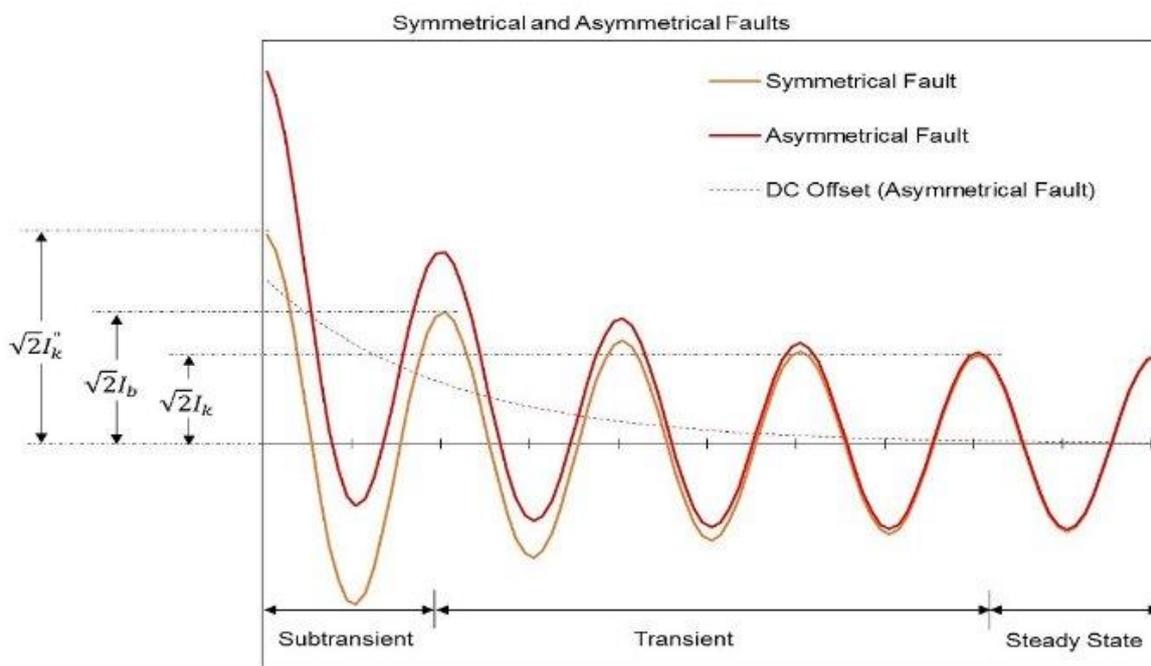


Figure 8-1: Illustration of Peak and RMS Short-Circuit Current

As seen in Figure 8-1, AC fault currents pass through 'current zero' during their frequency cycle. This is the optimal point to extinguish an arc in conventional circuit breakers and then prevent further current flow.

#### Current Interruption Theory

Within a circuit breaker, there is a need for a mechanism which can interrupt fault currents and maintain sufficient insulation to prevent further current flow.

The typical method for interrupting the flow of current in high-voltage systems is by introducing a non-conductive medium into the path of the arc plasma. This is currently achieved by separating two metallic contacts with a mechanical process in the presence of an interrupting medium; this gap is then automatically filled by the interrupting medium.

The basic requirement for current interruption in an AC system is for an exponential increase in resistance to the arc plasma at the current zero, to suppress and interrupt current flow. At this point, arc extinction will lead to a rise in arc voltage. The voltage rise can be

thought of as an attempt by the system to re-strike the arc and resume current flow across the contact gap.

The arc voltage can be defined as the voltage difference across the contacts during the arcing period. This is typically relatively low with a heavy current flow, however when the current reaches zero in its waveform cycle, the arc voltage will rapidly rise to a peak value in an effort to maintain the power flow. This high voltage develops in order to drive enough current through the interrupting medium to sustain the arc.

The process of current interruption (or arc extinction) is as follows [23]:

1. Initially, as the contacts separate, an arc will form across the contact gap. This arc then must be controlled and reduced during a high current phase, and then quenching it in the presence of a high voltage at current zero.
2. At and after the current zero, a sufficient resistance to the arc plasma must be present, in the form of a medium with a high dielectric, which suppresses and prevents further current flow.
3. Finally, any degradation of the dielectric strength between of the two contacts seeks to recover faster than the electrical stress due to the electrical system, which is that the contacts must survive the largest voltage which can be generated by the system without voltage breakdown occurring in the interrupting medium. Otherwise, the breakdown voltage would overpower the dielectric strength of the medium, and cause the arc to re-ignite.

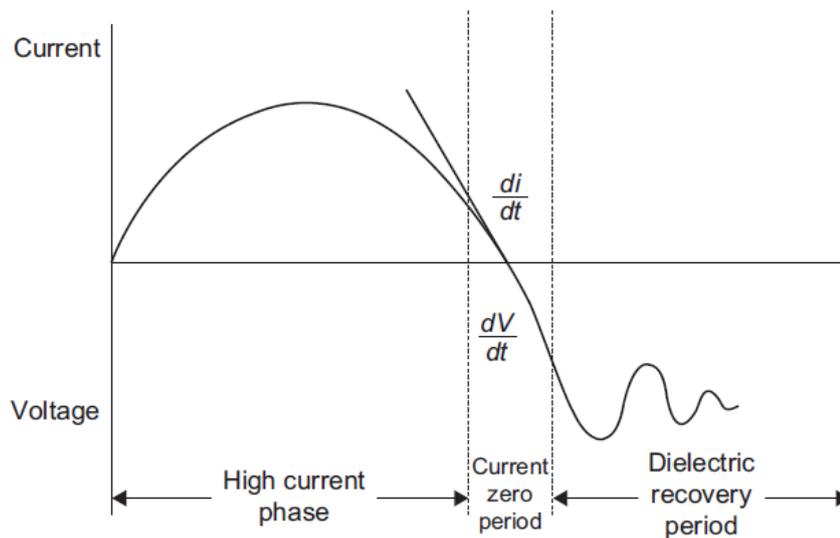


Figure 8-2: Current and Voltage profile during arc interruption [23]

The current zero mentioned previously is a natural part of an AC waveform and can be used to interrupt the current when it passes through zero during its natural 50/60Hz cycle which happens once every half-cycle. By interrupting the current at this point, the interruption occurs at the minimum rate of change of current which also minimises the induced voltage following the current interruption; this is true for conventional power systems which are inherently inductive. The current profile during the arc extinction process is shown in Figure 8-2.

## 8.2 Appendix B: SF<sub>6</sub> applied in various gas-insulated electrical equipment

This appendix outlines how SF<sub>6</sub> is practically used within the energy industry, as both an insulating medium and an interrupting medium. For the purposes of this report, switchgear and GIL have been discussed only. It should be noted that SF<sub>6</sub> can also be used as insulation in transformers and substations.

### Gas Insulated Switchgear

In GIS, the SF<sub>6</sub> is injected into a series of discrete chambers to insulate the different live parts from the earth and each other. This allows easy access for maintenance and repair services as each chamber can be de-pressurised and worked on without affecting the pressure of the other chambers. Furthermore, such modular designs have the capability for extensive in-plant preassembly and testing of large units & complete bays which reduces assembly and commissioning time on site, which optimises costs.

GIS will have a switching element, such as a circuit breaker, as part of the design.

An example GIS is illustrated in Figure 8-3 where all the blue elements denote the insulating barriers between the separate SF<sub>6</sub> chambers in an example GIS feeder circuit breaker. All equipment in red denotes electrically live equipment with the yellow showing sealed SF<sub>6</sub>. While Figure 8-3 shows an example operating at EHV (170kV), it demonstrates the different components of a typical GIS and how SF<sub>6</sub> can benefit the designs; as an insulating medium, it can allow much more compact designs of GIS with smaller insulating compartments. This reduces the overall plant footprint, reducing associated capital costs including land purchasing. Figure 8-4 shows the corresponding single line diagram.

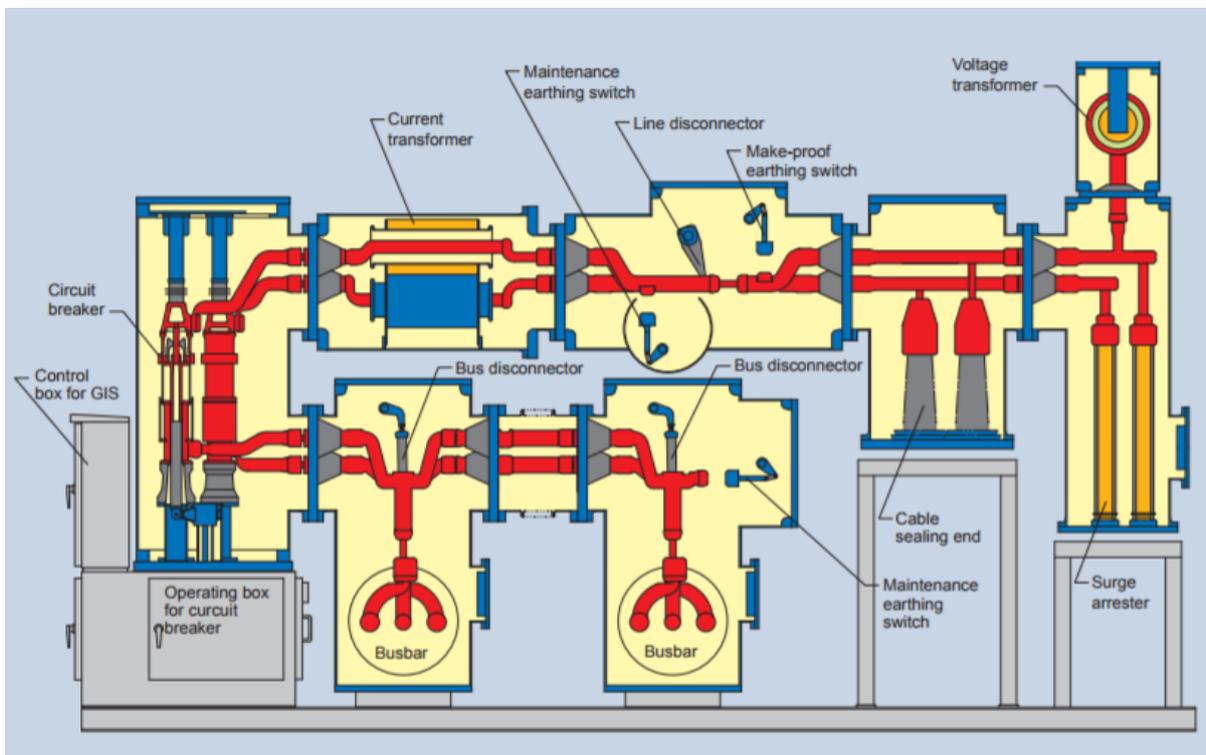


Figure 8-3: HV SF<sub>6</sub> GUS Cross Section (Fuji Electric 170kV) [28]

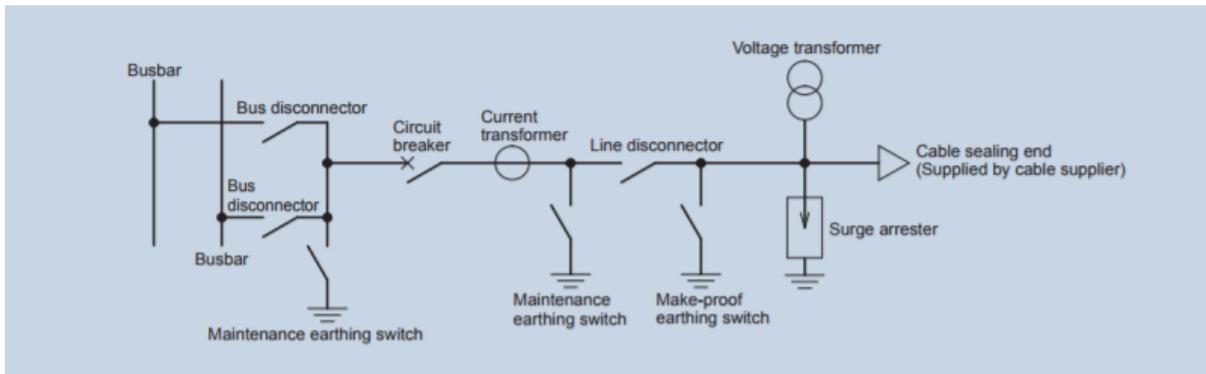


Figure 8-4: Single Line Diagram for Figure 8-3 [28]

Different types<sup>11</sup> of circuit breakers are discussed in further detail in section 3.2.3. The key desired parameters can include reliable performance, and maintenance-free. Each circuit breaker pole in a three phase unit will be operated by a spring mechanism; the components of this will include a charging system, mechanical energy storage, and an actuator per breaker pole.

GIS will also typically contain a disconnecter and earthing switch, which can sometimes be enclosed within the same compartment and operating mechanism. Earthing switches are typically slow in operation. These can be configured in different arrangements to provide flexibility.

The purpose of the disconnecter is to ensure that the equipment is de-energised for maintenance purposes and the earthing switch ensures that the equipment is to isolate the circuit after operation. There will be a separate maintenance and make-proof earthing switch. Typically, GIS will have mechanical interlocking systems to prevent personnel carrying out maintenance on energised equipment.

A fast-acting earthing switch may also be designed for GIS to ground switchgear sections. The additional benefit that fast acting earthing switches offer over maintenance earthing switches is that they can close on energised conductors without enduring significant damage and can earth capacitance from conductors or cables.

Other components such as voltage and current transformers, busbars, and cable terminations will be encapsulated in SF<sub>6</sub> in earthed enclosures to allow more compact design to the superior insulating properties of SF<sub>6</sub> in comparison to air.

Gas insulated switchgear can not only be used at higher voltages within substations, but also within the secondary substations and outdoor units, within the distribution network. One switchgear example is Ring Main Units (RMUs), which can contain switch disconnectors (fused or unfused) or circuit breakers as the switching equipment. They can be typically found in urban areas, large buildings, industrial sites, and wind farms.

<sup>11</sup> The different types are differentiated by the interrupting medium within the breaker. The main body discussed SF<sub>6</sub> and vacuum interrupters, with Appendix X providing further information on other units.

Their main benefit to the network is that, by connecting in a ring topology, a fault within the local circuit can be mitigated by supplying the loads through two alternate routes simultaneously.

They are typically used up to 24kV, with higher voltages being sealed with higher pressure insulating gas. Figure 8-5 illustrates an example of an indoor RMU which used SF<sub>6</sub> as the insulating gas and a vacuum interrupter.

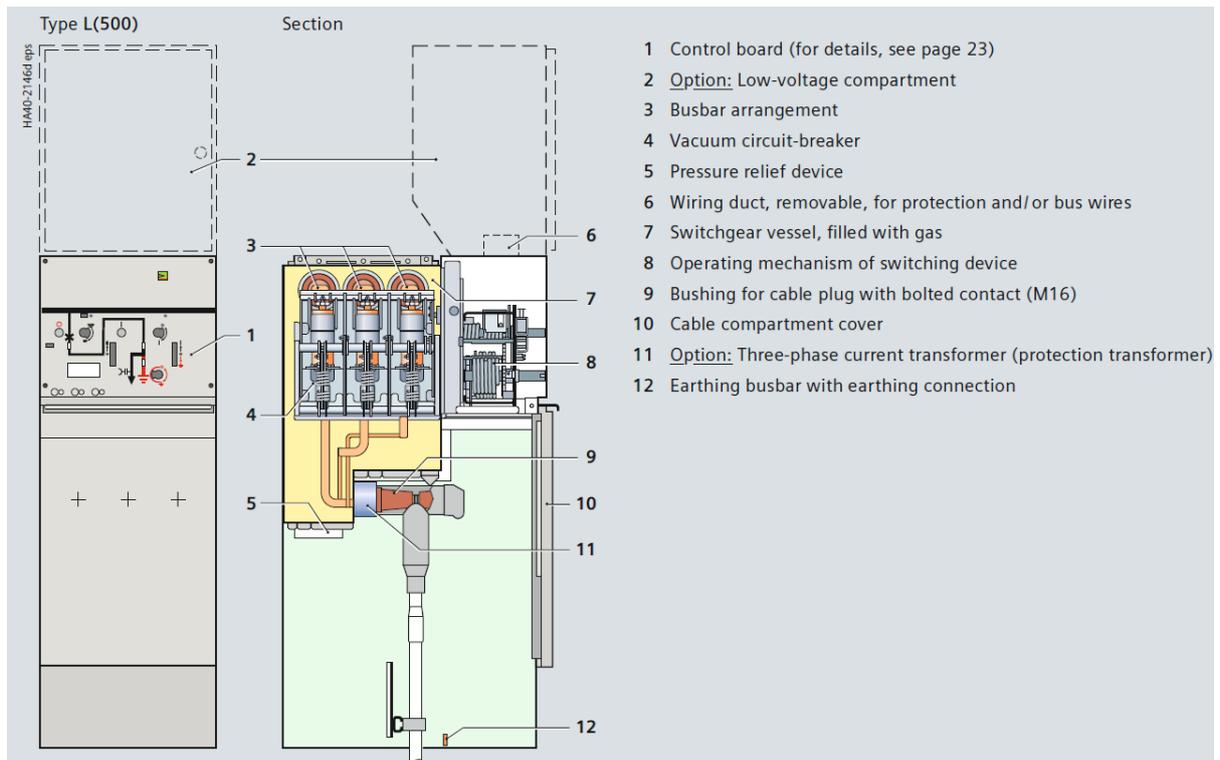


Figure 8-5: RMU example cross section (Siemens 8DJH Type L) [73]

### Gas Insulated Lines

Gas Insulated Lines were developed in parallel to GIS, utilising the same insulating properties of SF<sub>6</sub> to provide safe, reliable transmission of high-voltage electricity. Similarly to GIS, designs achieve reduced space and minimal electromagnetic radiation. The key difference between GIS and GIL is that there will not be any switching element within GIL to interrupt current [74].

Developments in GIL are using smaller amounts of SF<sub>6</sub>, mixed with nitrogen to comply with environmental regulations. An example illustration of a GIL cross section is shown in Figure 8-6 **Error! Reference source not found.** Alternative solutions are currently being trialled in GIL; as GIL uses significant amounts of SF<sub>6</sub>, an alternative solution rolled out across GB would significantly impact the amount of gas used by the energy industry.

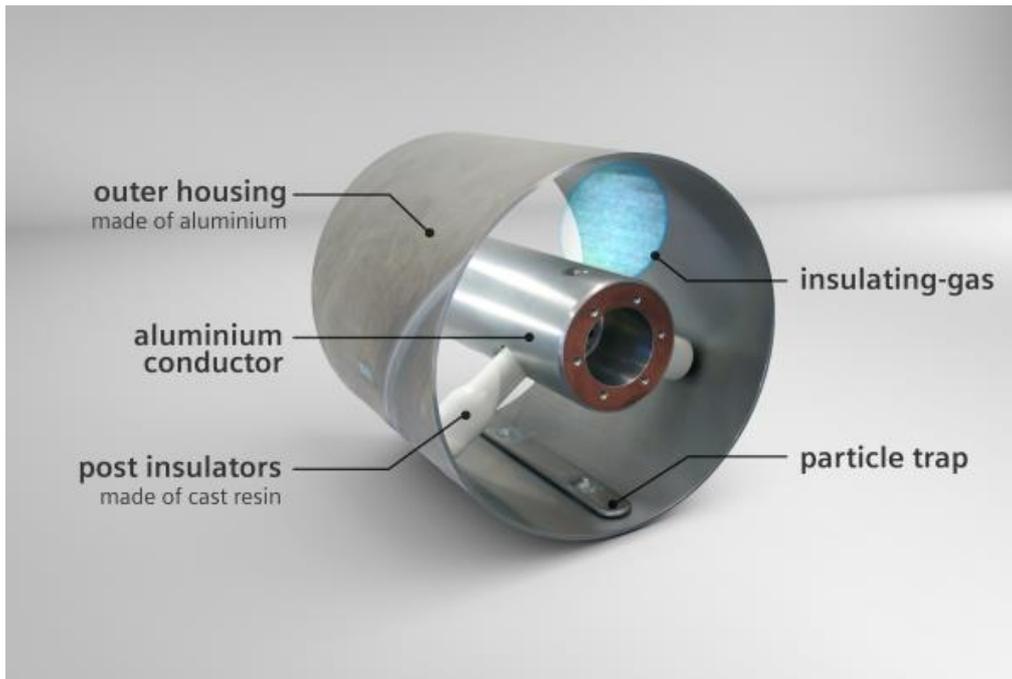


Figure 8-6: GIL Cross Section (courtesy of Siemens) [75]

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