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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_2	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_6	Sulphur Hexafluoride
TRL	Technology Readiness Level
TSO	Transmission System Operator
WPD	Western Power Distribution

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1 Executive Summary

This report summarises the available literature on SF_6 alternatives for the purposes of electrical insulation and arc-interruption in electrical switchgear.

SF_6 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_6 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_6 gas has been identified as a potent greenhouse gas and is estimated to be 23,900 times more harmful that CO_2 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_6 including AirPlus (developed by 3M and ABB), g^3 (developed by 3M and GE), HFO1234zee and solid epoxy.

The identified possible interrupting alternatives to SF_6 are g^3 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.

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2 Introduction

2.1 Overview

Sulphur Hexafluoride (SF_6)[1] gas is widely used in high-voltage[2] (HV) switchgear as an insulating and current-breaking medium. SF_6 has excellent insulating and arc-quenching capabilities which deliver reliable performance in relatively compact designs[3]. 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, SF6 on right) [1]

In recent years, SF_6 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_6 was included in the 1997 Kyoto Protocol [5] which has led to government taking action to reduce emissions and the consumption of SF_6 and specific regulations have now been put in place across industries. For the energy industry, this means that companies must operate and maintain SF_6 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.

[1] SF_6 will refer to the compound in its gaseous form, unless otherwise stated.

[2] >1kV

[3] In comparison to alternative mediums such as air or mineral oil.

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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_6 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_6 switchgear will require inbuilt leak detection technology.

The concerns over the environmental impact of SF_6, 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_6 gas from HV electrical equipment. In 2016/2017 alone, approximately 554kg of SF_6 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_6 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_6 Alternatives project seeks to identify a viable substitute for SF_6 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_6 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_6 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_6 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_6 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_6 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_6 has been banned in most industries, with remaining industries[4] 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_6 subject to strict compliance with the regulations.

3.1 Environmental Concerns Regarding SF_6

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_6 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_6 is so environmentally damaging.

In comparison to other greenhouse gases, the atmospheric concentration of SF_6 is extremely low. In 1993[5], it was estimated that the contribution of SF_6 to non-natural global warming was between 0.01% and 0.07%. The main concern with SF_6 is that its long atmospheric life time means that even small excursions of SF_6 will have a cumulative and permanent environmental impact [14].

The impact of SF_6 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_2. Specifically, it compares how much radiation energy can be absorbed by 1 tonne of a gas, relative to 1 tonne of CO_2 over 100 years [15]. Table 3-1 shows the GWP that SF_6 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.

[4] Where no suitable alternatives yet exist to replace SF_6

[5] 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_2)	Fire suppression, carbonated beverages, by-product of fossil fuel consumption	1
Methane (CH_4)	Consumed as fuel (also known as Natural Gas)	21
HFC[6]-152a	Refrigerant, aerosol spray propellant	140
Nitrous Oxide (N_2O)	Known as 'Laughing Gases, pain relief in dental procedures, car performance, and preservative.	310
HFC-32	Refrigerant	650
HFC-134a	Refrigerant, SF_6 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_4	Refrigerant, electronics fabrication	6,500
C_4F_{10}	Fire suppressant, ultrasonic contrast	7,000
C_2F_6	Semiconductor fabrication	9,200
Fluoroform (HFC-23)	Semiconductor fabrication, fire suppressant	11,700
SF_6	Electrical Switchgear	23,900

As can be seen from Table 3-1, SF_6 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_6. 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_6 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_6 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.

[6] HFC is an abbreviation for Hydrofluorocarbon

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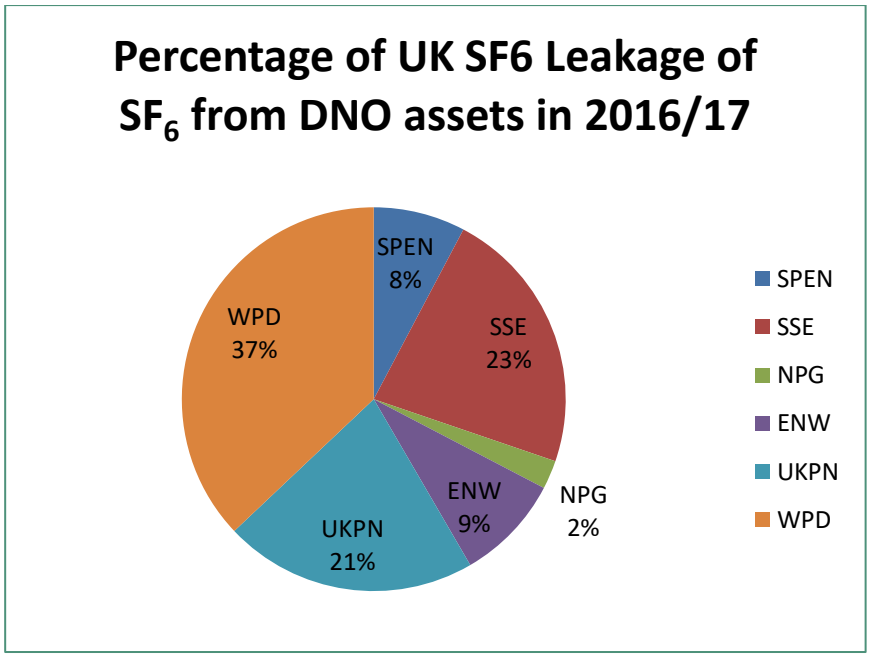


Figure 3-1: SF_6 leaked in 2016/17 from UK DNO Assets by DNO

Currently, UK DNOs are required to strictly monitor and report on the SF6 mass leaked from distribution and transmission network assets. Figure 3-1**Error! Reference source not found.** shows the distributed network asset SF_6 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 1st of July 2020, the European Commission will publish a report assessing the viability of replacing GHG gas medium-voltage switchgear. Until this time, SF_6 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_6 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_6 [28].

It should be noted that SF_6 GWP alone is not adequate to measure the environmental impact of electric power equipment using SF_6 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 SF6 filled 11kV RMUs within most UK DNO networks which contribute to the SF6 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_6 in the Energy Industry

Of the 8000 tonnes of SF_6 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_6 as an insulating or interrupting medium and are rated above 1kV will be discussed; hybrid technology such as SF_6 gas-insulating, vacuum-interrupting units are also included.

HV SF_6 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_6 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_6 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_6 applied in various gas-insulated electrical equipment as background information.

3.2.1 SF_6 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_6 is extremely stable giving it a high dielectric strength. In comparison to other common insulating mediums SF_6 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^2 (2.94 bar), SF_6 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_6 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_6, withsome 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_6 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_6-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_6 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_6 as an Interrupting Medium

When used as an interrupting medium, SF_6 is able to quickly quench the arc generated when the electrical contacts are separated.

SF_6 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_6 is thermally stable up to 500°C, the temperature at an arc-core can reach up to 20,000°C meaning SF_6 molecules will disassociate into multiple gasses. However, SF_6 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_6, 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_6 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_6 as an interrupting medium and vacuum interruption, as a known alternative.

3.2.3 Circuit Breakers

Over the 20th 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.

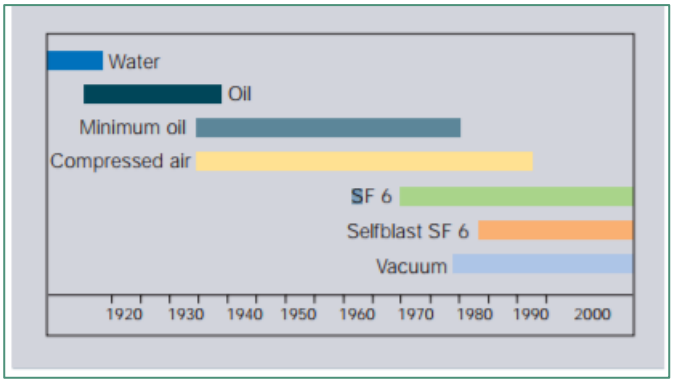


Figure 3-2: Circuit Breaker Interrupting Mediums over the 20th century [26]

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_6 breaker designs were first successfully manufactured by Westinghouse in 1957. By the 1970's, SF_6 HV switchgear was popular, with an increasing demand for gas leading to large scale production of SF_6 for this purpose. At this time, other industries were identifying other applications of SF_6 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].

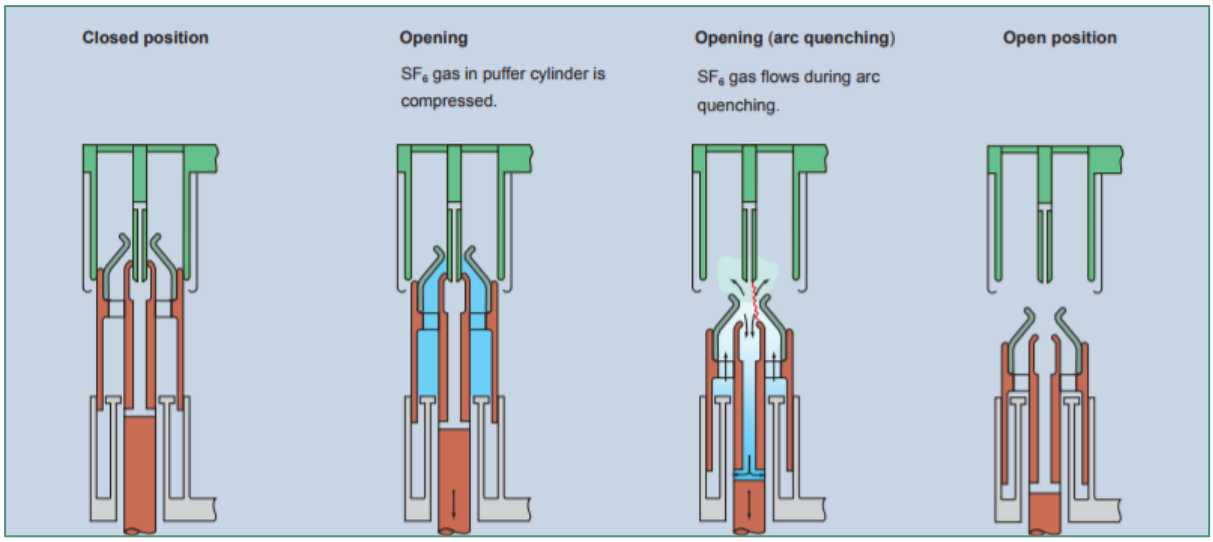


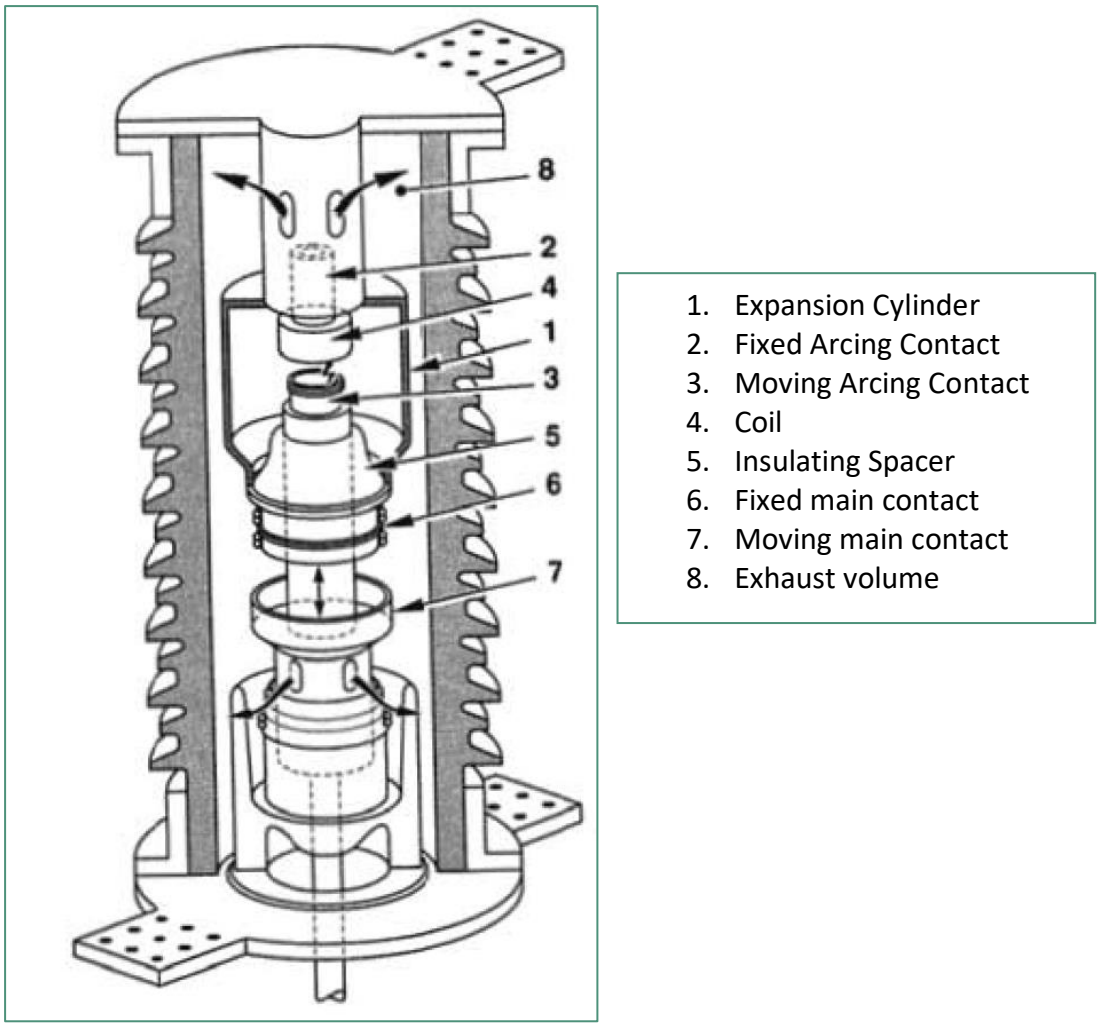
Figure 3-3: Single-Pressure Puffer Type Interrupter [28]

Single-pressure puffer type interrupters took advantage of the relative movement of the contacts to compress the SF_6; 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_6 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_6 switchgear, there will always be a source of SF_6 leakage regardless of the arc-quenching method used.

The concern surrounding SF_6 leakage is the driver for the current regulation which stipulates that switchgear containing significant volumes of SF_6 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.

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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].

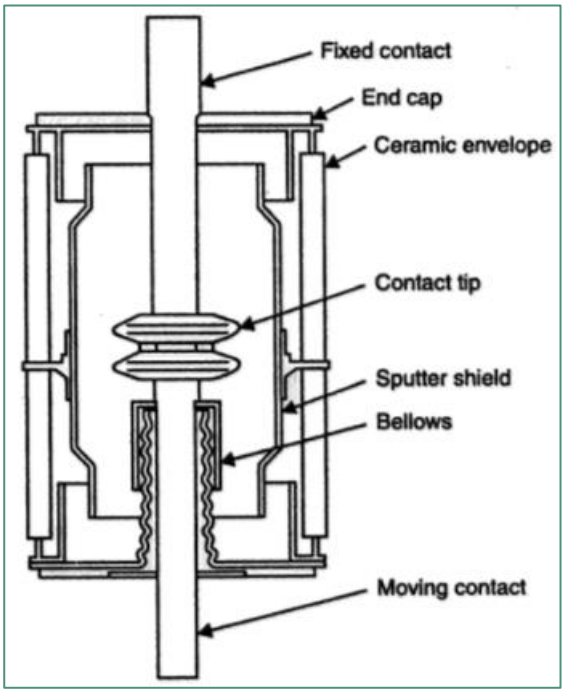

Figure 3-5: Vacuum circuit breaker cross-section [11]

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 groves 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.

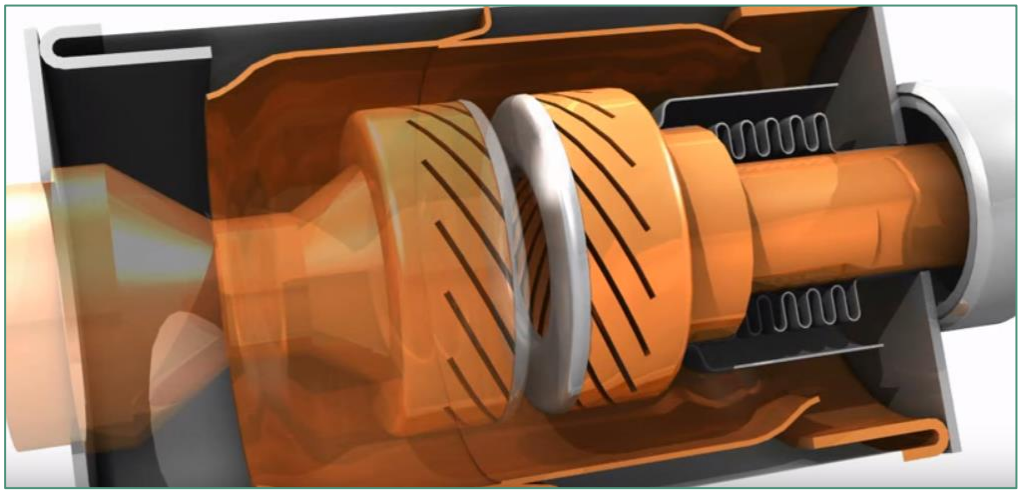

Figure 3-6: Vacuum Circuit Breaker Contact Illustration [30]

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_6 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_6 Properties

Other properties of SF_6 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_6 is non-toxic, it does not support life and can cause suffocation [33].

SF_6 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 SF6 gas within utility applications are described in Table 3-2. In addition, SF6 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_6. Section 4 presents the alternative mediums identified in literature and outlines where they meet or fall short of the given characteristics.

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Table 3-2: SF6 key properties for utility applications

Key Benefits of using SF_6 as an Electrical Insulator	Key Benefits of using SF_6 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_6. 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_6.

Switchgear Testing Policy

Given that a number of alternative mediums to SF_6 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_6 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_6 for electrical switchgear. This includes procuring, transporting, handling, maintaining, 'topping-up', and disposing (or re-using) of SF_6 and switchgear.

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

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Table 3-3: Applicable Technical Standards for working with SF_6 gas

Reference	Standard
ENA ER G69	Guidance on working with Sulphur Hexafluoride
ENA ER S38	Reporting of SF_6 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_6)
BS EN 60376:2005	Specification of technical grade Sulphur hexafluoride (SF_6) for use in electrical equipment
CIGRE Technical Brochure 234:2003	SF_6 Recycling Guide
CIGRE Technical Brochure 276:2005	Practical SF_6 handling instructions
CIGRE Technical Brochure 430:2010	SF_6 tightness guide
BS EN 60480:2004	Guidelines for the checking and treatment of sulphur hexafluoride (SF_6) taken from electrical equipment and specification for its re-use

3.4 SF_6 Switchgear Monitoring, Maintenance and Hazards

3.4.1 Monitoring and Maintaining SF_6 Switchgear

SF_6 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_6 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_6 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_6 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_6 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_6 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_6 is satisfactory, there is typically a compressor which can provide a gas sample to be assessed.

Moisture is also a primary issue in SF_6 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_6 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_6. However, during arcs or in the event of switchgear failure, SF_6 and its by-products can be released into the environment.

SF_6 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_6 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_6 gas (which must comply with IEC 60736), which will also impact any handling of used SF_6, 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_6 are listed in Table 3-4, prioritised based upon toxicity and risk.

Table 3-4: SF_6 Gas and By-product hazard description [34]

Chemical Formula	Chemical Name	Permissible Exposure Limit (over 1 working day) (ppm)[7]	Experimental Concentration (percent by volume)**
HF	Hydrogen fluoride	1.8ppm [35]	1
SOF_2 (SF_4)[8]	Thionyl sulphide (sulphur tetrafluoride)	0.1 ppm [36]	0.5
SOF_4	Sulphur tetrafluoride oxide	0.1 ppm [36]	0.085
SiF_4	Silicon tetrafluoride	0.5 ppm [37]	0.085
S_2F_{10} (SF_5)	Disulphur decafluoride	0.01 ppm [36]	0.025
SO_2F_2	Sulphuryl fluoride	5ppm [35]	0.006
SO_2	Sulphur dioxide	2ppm [35]	0.002

Furthermore, additional by-products can be formed as a result of electrical discharge or arcing; these include SF_2, SOF_{10}, $S_2O_2F_{10}$, and H_2S. In addition, some metal fluorides compounds can form including copper fluoride (CuF_2), aluminium fluoride (AlF_3) and tungsten compounds (such as WF_6 and WO_3) [34].

Of these by-products, S_2F_{10} 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_2F_{10} is odourless in a pure form.

Engineering recommendation G69 provides clear advice on how to mitigate risks and hazards when working with SF_6 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 SF6 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].

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

[8] SF_4 is readily hydrolysed (broken down by chemical reaction with water) to SOF_2

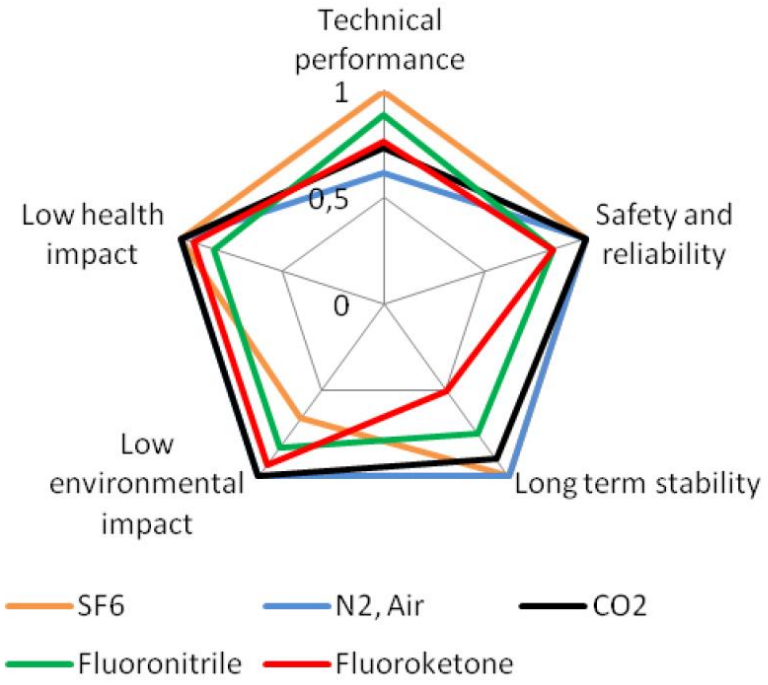

Figure 3-7: Outcome of holistic assessment of SF6 alternative mediums [38]

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4 SF_6 Alternatives

4.1 Requirements

Whilst the environmental impact of SF_6 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_6, 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_6 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_6 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_6 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_6 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_6 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

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can result in a significant proportion of the total capital expenditure; if physical size was not a constraint then AIS or CO_2 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_6 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_6 is not as comprehensive as the data detailing SF_6 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_6/N_2 mixtures

Initial work to reduce the SF_6 volume within switchgear was to mix pure Nitrogen (N_2) [43] or Carbon Dioxide (CO_2) [44].

Mixtures containing N_2 have already been in use within GIL, where large gas volumes are required. It was found that a mixture of N_2 with 10-20% of SF_6 showed a significant improvement in dielectric strength, however, the volume of SF_6 meant the mixture still possessed a high GWP.

In previous case studies, it was found that a mixture of SF_6 and N_2 in a 10/90 volume ratio yielded a dielectric strength of 59% , relative to pure SF_6, but the GWP is 8650 (38% of pure SF_6). 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_6 and can still potentially emit SF_6 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_6 [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_6 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 SF6, 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_5FK and C_6FK);**
  - Multiple compounds have been tested specifically for HV GIS applications. Studies have shown greater dielectric strength and low GWP when compared to SF_6. 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_4F_7N);**
  - Studies have shown promising results, with a high dielectric strength (approximately twice that of SF_6), 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_4F_8O, due to its low boiling point (0°C), low toxicity, and superior dielectric strength (relative to SF_6), 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_6) [21]

PFC	Dielectric Strength (% of SF_6)	GWP
CF_4	40%	7390
C_3F_8	88%	8830
C_4F_{10}	120%-130%	8860
C_4F_8	125%	10300
C_2F_6	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_6 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_2) 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_6, using computational methods. Furthermore, the paper has identified different criterion for identifying alternative solutions for SF_6 [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_6 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_6 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_6 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_6 free solution.

4.2.2.2 Synthetic Air

While previous sections in this report have outlined why SF_6 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_2, or CO_2 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_6, and such technology may require an increased physical footprint compared to that made possible when using SF_6 insulation. Therefore, any technology being evaluated to replace existing SF_6 assets should carefully assess this criterion.

4.2.3.2 Fluoroketones

Novec 5110 ($CF_3C(O)CF(CF_3)$) has been developed as an alternative to SF_6 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_6;
- 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_6 with trifluoroiodomethane (CF_3I) [59]. The superior dielectric strength of CF_3I, 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_2 or N_2, 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_3I 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_2 pure gas

While CO_2 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_6 [1] [63].

CO_2 has been previously investigated as both an insulating and interrupting medium. To enhance the arc-quenching ability of CO_2 without introducing corrosivity or flammability, an 85% CO_2/ 15% O_2 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_6 rated unit [44].

However, it has been noted in literature that common gases such as CO_2 and N_2, have significantly inferior interrupting capabilities compared to gas mixtures using SF_6 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_2 as a replacement for SF_6 have been developed, however they are much larger than SF_6 equivalent units [64].

4.3.2.2 Fluoronitrile

Novec 4710 has been developed as an alternative to SF_6 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_6;
- 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^3, a mixture of Novec 4710 and CO_2. Laboratory tests have been conducted to identify the technical characteristics of g^3 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_6 Alternatives

When an alternative medium to SF_6 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_6 gas is in:

- IEC 62271-303 – High-voltage switchgear and control gear: Use and handling of SF_6;
- 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_6, 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_6 switchgear for a significant period of time.

4.5 Summary of Identified Alternatives

Section 4 has outlined the key alternative solutions to SF_6 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_6 [39]

Mediums	SF_6	CO_2	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_6)	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_2 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_6 unit. However, CO_2 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_6 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[9]. 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_2 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_6 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_3HF_7) 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^3

The compound g^3, 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[10] (a C4-PFN) is blended with Nitrogen. At HV levels, CO_2 is blended to improve the gas electrical properties.

Technically, g^3 has been found to have similar performance characteristics to SF_6 For instance, it is able to deliver the same dielectric strength as SF_6 under ambient conditions.

[9] Referring to section 4.2.3.2

[10] Referring to section 4.3.2.2

Furthermore, g^3 has been tested for breaking capability and has been proved up to 420kV with similar dimensions and operating energy to SF_6 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^3 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^3. The project was commissioned in 2016;
- Scottish Power Energy Networks (Transmission) has awarded GE with a contract to supply a GIL with g^3 in Kilmarnock South Substation in the South West of Scotland; this project alone is estimated to save 1.7 tonnes of SF6; and
- Axpo, a TSO in Switzerland, is being supplied with a 145kV gas-insulated substation only using g^3 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_6 switchgear, matching the typical width of SF6 solutions. Furthermore, they have suggested that the capital and operational expenditure is lower when compared to SF_6 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_6 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_6 as an insulating medium, others such as Eaton and Schneider have developed SF_6-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_6 Alternatives

As outlined, there are multiple technologies arising which have the potential to replace SF_6 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^3, which do not have any literature demonstrating any switchgear at MV levels.

As this project is specifically looking to retro-fit SF_6 switchgear at a MV level, it is important to identify:

- Which current SF_6 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_6 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_6 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_6 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_6 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_6 within a circuit breaker. AirPlus and g^3 are both currently under test in live networks, and have been tested according IEC specifications. Furthermore, vacuum interrupting technology has been well researched with multiple companies offering commercial products using different insulating mediums; the alternatives to SF_6 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 SF6 gas which could be considered for retro-fitting into existing switchgear under laboratory conditions are AirPlus, g^3, HFC1234zee and solid epoxy. In addition, Nuventura's technology could be considered for UK field testing.

The interrupting alternatives to SF_6 gas which could be considered for retro-fitting into existing switchgear under laboratory conditions are g^3 and vacuum technology.

Table 7-1: Summary of Considered SF_6 Alternatives

Description	GWP	Suitable for Insulation	Suitable for Interruption	Comments
Pure CO_2	1	✗	✗	Not compact enough for SF_6 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^3' is a commercial product using this technology [40] [49]
CF_3I	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.

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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 he circuit) without failing. This will be the peak asymmetrical value (coloured red in Figure 8-1), as opposed to the RMS.

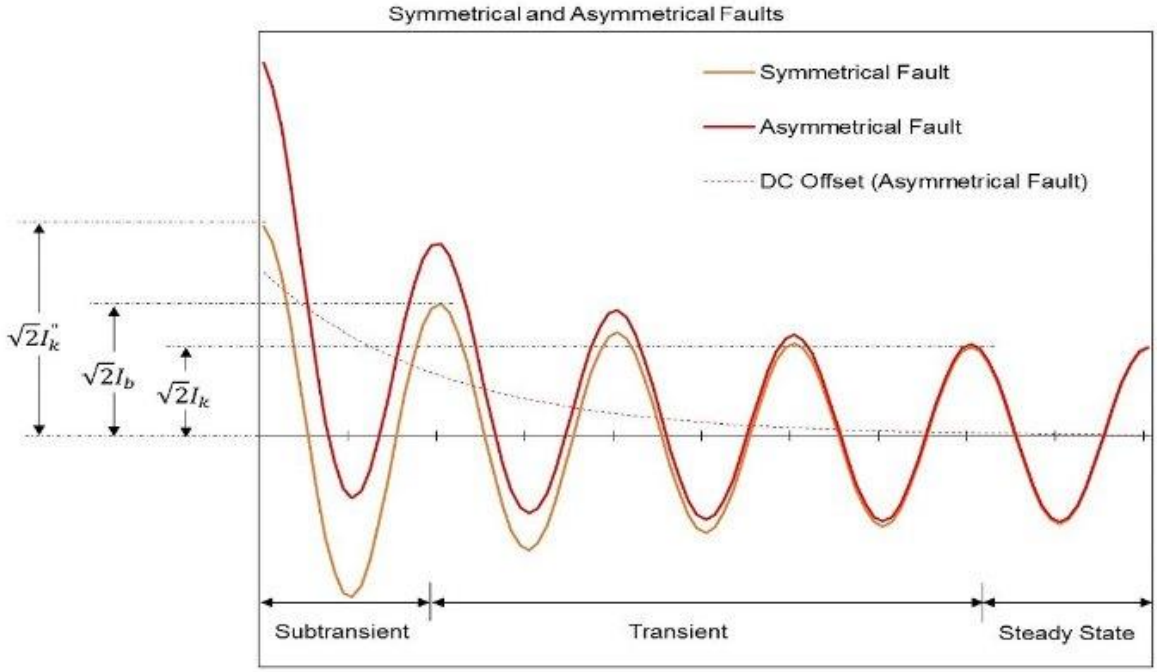

Figure 8-1: Illustration of Peak and RMS Short-Circuit Current

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 supress 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 supresses 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.

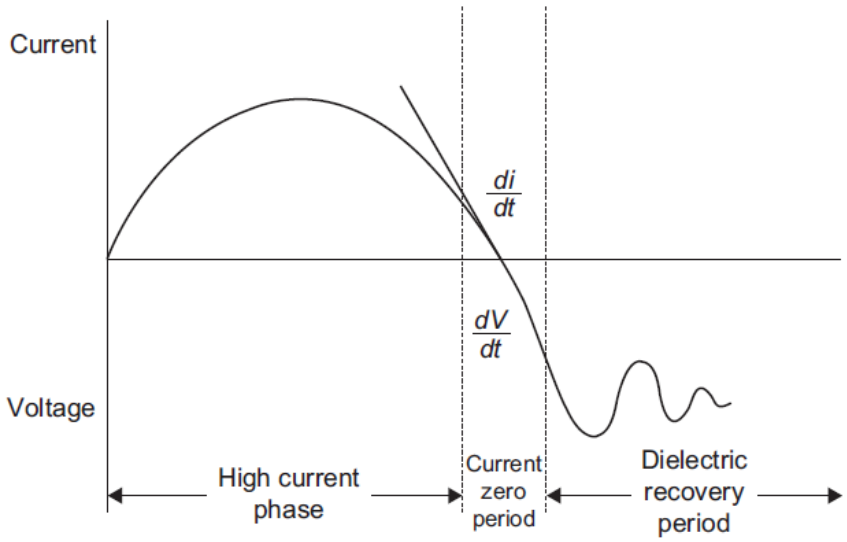

Figure 8-2: Current and Voltage profile during arc interruption [23]

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_6 applied in various gas-insulated electrical equipment

This appendix outlines how SF_6 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 SF6 can also be used as insulation in transformers and substations.

Gas Insulated Switchgear

In GIS, the SF_6 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 SF6 chambers in an example GIS feeder circuit breaker. All equipment in red denotes electrically live equipment with the yellow showing sealed SF_6. While Figure 8-3 shows an example operating at EHV (170kV), it demonstrates the different components of a typical GIS and how SF_6 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.

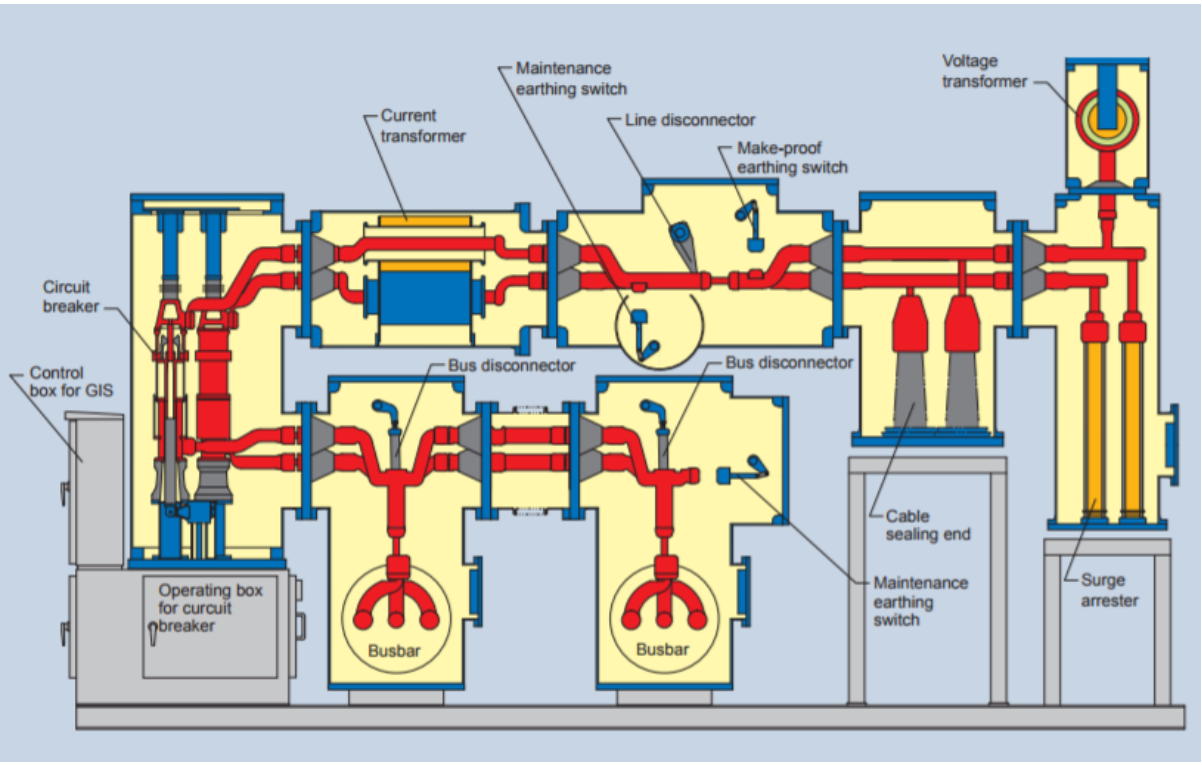

Figure 8-3: HV SF6 GUS Cross Section (Fuji Electric 170kV) [28]

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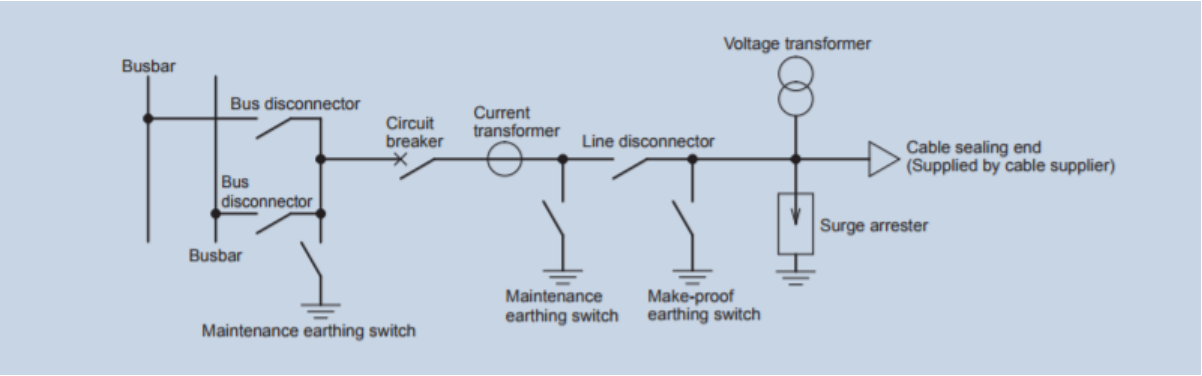

Figure 8-4: Single Line Diagram for Figure 8-3 [28]

Different types[11] 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 disconnector 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 disconnector 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_6 in earthed enclosures to allow more compact design to the superior insulating properties of SF_6 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.

[11] The different types are differentiated by the interrupting medium within the breaker. The main body discussed SF_6 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_6 as the insulating gas and a vacuum interrupter.

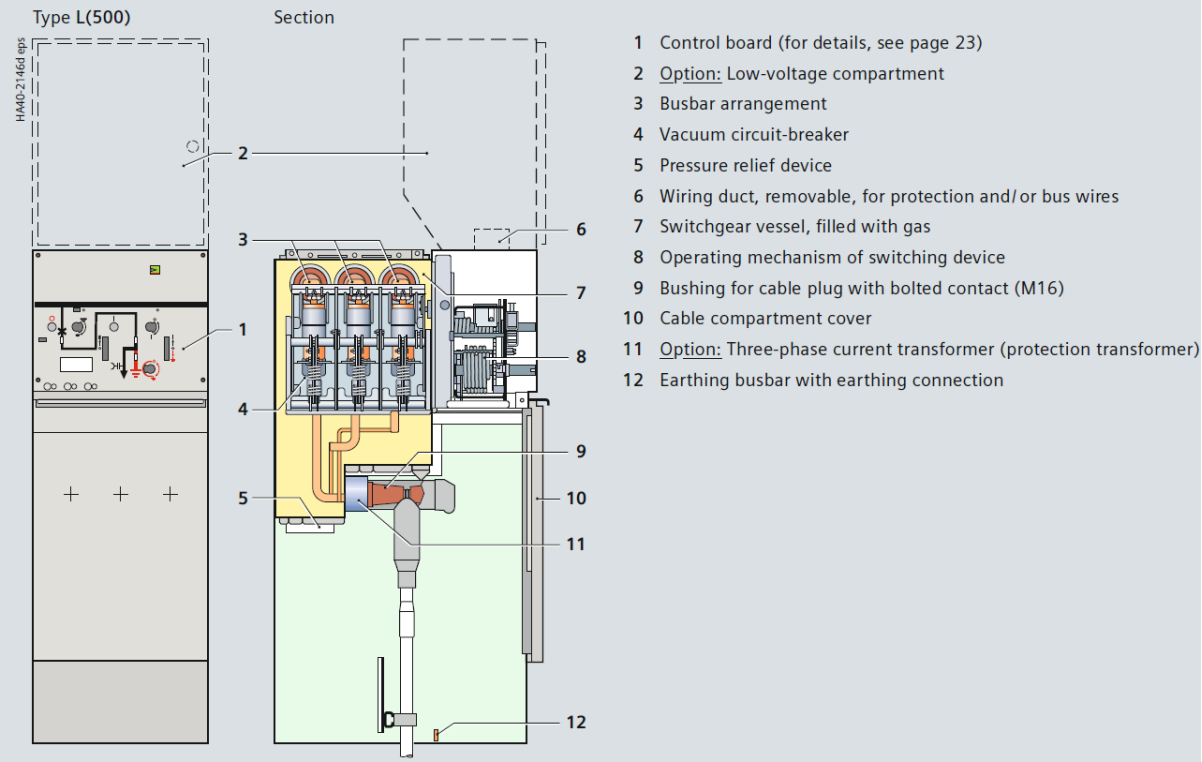

Figure 8-5: RMU example cross section (Siemens 8DJH Type L) [73]

Gas Insulated Lines

Gas Insulated Lines were developed in parallel to GIS, utilising the same insulating properties of SF_6 to provide safe, reliable transmission of high-voltage electricity. Similarly to GIS, designs achieve reduced space and minimal electromagnetic radiation. The key different 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_6, 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_6, an alternative solution rolled out across GB would significantly impact the amount of gas used by the energy industry.

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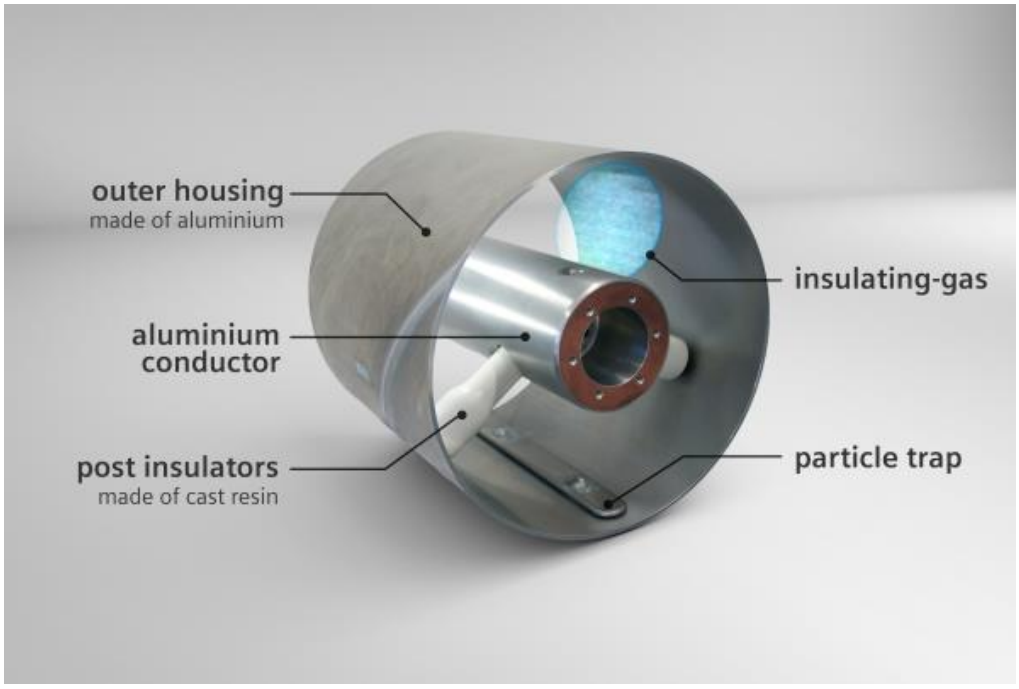

Figure 8-6: GIL Cross Section (courtesy of Siemens) [75]

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