The European Association of the Electricity Transmission and Distribution Equipment and Services Industry

TECHNICAL REPORT

5th March 2020

Technical report on alternative to SF6 gas in medium voltage & high voltage electrical equipment

FOREWORD

T&D Europe is the European Association of the Electricity Transmission & Distribution Equipment and Services Industry, which members are the European National Associations representing the interests of the electricity transmission and distribution equipment manufacturing and derived solutions.

1 - METHODOLOGY

This updated report issued 2020 is based on information made public before end of 2019.

Content is supported by “facts and figures”.

The report reflects the expertise of European medium voltage (MV, 1 to 52kV) and high-voltage (HV, above 52kV) switchgear manufacturers and shall provide an accurate and valuable overview of the European region, covering present and emerging technologies by applications, as well as its opportunities, limitations and drawbacks from today’s perspective (up to end 2019)

Other regions throughout the world are reported only if being of interest, for instance when the technologies used are significantly different to the ones in Europe but also applicable for European electrical networks.

For the mapping of present insulation & switching media for MV and HV switchgear apparatus, the installed base is considered up to end of 2019 and typical offers are considered for the last 7 years up to end of 2019.

To respect the limitations imposed by antitrust rules, only rough estimates for shares by common technologies are given.

Recent technical moves concerning alternatives to MV and HV SF_6 gas filled switchgear which occurred during the last 5 years: 2015 – 2019 are considered. “Alternatives” means all the switchgear using electrical insulation and switching media which have or may show a potential to become an alternative to SF_6 gas filled switchgear; non-gaseous media for insulation are also considered.

“Alternatives” does not necessarily mean that it will be able to replace SF_6 in all its electrical, physical, environmental, health, safety and handling properties.

To respect the limitations imposed by antitrust rules, manufacturer’s brands will not be shown. However, references to public available information about alternative products, pilots and research programs communicated before end of 2019 will be included.

2 - SCOPE

The purpose of this report is to provide a mapping of the status of alternatives to SF_6 gas filled switchgear by the end of 2019. The intent of T&D Europe is to provide a collection of documentations and to give an overview on the present situation. T&D Europe intends to revise this mapping when technical changes or progress will justify it.

The objective is to deliver a global perspective being valued by experts with general technical background. In-depth technical analyses shall be covered by other professional organizations like Cigré or IEEE and International standardization authorities like IEC. This report does not intend to cover economical comparison between SF_6 based switchgear and SF_6 free switchgear nor to deliver general conclusions or recommendations on alternatives to SF_6".

This report will support T&D Europe's management when updating its official position on this topic towards National, European or International authorities. It will contribute to the visibility of T&D Europe as a major stakeholder in the domain of switchgear technology.

This report is intended for both internal (T&D Europe) and external (public) use.

3 - INTRODUCTION

SF_6 is a reliable gas known for switchgear applications since the early 1960-ties and nowadays is one factor to ensure the reliability of power supply in electrical systems. SF_6 is neither toxic nor flammable and does not have any carcinogenic, mutagenic or repro-toxic (CMR) characteristics. On the other hand, SF_6 shows a high global warming potential (GWP) of 22 800 according to the European F-gas regulation 517/2014. Any alternative will need to be benchmarked with SF_6 and its characteristics, especially concerning electrical, physical and environmental, health and safety properties. The total ecological foot-print of any alternative needs to be evaluated considering the entire life-cycle.

Looking for SF_6-free solutions, some alternative technologies already exist and are available for specific applications.

Gas mixtures partly based on SF_6, partly using known gases or partly employing totally new gases are being researched and developed to reach electrical equipment having performances, dimensions and cost comparable to SF_6 switchgear but with a much lower global warming potential.

In the following, the current situation, published SF_6-free pilot switchgear applications, available products, published recent moves in SF_6-alternative technologies and future perspectives are presented.

Pictures which have no source listed have been supplied by members of T&D Europe.

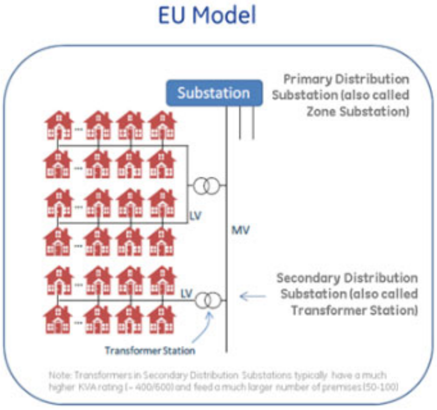
4 - TERMS AND DEFINITIONS

4.1 MEDIUM VOLTAGE (MV)

Medium Voltage: Alternating current (AC) high-voltage above 1 kV up to and including 52 kV.

MV is typically used for distribution of electrical energy in public and private (including industrial) networks.

Picture 1 Typical structure of European most common model of MV network



Source: Diagrams provided by Navigant Consulting

4.1.1 Secondary switchgear

In most cases found in MV/LV substations (S/S) with mainly load switching functions and rated for load current up to 630A and short-circuit current up to 25kA. It can also be found outdoor on overhead lines (OHL) pole-mounted with load-break switch or circuit-breaker (reclosers) and rated for load current up to 630A and short-circuit current up to 20kA.

4.1.2 Primary switchgear

In most cases found in HV/MV S/S with mainly circuit-breaker switching functions and rated for load current above 1250A and short-circuit current 25kA and above.

In this report, Secondary & Primary switchgear mean families of products. Details are given in the tables of chapter 5.

4.2 GENERATOR CIRCUIT-BREAKER SWITCHGEAR (GCB)

Switchgear that is installed between the generator and the transformer terminals, intended for use with generators and transformers rated 10 MVA or more and following the standard IEC/IEEE 62271-37-013.

4.3 HIGH VOLTAGE (HV)

High Voltage: Alternating current (AC) high-voltage above 52 kV.

HV is typically used for transmission of electrical energy from generation to distribution networks.

4.4 TYPES OF SWITCHGEAR

AIS (Air Insulated Switchgear): MV or HV Switchgear in which the electrical insulation is ambient air. Gas or vacuum interrupter may be used for switching purpose.

GIS (Gas Insulated Switchgear): MV or HV Switchgear in which the electrical insulation is mainly a gas within a gas-tight enclosure.

SIS (Solid Insulated Switchgear): MV switchgear in which the electrical insulation is mainly in solid insulating materials. Ambient air or gas may be, however, part of main insulation and/or for switching purposes, if applicable, in mechanical switches.

SSIS (Screened Solid Insulated Switchgear): SIS type of MV switchgear where the external surface of solid insulating materials is fully covered by a conductive or semi-conductive earthed screen.

4.5 FURTHER DEFINITIONS

The following terms are applicable within this document:

Air = ambient air (atmospheric pressure)

Filtered air = filtered ambient air (overpressure)

Dry air = dried ambient air

Synthetic air = mixture of O_2 and N_2 (20%: 80%, overpressure)

Natural origin gases = N_2, O_2 and CO_2 and their mixtures

Gas = all gases except ambient air at atmosheric pressure

5 - MAPPING OF PRESENT INSULATION & SWITCHING MEDIUM FOR SWITCHGEAR

5.1 EUROPEAN APPLICATIONS

5.1.1 MV applications

5.1.1.1 Segmentation by functions

An overall segmentation of MV applications with respect to main functions and ratings is given in the table 1:

Table 1 – Comparison of key characteristics for different MV applications and commonly used switching devices

		Utilities			**Private**
SECONDARY		MV/LV substation	MV switching substation	MV overhead lines pole-mounted switchgear	Commercial and ind. Building (Supermarket, Hotel, etc.), industry and infrastructure (Automotive, Food, Hospital, Airport, Data Centre, etc.)
	Main function	Switch for the ring, switch-fuse or CB for transformer protection	Circuit breaker or switch	Overhead line switch Overhead line recloser	Circuit breaker, switch and switch-fuse
	Feeder current	400 A or 630 A	630 A or 1250 A	400 A or 630 A	400 A or 630 A
	Short-circuit feeder	12.5 to 25 kA	12.5 to 25 kA	12.5 to 20 kA	12.5 to 25 kA
	Product's rated Voltage	12 kV to 36 kV (in Europe)	12 kV to 36 kV (in Europe)	12 kV to 36 kV (in Europe)	12 kV to 36 kV (in Europe)
PRIMARY		HV/MV & MV/MV substation			High power industry (oil & gas, metallurgy, mining, Cement, etc.)
	Main function	Circuit breaker			Circuit breaker, contactor
	Feeder current	1250 to 2500A			630 to 4000 A
	Short-circuit feeder	12.5 to 25 kA			31.5 to 50 kA
	Product's rated Voltage	12 kV to 36 kV (in Europe)			12 to 36 kV (in Europe)

5.1.1.2 Present type of insulating and switching medium

The split of switchgear on different insulating media is estimated for the switchgear offer of the last 5 years. It is important to note that the split of the installed base may be significantly different driven by an evolution from AIS to GIS and progressive replacement of ageing equipment. Information about installed base equipment might be collected via network operators.

Definitions of primary switchgear and secondary switchgear are given in §4.

5.1.1.2.1 Secondary switchgear

Technologies are decided mainly by utilities for secondary distribution.

2 types of functional units are considered:

- "SWITCH" in these tables designates a functional unit with switch or switch-fuse combination (switch and a fuse in series),
- "CB" in these tables designates a functional unit with a circuit-breaker.

An overall Segmentation of secondary switchgear with respect to insulating & switching media is given in table 2.

Table 2 – Main insulating and switching media per segments for secondary switchgear

		Utilities			**Private**
SECONDARY		MV/LV substation	MV switching substation	MV overhead lines pole-mounted switchgear	Commercial and industrial building (supermarket, hotel), industry and infrastructure
	SWITCH Insulating medium	SF_6: High Air: Low Dry air in sealed tank + solid (hybrid): Very low			SF_6: Medium Air: High Solid: Low
	SWITCH Breaking medium	SF_6: Very high Vacuum: Low Air: Very low			SF_6: High Air: Low Vacuum: Low
	CB Insulating medium	SF_6: High Air: Low Dry air in sealed tank + solid (hybrid): Very low			SF_6: Low Air: High Solid: Low
	CB Breaking medium	SF_6: Low Vacuum: High			SF_6: Low Vacuum: High

Stated percentages of Table 3 reflect estimated repartition of functional units and media used for insulation and switching, in secondary distribution

Table 3 – Estimated repartition of functional units for secondary switchgear

Secondary switchgear				
Switch (80 %)		CB (20%)		
Insulating medium	Switching medium	Insulating medium	Breaking medium	Disconnect medium
SF_6: 45 % Air: 50% Solid < 5 % Dry air < 2 %	SF_6: >90 % Air < 5 % Vacuum < 5 %	SF_6: 25 % Air: 75% Solid < 5 % Dry air < 2 %	SF_6: 30 % Vacuum: 70 %	95% SF_6

In CB functional units, mostly disconnector switches are also used which rely to a high percentage on SF_6 insulation, so that finally estimated 95% of all CB functional units have some SF_6 inside & only estimated 5% have no SF_6 at all.

For switch functional units, less than estimated 10% of the units use no SF_6 at all.

Outdoor secondary distribution switchgear often is mounted on poles and towers out-of-reach. They have been typically AIS type (rarely operated in the past), but with smart grids, higher concern on quality of service and on people and worker's safety, many of them are being replaced during last 10 years by pole mounted SF_6 filled switchgear (for load switches) and pole mounted vacuum interrupters (for circuit-breakers).

The order of magnitude of installed base of secondary functional units in Europe is estimated to 10 million units. Typical quantity of SF_6 per functional unit is between 0.2 and 1 kg.

Typical filling pressure of SF_6 in MV switchgear compartments is 1.2 to 1.4 bar absolute.

Typical width of one functional unit is 375 to 750 mm for AIS (12 – 24kV), and 310 to 500 mm for GIS (24 – 36kV).

Typical indoor AIS and GIS secondary switchgear: switch, switch-fuse & CB functional units:





5.1.1.2.2 Primary switchgear

An overall segmentation of primary switchgear with respect to insulating & switching media is given in table 4.

Table 4 – Main insulating and switching media per segments for primary switchgear

		Utilities	Private substations	
PRIMARY		HV/MV & MV/MV substation	Electro-intensive Industry (Oil & Gas, Metallurgy, Mining, Cement ...)	Medium Industry and Infrastructure (Automotive, Food and Beverage, Hospital, Airport, Data Centre...)
	SIS	No	No	Low
	GIS	Medium	Medium	Medium
	AIS	High	Medium	Medium

Stated percentages of Table 5 reflect estimated repartition of functional units and media used for insulation and switching, in primary distribution

Table 5 – Estimated repartition of functional units for primary switchgear

Primary switchgear					
SIS (< 5 %)		GIS (30 %)		AIS (65 %)	
Insulating medium	Breaking medium	Insulating medium	Breaking medium	Insulating medium	Breaking medium
Epoxy: 100%	Vacuum: 100%	SF_6: 100 %	Vacuum: 90% SF_6: 10%	Air: 100%	Vacuum: 70% SF_6: 30%

In SIS, ambient air or gas is required for insulation or disconnecting purposes in mechanical switches.

The order of magnitude of installed base of primary functional units in Europe is estimated with 1 to 2 million. Typical SF_6 quantities are between 2 and 3kg for GIS and between 0.1 and 0.6 kg for AIS equipped with SF_6 circuit-breakers.

Typical filling pressure of SF_6 in MV switchgear compartments is 1.4 to 1.8 bar absolute.

Since the 1980ies there is a trend to install more SF_6 GIS switchgear. The higher is the rated operating voltage the higher is the share of SF_6 GIS switchgear compared to other technologies.

The ratio AIS to GIS may also depend on the specific country.

At European level, an approximate share of 30% of all primary switchgear is roughly estimated for SF_6 GIS as shown in the table above.

Typical width of one functional unit is 500 to 1000 mm for AIS (12 – 24kV), and 450 to 800 mm for GIS (24 – 36kV).

Typical indoor AIS and GIS primary switchgear functional unit:

5.1.1.3 Impact criteria

For both, primary and secondary switchgear, a very large variety of equipment is available depending on required switchgear arrangements and specified performances such as: rated values, use for indoor or outdoor applications, withstand to climatic conditions, offering specific operating functionality such as recloser, requested maintenance functionality (e.g. for withdrawable equipment), technology and more.

Primary switchgear can additionally be differentiated in single and double bus-bar designs, related to different levels of service conditions for the power supply. Double bus-bar designs also rely on switch disconnectors, which mostly use SF_6 as insulating medium due to space limitations.

The maximum leakage rate for MV sealed pressure systems, mostly agreed throughout manufacturers and operators, is 0.1 % p.a.

For non-sealed for life equipment the standardized maximum leakage rate is 0.5 % or 1 % p.a. according IEC 62271-1.

Current offer for MV secondary and primary distribution switchgear using SF_6 is 100 % sealed pressure system, usually also named “sealed for life” type.

Contactors are used to frequently operate motors, mainly for industrial applications. Primary AIS type equipment mostly uses vacuum interruption. This is an element to be easily replaced in case of failure or when reaching its end of life.

Customers often choose switchgear suitable for particular environmental surrounding conditions. In this case, fully “insulated & screened” switchgear is preferred by many user’s due to:

- Low necessity of maintenance → High availability → Reduced OPEX
- Insensibility to altitude and/or moisture → Flexible use → Reduced OPEX
- Longer life expectancy → Deferred CAPEX
- Same small size of equipment from 1 to 24 kV up to 630 A → Flexible selection & installation design & future evolution → Reduced CAPEX
- Safety with all MV parts fully encapsulated and screened

DNOs (Distribution Network Operators) and engineering companies are used to specify the main technology of insulation of MV switchgears depending on previous experience and number of possible suppliers.

5.1.2 Generator Circuit-Breakers

Generator Circuit-Breakers (GCB) are used to protect generators in power plants at voltages between 1 and 33 kV. These are medium voltage devices designed for operating with high continuous currents and high short-circuit currents. Generator Circuit-Breakers are used in Generator Circuit-Breaker systems which can also include disconnectors, earthing switches and instrument transformers.

In this report only the Generator Circuit-Breaker function where SF_6 can be used at time is considered under the “Generator Circuit-Breaker” designation.

Typical GCB systems:

For designs above 10 MVA, a specific IEC/IEEE standard for GCB is applicable (IEC/IEEE 62271-37-013).

The Generator Circuit-Breaker applications are segmented into different power generation classes, starting from 10 MVA up to more than 800 MVA per unit, where the power in MVA is used on the basis of the rated voltage multiplied by the rated continuous current.

For powers below 50 MVA, most applications are covered by vacuum Generator Circuit-Breakers, whereas above 50 MVA the use of SF_6 Generator Circuit-Breakers is by far the technology which is most applied (typically 95 %).

The remaining 5 % of the applications in the upper range either use vacuum technology or air-blast technology. Because of the relatively low arc voltage the vacuum technology is restricted to niche applications, where delayed current zeros are insignificant. The air-blast technology is still used and overhauled in older power plants but due to its large maintenance time and costs no longer installed in new installations and more and more replaced in old installations Respective ratings of SF_6 and Vacuum technologies for GCB are:

- Generator Circuit-Breaker in the 10 to 2000 MW range with SF_6 technology cover short-circuit ratings up to 33 kV and 300 kA, with continuous currents up to 50000 A.

- Generator Circuit-Breakers in the 10 to 400 MVA range with vacuum technology cover short-circuit ratings up to 24 kV and 100 kA, with continuous currents up to 12500 A

Worldwide, approximately 2/3 of all power generators are installed with GCB.

GCB installed base in Europe is estimated less than 1500 units (3 phases) including SF_6, VI and pressurized air technologies.

SF_6 GCB installed base in Europe is estimated less than 1000 units.

The quantity of SF_6 used per unit is depending on the maximum rating of the GCB. A typical range is between 5 and 20 kg per unit.

5.1.3 HV applications

5.1.3.1 Different types of applications

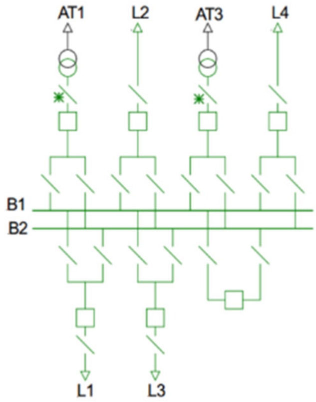
For rated voltage above 52 kV i.e. high voltage, the switchgear is associated with so called “Gas Insulated Substations (GIS)” and “Air Insulated Substations (AIS)”:

5.1.3.1.1 Gas insulated substations (GIS) and related switchgear

In GIS, all the functions of the S/S are enclosed in metallic enclosures filled with SF_6. The typical components of a GIS are circuit-breakers, bus-bars, bus-bar & line disconnectors, maintenance earthing switches with or without short-circuit making capability, instrument transformers (current & voltage measurement), interfaces with overhead lines (SF_6 to air bushings), cable ends, direct connections to transformers, and surge arresters.

SF_6 is used for insulation, as well as for interrupting & making short-circuit currents and switching continuous or induced currents.

Typical single line diagram of a double bus-bar substation (GIS or AIS):



Typical 145kV GIS arrangement – with all functions SF_6 insulated:

A special application is the Gas Insulated Line which can be used instead of cables or overhead lines. It covers also Gas Insulated Busduct (GIB) for connecting various parts of equipment inside a substation. These connections are available at all rated voltages. The quantity of SF_6 applied may be quite large depending of the voltage and of the length of the duct.

Alternatives with a gas mixture N_2 & SF_6 (ratio between 90/10 and 70/30 %) have been used in a couple of cases to cope with very low temperatures or to reduce the GWP by reducing the quantity of SF_6 applied in the bus ducts. However, with typical GWP per kg around 15000, these gas mixtures have not been considered as real alternative to SF_6.

Typical 420kV gas insulated bus ducts:

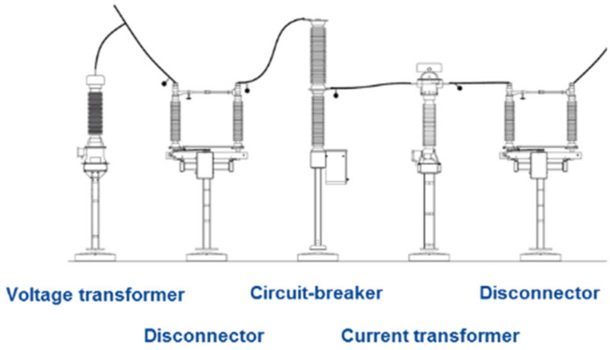
5.1.3.1.2 Air Insulated Substations (AIS) and related switchgear

In AIS, the phase to ground insulation is generally insured by air. The parts intended to be operated at high voltage are supported by solid insulators made of ceramic or compound material. In AIS, SF_6 is used mainly for interrupting purposes and internal insulation between open contacts or along insulating mobile rods in SF_6 circuit-breakers. Sometimes SF_6 is also used in instrument transformers (current, voltage or combined current & voltage measuring equipment) instead of oil insulation which is commonly used in instrument transformers in AIS. Other components like disconnectors, bus-bars, earthing switches, surge arresters, lines, cables and transformers interfaces are insulated by air.

The circuit-breakers in AIS use 2 types of architectures, the “live tank” breaker where the interrupting unit is enclosed in insulators made of ceramic or insulating compound materials & “dead tank” circuit-breaker where the interrupting unit is enclosed in an earthed metallic housing like the enclosure used in GIS. In the latter case, the connection to the other components of the S/S is provided by SF_6 to air bushings.

Typical AIS substation with live tank circuit-breakers:

Typical arrangement of AIS switchgear in AIS substation with live tank circuit-breakers:



Typical "dead tank" circuit-breaker arranged in AIS substation:

5.1.3.1.3 Mixed Insulated Technology Switchgear (MITS)

In MITS, also called Hybrid Insulated Switchgear (HIS), all the components except the bus-bar are SF_6 insulated. The bus-bars are insulated by air. Bus-bars and overhead lines are connected to the SF_6 insulated parts by SF_6 to air bushings. When cables are used, they are connected to SF_6 switchgear by direct interfaces, and when transformers are used they are generally connected through air insulated connections.

Typical 145 kV Mixed Insulated Technology S/S:

5.1.3.1.4 Bushings

A bushing enables one or several conductors to pass through a partition such as a wall or a tank and insulate the conductors electrically from it.

Most of applications are interfaces with switchgear and are considered in previous paragraphs dealing with GIS, AIS or MITS substations.

Additional applications are wall bushings, bushings for cables to pass from solid or oil insulation to air insulation and bushings for power transformers to pass from oil insulation to air insulation.

A bushing is designed to withstand the electrical field strength all along the length of the bushing. The main insulation including grading capacitor is insured by oil impregnated paper or resin impregnated paper. In limited number of applications like for HVdc wall bushings, the main insulation is insured by pressurized SF_6.

In the case of resin impregnated paper and in order to ensure the voltage withstand in the small space around the main insulation and conductor, most HV bushings have the space between the outer, enclosing insulation part (e.g. porcelain) and the resin and the conductor filled with an insulating gel (typically silicone) or a foam (typically polyurethane based). Foams are manufactured under SF_6 or Nitrogen atmosphere. SF_6 ensures a better withstand even in case of a sudden damage of the bushing due to an impact (vandalism).

In the case of resin impregnated paper bushings filled with foam and SF_6, today the whole amount of SF_6 used during manufacturing process of the insulating foam is reported as emission although - except of the part of SF_6 consumed by the manufacturing process - all the SF_6 is captured within the foam during the bushing's lifetime. Only in case of a damage of a bushing some SF_6 would be released from destroyed foam-bubbles only. Nevertheless, since there is no end-of-life procedure available for bushings – these bushings sometimes have a length of several meters, it cannot be assured that the used SF_6 will be recovered.

Typical power transformer with bushings & wall bushings:

5.1.3.2 European applications

European HV networks are typically rated 72 & 90 kV, 123 kV, 145 kV, 170 kV, 245 kV, 300 kV & 420 kV. Higher voltages (such as 550, 765 or 1100 kV ac) are not used today in Europe.

5.1.3.2.1 GIS

GIS is widely using SF_6 insulation technology in Europe, but SF_6-free GIS are in service, too. The first SF_6 GIS has been put into service in the1960ties. Before 1970, HV networks were essentially using Air Insulated Substations.

Main applications of GIS are found in dense urban areas, in highly polluted environments or in areas under climatic constraints (coast, industrial, high altitude, low temperature, etc.) and in other locations with strong footprint constraints (offshore platforms, hydraulic power plants in mountains, caverns, etc.).

In terms of number of assets in operation (installed base), for Europe an approximate percentage of 90 % for AIS and 10 % for GIS can be considered. This overall estimate may vary depending on countries and rated voltages.

In terms of number of new assets yearly put into operation, an approximate percentage of 80 % for AIS and 20 % for GIS can be estimated which also depends on countries and rated voltages.

Quantities of SF_6 banked in the switchgear are important. The order of magnitude for SF_6 insulated equipment depends on the rated voltage and on the functional units included in the specific single line diagram. Generally, the size of a S/S is defined by the number of lines connected; each line corresponds to a “bay” of equipment. Typical quantities of SF_6 per bay of a recent GIS are in the range 30 to 1200 kg normally increasing from 72 to 420 kV. Typical filling pressure of SF_6 in HV GIS is 5.0 to 7.5 bar absolute.

Typical ratings available for GIS are:

1. HV SF_6-gas insulated switchgear is used in Europe for substations up to 420 kV, 63 kA, and 6300 A continuous current. Up to 170 kV, 3-phase enclosures are commonly applied, whereas for higher voltages single-phase enclosures prevail.
2. For non-European applications, switchgear up to 1100 kV rated voltage is available.

5.1.3.2.2 AIS

AIS in Europe is mainly built using “Live tank” type circuit-breakers (estimate: more than 95 %) with niche applications for dead tank circuit-breakers and MITS technologies. “Dead tank” & MITS are exclusively SF_6 insulated.

Very few exceptions have to be reported for very low minimum operating temperatures with gas mixtures of SF_6 & N_2 or SF_6 and CF_4. However, with typical GWP around 15000 per kg, these gas mixtures have not been considered as real alternative to SF_6.

Live tank circuit-breakers are as old as the network itself. Different types of interrupting media have been used such as bulk oil, low volume oil, pressurized air and SF_6. This is illustrated by an extract taken from the introduction of IEC standard 62271-100 on CB:

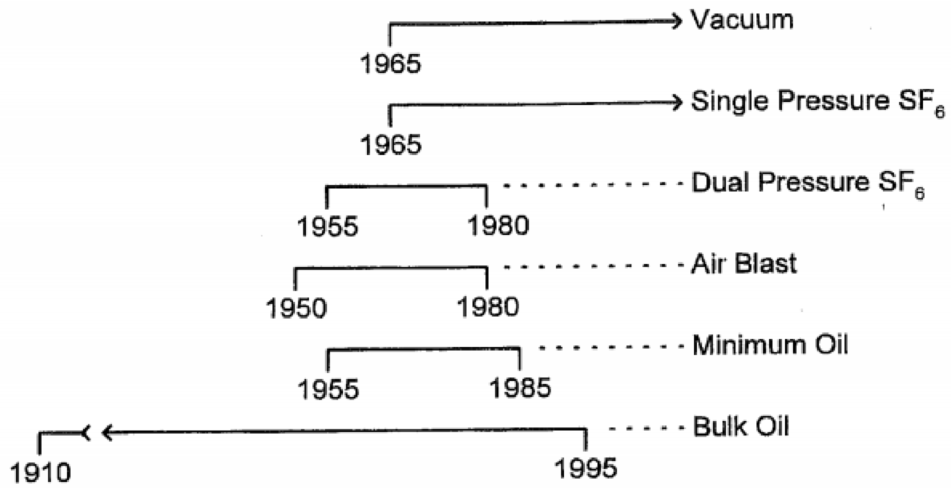


Figure 1 - Timelines for application of different circuit-breaker types. Solid lines indicate approximate or ongoing manufacturing periods

At time being all the HV AIS CB delivered in Europe are of SF_6 type. Manufacturing of the other types has been stopped at the end of 1990ties or even before. The move to SF_6 enabled a huge reduction in switchgear size, cost, energy for operating mechanism and number of interrupting units in series for highest voltages. In terms of safety the benefit was also remarkable (reduced fire risk compared to oil breakers, reduced operating pressures - typically by 10 times - compared to pressurized air breakers).

Typical ratings of AIS today available are:

- HV live tank SF_6 circuit-breakers are applied from 72.5 kV up to 420 kV in Europe and up to 1100 kV worldwide for short-circuit currents up to 80 kA and continuous currents up to 5000 A. Up to 300 kV one interrupter unit per pole is used, up to 550 kV two, and above 1100 kV up to four interrupter units in series are applied. In addition, 72.5 kV live tank circuit-breakers started using VI technology (in 2010).
- HV dead tank SF_6 circuit-breakers are applied from 72.5 kV up to 300 kV in Europe and up to 800 kV worldwide, for short-circuit currents up to 90 kA and continuous currents up to 5000 A. The breaker's enclosure is filled with SF_6 and connection to overhead lines or bus-bars is achieved by SF_6 to air bushings.

In terms of existing assets, the number of non SF_6 CB is estimated to be in the same order of magnitude as the number of SF_6 breakers. Ageing equipment is now replaced by SF_6 breakers. Therefore, the ratio is evolving to more SF_6 equipment than pressurized air or oil filled equipment.

Typical quantities of SF_6 per three poles in a "live tank" circuit-breaker are between 2 and 50 kg. Typical filling pressure of SF_6 in HV Live tank CB is between 5.0 and 7.5 bar absolute.

A variant of HV Live tank circuit-breaker is a switchgear combining functions of both, circuit-breakers and disconnectors, called DCB for disconnector circuit-breaker. Today this is a minor application in Europe which represents a very limited number of units and therefore a small quantity of applied SF_6 compared to the units with standard live tank design. For this technical report on SF_6 alternatives, it will not be considered separately from the live tank circuit-breakers application.

Instrument transformers:

Another use of SF_6 in AIS in Europe is found in a limited number of instrument transformers, current, voltage & combined metering units. SF_6 is preferred for safety reasons (fire risk) and for environmental reasons (avoid soil pollution risk).

At time being, the estimated order of magnitude is around 90 % for use of oil for insulation of instrument transformers and 10 % for SF_6.

Typical available ratings are:

- HV instrument transformers using SF_6 as the main insulation medium between high-voltage and earth potential are rated up to 420 kV and 6000 A concerning current transformers and up to 420 kV concerning voltage transformers. The performance is equivalent to the performance of oil insulated instrument transformers.
- The typical quantity of SF_6 per pole of an instrument transformer is in the range of 10 to 60 kg depending on the type & voltage rating. Typical filling pressure of SF_6 in HV instrument transformers is 5.0 to 7.5 bar absolute.
- A special niche application of instrument transformers are power voltage transformers with an extended burden making it suitable to supply power to remote isolated locations. Typical performance of SF_6-insulated power voltage transformers for AIS range from 72.5 kV up to 420 kV with an output power up to 125 kVA (single-phase operation).

Disconnectors in AIS are always ambient air insulated delivering a visible gap for extended personnel safety during operation and maintenance.

5.1.3.2.3 Mixed Insulated Technology Switchgear (MITS)

This type of switchgear and applications with special combined functions have typical performances as follows:

HV Hybrid dead tank compact switchgear combining SF_6 encapsulated components and ambient air-insulated devices is available with ratings up to 245 kV, 63 kA, 4000 A with a few 420 kV 40 kA applications in Europe.

This technology represents a limited part of the CB installed yearly in Europe and is estimated to 3% or less. Since MITS is relatively new (later than year 2000), the installed base represents an even smaller part of the total European installed base of circuit-breakers (<1%).

Typical mass of SF_6 per unit depends on the rated voltage and switchgear architecture (e.g. single or double bus-bar) and may be considered being between 15 kg & 60 kg of SF_6 per a 3 phases unit.

5.2 AMENDMENTS FROM OTHER REGION'S APPLICATIONS AND USE CASES:

5.2.1 MV applications

Globally, CBs (interrupting in SF_6 or vacuum interrupters) for transformer protection are of higher significance than in Europe where switch-fuse combinations are preferred (switching in SF_6).

USA have a quite different network structure which is not comparable to the one in Europe.

In USA & North America, the main applied technology for primary distribution networks is AIS, with interruption by vacuum breakers and insulation in air.

In North America, pad mounted arrangements for secondary distribution underground networks commonly use oil or SF_6 for insulation purposes. Air-break switches are commonly used in overhead secondary distribution networks.

In China, GIS is more common than AIS for secondary distribution. SIS (Solid Insulation switchgear) has been pushed by National State Grid in the past (to reach a share of 10 % in 5 year's plan) for secondary distribution.

5.2.2 Generator Circuit-Breakers

Requirements for Generator Circuit-Breakers for the worldwide market are the same as in Europe.

5.2.3 HV applications

3 main differences can be reported:

- The use of GIS versus AIS is estimated to be higher in some regions like Japan, Korea, and China. The technologies used for GIS & AIS are the same as in Europe.
- The use of the "dead tank" breaker instead of the "live tank" breaker is more common for AIS is in some areas, mainly North America and to less extend in Japan. The quantities of SF_6 are larger in "dead tank" breakers than in "live tank" breakers.
- For specific 72/84 kV "dead tank" breakers in Japan, vacuum interrupters are frequently used. A few thousands of vacuum CB's are in operation in Japan and USA.

6 – RESEARCHES ON ALTERNATIVE GASES

6.1 COMMON REQUIREMENTS

Research has been ongoing to find a gas or gas mixture as alternative to SF_6 for use in medium and high voltage equipment. Such a new gas or gas mixture must have negligible impact on health and environment, including the safety of switchgear operators and public. It ideally has:

- Sufficient dielectric strength even at low operating temperatures;
- Stable behavior over lifetime, even under electrical stress;
- Good arc quenching and current interruption capability;
- Load current switching capability for MV load switches;
- High heat dissipation and heat capacity for current carrying purposes;
- Applicable for indoor and outdoor switchgear down to ambient temperatures of at least -30°C;
- Compatibility with switchgear materials (the gas must not be degraded by materials and materials must not be degraded by the gas and its by-products during the equipment's life cycle) and low diffusion across sealing materials;
- Low toxicity i.e. be non-toxic or have a low acute toxicity, be non-carcinogenic, nor mutagenic, nor repro-toxic, generate no toxic metabolites;
- Minimal environmental impact i.e. having low GWP and showing no ozone depletion potential (ODP), no water pollution potential, etc.;
- High safety characteristics like: be non-flammable, nor explosive, nor corrosive, etc.;
- Reasonable availability of the gas by multi-sourcing on the market and at affordable costs;
- Allowing equipment design compactness like today's equipment;
- Easy gas handling.

6.2 AVAILABLE OR RECENTLY DEVELOPED TECHNOLOGIES

Natural origin gases such as dry air [19], [20], [22], [27], Nitrogen, CO_2 or their mixtures have advantage in regard of low global warming potential but show drawbacks concerning their limited dielectric strength being approximately 40 % or less compared to SF_6.

Use of such a gas or gas mixture as insulating or current interrupting medium and keeping today's technical performance would lead to drawbacks specifically for high voltage switchgear. For high voltage, the product design – i.e. either HV equipment filling pressure or HV apparatus dimension is estimated to increase considerably. Increasing the pressure would thereby impact vessels and enclosure design. An increase of the equipment size to compensate the reduced dielectric strength e.g. by unchanged pressure would directly impact the dimensional footprint and thus material cost of the switchgear. Especially the footprint topic would have to be considered if replacement of existing equipment in HV substations is targeted. Considering gas-breaker applications, CO_2 has a higher thermal interruption capability than N_2 or air.

Oil was used decades ago for current interruption, however imposes the risk of explosion in case of interruption failure or in the event of an internal fault. Thus, today almost no acceptance can be seen for this alternative. In addition, precautionary measures will have to be considered to avoid any pollution of the environment (e.g. of soil) during the equipment's life cycle.

CF_3I – trifluoro iodomethane - presents the advantage to combine high dielectric strength and current interruption capability with a low global warming potential (below 10) but is classified CMR category 3 [1][2]. This means it is suspected to be mutagenic and therefore not suitable for widespread application in equipment in contact with the public [3] unless escape of gas is ensured to never occur during its entire life cycle.

Other gases and gas mixtures:

At present, other gases are applied or under consideration for insulation, in particular gas mixtures that include C_5-Fluoroketones (C5-FK, $C_5F_{10}O$) [8], C_4-Fluoronitriles (C_4-FN, C_4F_7N) [9] and hydrofluoroolefins (HFO1234zeE). These pure substances have considerable lower global warming potential (GWP) than SF_6 and C_5-FK even at the level of CO_2. One disadvantage is that the pure substances show low liquefaction temperatures of 26.5 °C for C_5-FK and -4.7°C for C_4-FN at 1 bar (eq. standard atmospheric pressure). Therefore, an admixture of a buffer gas is needed to ensure operation at typical ambient temperatures [14] (according to standards, a switchgear operating temperature of -5°C is at least required for indoor switchgear, and at least -25°C for outdoor switchgear). HFO1234zeE has a boiling point of -19°C at 1 bar absolute and might be useable without buffer gas but could be limited to dielectric insulation without current switching.

These alternative gases or gas mixtures generally do not provide the same current interruption ability as SF_6 has. Designs adaptions might be necesary to reach equal current interuption abilities, dependant on the interruption technology, ratings and used gas or gas mixture [note: CIGRE WG A31 is currently studying on this subject].

Vacuum is widely used in medium voltage equipment as reliable interruption medium and is well established for this purpose. Application in high voltage equipment at 72.5 kV is now state of the art and designs up to 145 kV exist. Due to the intrinsic insulating characteristics of vacuum, its insulation capability is not directly proportional to the insulating gap as it is for pressurized gas. A saturation of the insulation capability for large gaps in vacuum can be stated making the use of vacuum interrupters for higher voltages a challenge [14].

7- RECENT TECHNICAL MOVES ON ALTERNATIVE GASES TO SF_6 FOR SWITCHGEAR

7.1 INTRODUCTION

As already written in section 6, gas mixtures partly using other known gases and partly employing totally new gases (at least new for electrical switchgear applications) are being researched and developed to obtain electrical equipment having performance, dimensions and cost comparable to SF_6 switchgear, however, with a much smaller GWP than SF_6.

All alternatives must be duly proven before they are placed on the market, where the security and people safety of the electrical equipment in distribution and transmission networks are of highest priority. Consequently, for widespread implementation of a new alternative, it is desirable to develop and agree on harmonized performance criteria to ensure a comparison of the currently discussed alternatives with SF_6 solutions with respect to ratings, dimensional footprint, switching performance, chemical and physical data, environmental aspects, health and safety issues, life-cycle and handling.

In the following, pilot switchgear applications, launched products and recent moves in technology are presented. The information is based on public available literature by research institutes, equipment manufacturers and users.

7.2 EUROPEAN REGION

7.2.1 MV Applications

M1.1: 24 kV GIS with synthetic air and Fluoroketone mixture for insulation

Type	24k V / 36 (40,5) kV GIS (Primary distribution)			
Insulation /GWP	C_5-Fluoroketone gas mixed with synthetic air at 1.3 bar abs. / <1			
Breaking /GWP	Vacuum interrupter / 0			
Rated performance	Ur (kV)	Ir (feeder) (A)	Isc (kA)	Min. op. Temp. (°C)
	24 / 36 (40,5)	2000	25 / 31,5	-15
Product first exhibition & year	Prototype shown in Hanover fair 2015			
Pilots & year of delivery/ service	2 S/S, in Switzerland and Germany, first one in service since beginning of 2016			
Footprint versus SF_6	Same			
Weight vs SF_6	Similar weight			
Comments				

Sources: Cigre session 2016, publication B3-108 & manufacturer & EWZ publications

M1.2: 12-24 kV 2000A GIS with air insulation

Type	12- 24 kV GIS (Primary distribution)			
Insulation /GWP	Filtered air, 1.4 bar abs for 12 kV, 2.5 bar abs for 24 kV, GWP = 0			
Breaking /GWP	Vacuum interrupter / 0			
Rated performance	Ur (kV)	Ir (feeder) (A)	Isc (kA)	Min. op. Temp. (°C)
	12 - 24	2000	31.5	- 25°C
Product first exhibition & year	CIRED Q2/2019			
Pilots & year of delivery/ service	2020			
Footprint versus SF_6	Same			
Weight vs SF_6	Same			
Comments				

Source: CIRED presentation Q2 2019

M1.3: 12kV with Vacuum interrupter breaking and natural origin gases for insulation

Type	12kV GIS (Primary distribution)			
Insulation /GWP	Natural origin gases /≤1			
Breaking /GWP	Vacuum interrupter / 0			
Rated performance	Ur (kV)	Ir (feeder) (A)	Isc (kA)	Min. op. Temp. (°C)
	12	2750	40	-25
Product first exhibition & year	Shown at Hanover Fair 2018			
Pilots & year of delivery/ service	In service since beginning of 2018			
Footprint versus SF_6	Same			
Weight vs SF_6	Similar weight			
Comments	Derating of rated current vs. similar SF_6 switchgear			

Source: Manufacturer

M1.4: 36 kV GIS with HFO1234zeE for insulation

Type	36 kV GIS (Primary distribution)			
Insulation /GWP	HFO1234zeE 1.4 bar abs / GWP < 1			
Breaking /GWP	Vacuum interrupter / 0			
Rated performance	Ur (kV)	Ir (feeder) (A)	Isc (kA)	Min. op. Temp. (°C)
	36	2000	31.5	- 15 °C
Product first exhibition & year	Q4/2019			
Pilots & year of delivery/ service	2020			
Footprint versus SF_6	Same			
Weight vs SF_6	Same			
Comments				

Source: Manufacturer

M2.1: 12 and 24 kV Ring Main Unit with vacuum interrupters

Type	12 kV GIS for RMU (Secondary distribution)			
Insulation /GWP	Synthetic air 1.4 bar abs. also for disconnectors & earthing switch / 0			
Breaking /GWP	Vacuum interrupter / 0			
Rated performance	Ur (kV)	Ir (feeder) (A)	Isc (kA)	Min. op. Temp. (°C)
	12	630	20	-25
Product launch & year	Q4 2014			
Pilots & year of delivery/ service	more than 100 RMU installed all over the world			
Footprint vs SF_6 RMU	Same footprint as 12kV SF_6			
Weight vs SF_6 RMU	Slightly higher weight than 12 kV SF_6			
Comments	Switch-fuse protections are replaced by circuit-breakers.			

Type	24 kV GIS for RMU (Secondary distribution)			
Insulation /GWP	C_5-Fluoroketone gas plus synthetic air, 1.4 bar abs. also for disconnector & earthing switch / <1			
Breaking /GWP	Vacuum interrupter / 0			
Rated performance	Ur (kV)	Ir (feeder) (A)	Isc (kA)	Min. op. Temp.(°C)
	24	630	16	-25
Product first exhibition & year	Q2/2016			
Pilots & year of delivery/ service	Deliveries started end 2016			
Footprint s. SF_6 RMU	Same footprint as 24kV SF_6			
Weight vs SF_6 RMU	Slightly higher weight than 24 kV SF_6			
Comments	Switch-fuse protections are replaced by circuit-breakers.			

Source: Manufacturer web site

M2.2: 12 and 24 kV Ring Main Unit with air insulation and vacuum interrupters

Type	12 - 24 kV GIS for RMU (Secondary distribution)			
Insulation /GWP	Filtered air, 1.4 bar abs for 12 kV, 2.5 bar abs for 24 kV also for disconnector & earthing switch / GWP = 0			
Breaking /GWP	Vacuum interrupter / 0			
Rated performance	Ur (kV)	Ir (feeder) (A)	Isc (kA)	Min. op. Temp.(°C)
	24	630	25	-25
Product first exhibition & year	Q2/2019			
Pilots & year of delivery/ service	2020			
Footprint s. SF_6 RMU	Same footprint as 24kV SF_6			
Weight vs SF_6 RMU	Slightly higher weight for 24 kV			
Comments	Transformer protection by switch-fuse or circuit-breaker. New breaking technology of load break switch enables to keep today's operating procedure			

Source: CIRED presentation Q2 2019

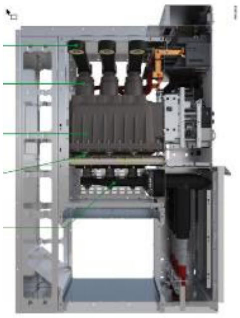
M2.3: 12 kV Ring Main Unit with new switching principle and natural origin gases for insulation

Type	12 kV GIS for RMU (Secondary distribution)			
Insulation /GWP	Natural origin gases / <=1			
Breaking /GWP	New load-break switching principle Vacuum interrupter / 0			
Rated performance	Ur (kV)	Ir (feeder) (A)	Isc (kA)	Min. op. Temp. (°C)
	12	630	20	-25
Product launch & year	At Hannover fair 2019			
Pilots & year of delivery/ service	2019			
Footprint vs SF_6 RMU	Same footprint as 12kV SF_6			
Weight vs SF_6 RMU	Similar weight			
Comments	New breaking technology of load break switch enables to keep today's operating procedure			

Source: Manufacturer

M3: 17.5 kV Shielded solid insulation switchgear with vacuum interrupter

Type	17.5 kV (Secondary and Primary distribution)			
Insulation /GWP (gas)	Dry air & Shielded Solid epoxy or EPDM, disconnecting by vacuum interrupter, air earthing-switch. / 0			
Breaking /GWP (gas)	Vacuum interrupter / 0			
Rated performance	Ur (kV)	Ir (feeder) (A)	Isc (kA)	Min. op. Temp. (°C)
	17.5	1250	25	-25
Product launch & year	2012			
Pilots & year of delivery/ service	No specific pilots. First commercial equipment in Sweden and Netherlands in service since end of 2012,			
Footprint vs SF_6	Similar			
Weight vs SF_6	Higher weight than a SF_6 GIS RMU & similar weight for CB functions			
Comments	Switch-fuse protections are replaced by circuit-breakers			



Source: Manufacturer brochure

M4: 12-24 kV SF_6 free AIS for secondary distribution

Type	12 - 24 kV AIS (Secondary distribution) with gas-insulated switching compartment			
Insulation /GWP (gas)	Filtered air within switching compartment, 1.4 bar abs for 12 kV, 2.5 bar abs for 24 kV / 0			
Breaking /GWP (gas)	Vacuum interrupter / 0			
Rated performance	Ur (kV)	Ir (feeder) (A)	Isc (kA)	Min. op. Temp. (°C)
	12 - 24	630	25	-25
Product launch & year				
Pilots & year of delivery/ service	2019			
Footprint vs SF_6	Same			
Weight vs SF_6	Same			
Comments	Transformer protection by switch-fuse or circuit-breaker. New breaking technology of load break switch enables to keep today's operating procedure			

Source: CIRED presentation Q2 2019

M5: 24 kV SF_6 free GIS for secondary distribution

Other MV secondary switchgear have been presented during 2017 Hanover fair, using alternative gas mixtures for insulation – details of the gas mixture are not published -, but these switchgears are SF_6-free, only for CB functions supplied by vacuum interrupter. GWP is reduced around 90 % versus SF_6. There are not enough public data at end 2019 to evaluate perspectives and to consider it in the chapter 8

Source: 24 kV SF_6-free GIS for secondary distribution (picture from 2017 Hanover fair)

7.2.2 Generator Circuit-Breakers

GCB1: 24 kV, 12500 A, 100 kA ambient air & VI

Type	GCB 24 kV			
Insulation / GWP	Air / 0			
Breaking / GWP	Vacuum Generator Circuit-Breaker (3 VI per phase) / 0			
Rated performance	Ur (kV)	Ir (feeder) (A)	Isc (kA)	Min. op. Temp. (°C)
	24	12500	100	-25
Product first exhibition & year	Launched in 2015			
Pilots & year of delivery / service	Launched in 2015			
Footprint versus SF_6	Similar			
Comments				

Source: Manufacturer’s brochure

7.2.3 HV Applications

First industrial SF_6-free prototypes have appeared recently for HV switchgear which can be split in 3 categories:

- Synthetic air insulation and using vacuum interrupters for breaking;
- Insulating and switching by use of a gas mixture of CO_2 and O_2 & Fluoroketone, (C_5 - Fluoroketones (C_5-FK) [8];
- Insulating and switching by use of a gas mixture of CO_2 and O_2 & Fluoronitrile, (C_4 Fluoronitriles (C_4-FN) [9]

Overall, the dielectric and quenching characteristics of these gases are demonstrated:

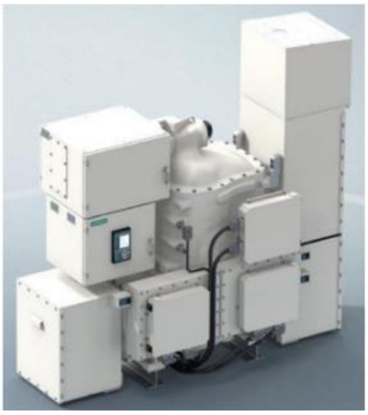
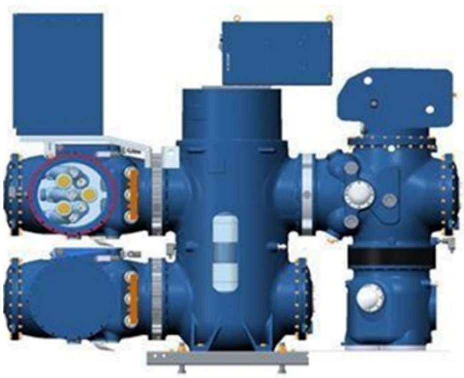
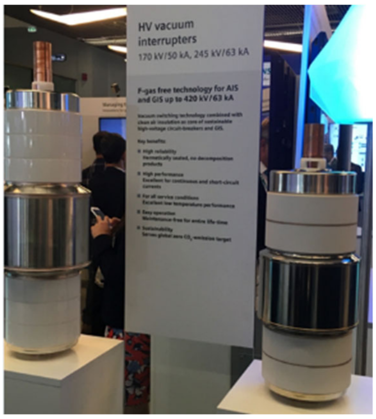
- For insulation: up to 420kV,
- For breaking by circuit-breaker: up to 170kV, 40kA.

Solutions are proposed for both GIS & AIS and for different minimum operating temperature between -50°C & +5°C.

7.2.3.1 GIS Applications

G1: 72.5 kV & 145 kV GIS with synthetic air insulation and vacuum interrupter

Type	72.5 kV GIS & 145 kV GIS			
Insulation /GWP	Synthetic air / 0			
Breaking /GWP	Vacuum interrupter / 0			
Rated performance	Ur (kV)	Ir (feeder) (A)	Isc (kA)	Min. op. Temp.(°C)
	Up to 145	Up to 40 kA	Up to 3150 A	Up to -50
Product first exhibition & year	72.5 kV prototype shown in Hanover fair 2015 respectively 145 kV at Cigre exhibition 2016; first VI prototypes for 170 kV and 245 kV up to 63 kA current interruption shown at Cigre exhibition in 2018			
Pilots & year of delivery/ service	First 4 pilot bays delivered in 2016 and started operation in 2017, meanwhile more than 20 bays in operation and more than 1000 bays ordered,			
Footprint versus SF_6	Larger			
Comments	72.5 kV GIS is designed especially for on-/offshore windfarm application (transition peace or inside tower installation)			

Source: Cigre publication B3-108 and manufacturer information

G2: 145 kV GIS CO_2 & Fluoronitrile and O_2 for insulation and interruption.

Type	145 kV GIS			
Insulation /GWP	CO_2 and C_4-Fluoronitrile and O_2 / ~450			
Breaking /GWP	CO2 and C4-Fluoronitrile and O_2 / ~450			
Rated performance	Ur (kV)	Ir (feeder) (A)	Isc (kA)	Min. op. Temp.(°C)
	145	3150	40	-25
Product first exhibition & year	Prototype shown at Cigre session 2016			
Pilots & year of delivery/ service	5 substations with 30 bays are in operation in Switzerland, France, Netherlands & Denmark. 8 substations to be energized in 2020-21 with 47 bays, in Germany, Denmark, Spain, Switzerland and UK.			
Footprint versus SF_6	Same			
Comments				

Source: Think Grid article on world first C4-FN substation testing at 145 kV, 2017

G3: 170 kV GIS CO_2, Fluoroketone & O_2 for insulation & interruption.

Type	170 kV GIS			
Insulation /GWP	CO_2 and C_5-Fluoroketone and O_2 / <1			
Breaking /GWP	CO_2 and C_5-Fluoroketone and O_2/ <1			
Rated performance	Ur (kV)	Ir (feeder) (A)	Isc (kA)	Min. op. Temp.(°C)
	170	1250	40	+5
Product first exhibition & year	IEEE conference 2015			
Pilots & year of delivery/ service	S/S in operation in Zurich for EWZ (Switzerland) since 2015			
Footprint versus SF_6	Larger			
Comments				


Sources: Cigre session 2016, publication B3-108 & manufacturer & Ewz publications – Hanover 2015 press release – Press conference 28/01/2015

G4: 420 kV GIB gas insulated bus-duct insulation made of CO_2 & Fluoronitrile.

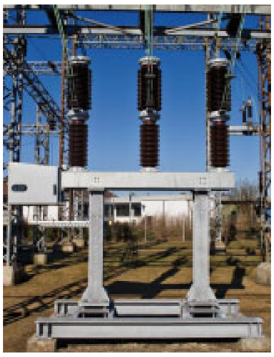
Type	420 kV GIB			
Insulation /GWP	CO_2 and C_4-Fluoronitrile gas mixture / ~350			
Breaking /GWP	Not applicable			
Rated performance	Ur (kV)	Ir (feeder) (A)	Isc (kA)	Min. op. Temp.(°C)
	420	4000	63	-25
Product first exhibition & year	Prototype shown at Cigre session 2016			
Pilots & year of delivery/ service	Applications: Sellindge S/S for National Grid (UK) energized Q1 2017, Kilmarnock South S/S for Scottish Power Energy Networks (SPEN) energized mid-2019, 2 other projects in Scotland and one in Netherland to be energized in 2020.			
Footprint versus SF_6	Same			
Comments	3.4 tons of SF_6 saved for Kilmarnock South installation			

Sources: Shown at Cigre 2016. National Grid & 3M press release – Cigre publications

7.2.3.2 AIS Applications

A1: 72 kV LT synthetic air or nitrogen and vacuum CB, from two different suppliers

Type	72 kV live tank circuit-breaker			
Insulation /GWP	Synthetic air or N_2 depending on suppliers / 0			
Breaking /GWP	Vacuum circuit-breaker / 0			
Rated performance	Ur (kV)	Ir (feeder) (A)	Isc (kA)	Min. op. Temp. (°C)
	72	2500	31.5	-30
Product first exhibition & year	Prototype shown at Cigre session 2012			
Pilots & year of delivery/ service	France (several sites); another European countries & New-Zealand / 2012			
Footprint versus SF_6	Same			
Comments				



Source : Cigre session 2016, publication B3-108

A2: 72/145 kV LT CO_2 & O_2 circuit-breakers

Type	72 kV AIS Live Tank circuit-breaker 145 kV AIS Live Tank circuit-breaker			
Insulation /GWP	CO_2 & O_2 / 1			
Breaking /GWP	CO_2 & O_2 circuit-breaker / 1			
Rated performance	Ur (kV)	Ir (feeder) (A)	Isc (kA)	Min. op. Temp. (°C)
	72.5/145	2750	31.5	- 50
Product first exhibition & year	72.5 kV CB was first exhibited in 2012			
Pilots & year of delivery/ service	Pilot (capacitor bank switching) of 145 kV CB in operation since 2010. No deliveries.			
Footprint versus SF_6	similar			
Comments				

Source: supplier web site / Cigre session 2012, publication A3 – 302

A3: 245 kV Current Transformers. CO_2 & Fluoronitrile insulated

Type	245 kV AIS Current Transformer			
Insulation /GWP	CO_2 and C_4-Fluoronitrile gas mixture / ~350			
Breaking /GWP	Not applicable			
Rated performance	Ur (kV)	Ir (feeder) (A)	Isc (kA)	Min. op. Temp. (°C)
	245	4000	50	-30
Product first exhibition & year	Prototype shown at Hanover Fair 2015 & Cigre session 2016			
Pilots & year of delivery/ service	First units for Germany energized 2017			
Footprint versus SF_6	same			
Comments				

Source: Cigre session 2016

A4: 72.5 kV – 420 kV synthetic air Instrument Transformers

Type	72.5 kV – 420 kV synthetic air combined Instrument Transformer for AIS			
Insulation /GWP	Synthetic air / 0			
Breaking /GWP	Not applicable			
Rated performance	Ur (kV)	Ir (feeder) (A)	Isc (kA)	Min. op. Temp.
	72.5	1200A	31,5	-35°C
Product first exhibition & year	Prototypes shown at Cigre session 2016			
Pilots & year of delivery/ service	NA			
Footprint versus SF_6	slightly larger, but no impact for the substation footprint			
Comments				

Type	145 kV- 420kV synthetic air combined Instrument Transformer for AIS			
Insulation /GWP	Synthetic air / 0			
Breaking /GWP	Not applicable			
Rated performance	Ur (kV)	Ir (feeder) (A)	Isc (kA)	Min. op. Temp.
	420	unknown	unknown	-35°C
Product first exhibition & year	Prototypes shown at Hanover fair 2017			
Pilots & year of delivery/ service	NA			
Footprint versus SF_6	Similar or larger (for 72.5 kV)			
Comments				

Source: Manufacturer's brochure

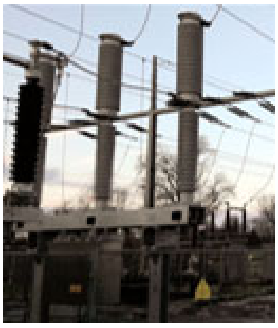
A5: 145kV Live tank – prototype

Type	145 kV AIS Live tank circuit-breaker			
Insulation /GWP	CO_2 and C_4-Fluoronitrile and O_2 / ~300			
Breaking /GWP	CO_2 and C_4-Fluoronitrile and O_2 / ~300			
Rated performance	Ur (kV)	Ir (feeder) (A)	Isc (kA)	Min. op. Temp. (°C)
	145	3150	40	-30
Product first exhibition & year	First 3 substations to be energized in 2020 in Denmark, Germany and Switzerland			
Pilots & year of delivery/ service	no			
Footprint versus SF_6	same			
Comments				

Source: Manufacturer product leaflet

A6: 145 kV LT with synthetic air and vacuum CB

Type	145 kV live tank circuit-breaker			
Insulation /GWP	Synthetic air / 0			
Breaking /GWP	Vacuum circuit-breaker / 0			
Rated performance	Ur (kV)	Ir (feeder) (A)	Isc (kA)	Min. op. Temp. (°C)
	145	3150	40	-60
Product first exhibition & year	Prototype shown at Hanover fair 2017			
Pilots & year of delivery/ service	First pilot delivery in 2017 and operation started in 2018 (Germany), meanwhile more than 50 breakers in operation			
Footprint versus SF_6	Same			
Comments				



Source: From press release and manufacturer web site

7.3 AMENDMENTS FROM OTHER REGION'S APPLICATIONS AND USE CASES:

7.3.1 MV Applications

No significant other move to report.

7.3.2 Generator Circuit-Breakers

No significant other move to report.

7.3.3 HV Applications

NE1: DT 72kV 31.5kA from Japan

Type	72.5 kV AIS Dead tank circuit-breaker			
Insulation /GWP	Synthetic air 1.5 bar/ 0			
Breaking /GWP	Vacuum interrupter / 0			
Rated performance	Ur (kV)	Ir (feeder) (A)	Isc (kA)	Min. op. Temp. (°C)
	72.5	2000	31.5	<-30°C
Product first exhibition & year	Type tests completed and presented during Cigre 2012			
Pilots & year of delivery/ service	A few pilots in operation in Japan and USA			
Footprint versus SF_6	Similar overall footprint but larger tank diameter			
Comments				

Source : Cigre session 2012

NE2 : DT 72 kV from Japan

Type	72.5 kV AIS Dead tank circuit-breaker			
Insulation /GWP	N_2 at atmospheric pressure and solid insulation / 0			
Breaking /GWP	Vacuum interrupter / 0			
Rated performance	Ur (kV)	Ir (feeder) (A)	Isc (kA)	Min. op. Temp. (°C)
	72	2000	31.5	<-30
Product first exhibition & year	Prototype presented during IEEE 2015			
Pilots & year of delivery/ service	Unknown			
Footprint versus SF_6	Unknown			
Comments				


Source: IEEE conference 2015

NE3: GIS 145kV from South Korea

Type	145kV GIS			
Insulation /GWP	Unknow			
Breaking /GWP	Vacuum interrupter / 0			
Rated performance	Ur (kV)	Ir (feeder) (A)	Isc (kA)	Min. op. Temp. (°C)
	145	Unknow	Unknow	Unknow
Product first exhibition & year	Cigre session 2016 (publication)			
Pilots & year of delivery/ service	Unknown			
Footprint versus SF_6	Unknown			
Comments				

Source : Cigre session 2016, publication A3-105

NE4: GIS 170kV from South Korea

Type	170 kV GIS			
Insulation /GWP	CO_2 and C_4-Fluoronitrile and O_2 / ~350			
Breaking /GWP	CO_2 and C_4-Fluoronitrile and O_2 / ~350			
Rated performance	Ur (kV)	Ir (feeder) (A)	Isc (kA)	Min. op. Temp. (°C)
	170	4000	50	-25
Product first exhibition & year				
Pilots & year of delivery/ service	First pilot to be energized in 2020 on South Korean network			
Footprint versus SF_6	Same as SF_6			
Comments				

Source : manufacturer information

8 - PERSPECTIVES BY SEGMENT OF APPLICATION

The objective is to deliver an overview of perspectives by applications for alternatives to SF_6 described in previous chapters.

This overview aims to:

- Deliver the best possible perspective by segment of application from today, based on present alternatives, public researches & first pilots and applications known at end of 2019.
- Deliver as far as possible the T&D Europe perception of the potential of further development of the different alternatives and the opportunities of its use in Europe.
- Deliver also the T&D Europe perception on risks which still need to be further evaluated and expected limitations or difficulties to the use of these different alternatives.

It is not the purpose of the report to give a relative weight to each main characteristic, nor any ranking of the various alternatives. In this chapter, only European applications are considered.

8.1 MV APPLICATIONS

8.1.1 Common considerations

8.1.1.1 Insulation

With respect to electrical insulation i.e. phase-to-earth, across open gaps of switching devices (switches, disconnectors, earthing switches and circuit-breakers) and phase-to-phase, existing alternatives are (ref. to chapter 5):

- Air
- Solid insulation without earthed screen
- Solid insulation with earthed screen
- Dry air

In addition, with respect to electrical insulation, emerging alternatives used in pilots or first applications are (ref. to chapter 7):

- Synthetic air (overpressure);
- Filtered air (overpressure)
- Natural origin gases (overpressure)
- New generation of solid insulation with earthed screen;
- Synthetic air with Fluoroketones (C5-FK) (overpressure);
- HFO1234zeE (piloting beginning of 2020).

Limitations might exist in terms of minimum operating temperature, for instance, when comparing the different alternatives to existing SF_6 equipment.

Some of the alternative gases interact with materials in contact making a selection necessary

Some of the new gases have non-technical questions to be considered, mainly the very limited number of manufacturers of such gases and existing patents for electrical switchgear applications.

A simplified comparison table shows the difference between these alternatives and SF_6 with respect to major characteristics. Numbers are good estimations or based on published literature.

Table 6 – Comparison of key characteristics for main insulating alternatives and SF_6 for MV applications

<table>
<tr><th>Gas or mixture (at 1.3 bar abs) (1)</th><th>Dielectric % (2)</th><th>Voltage available kV (3)</th><th>GWP of gas or gas mixture (4)</th><th>Minimum operating temperature °C (5)</th><th>Material compatibility (6)</th><th>Heat dissipation % (7)</th><th>EHS</th><th>Gas handling (8)</th></tr>
<tr><td>SF_6</td><td>100</td><td>40.5</td><td>22800</td><td>-25°</td><td>Proven</td><td>100</td><td rowspan="7">Additional to all technical and operational information, EHS topics are mandatory characteristics to highlight:
T&D Europe has published a “Technical guide to validate alternative gas for SF6 in electrical equipment” [16] that shall be considered for EHS topics. Please contact individual manufacturer</td><td>Proven, end of life closed cycle</td></tr>
<tr><td>Filtered air and synthetic air</td><td>~45</td><td>12</td><td>0</td><td>-25°</td><td>Proven</td><td>80 to 90</td><td>Proven</td></tr>
<tr><td>Natural origin gas</td><td>~45</td><td>12</td><td>≤1</td><td>-25°</td><td>Proven</td><td>80 to 90</td><td>Proven</td></tr>
<tr><td>Solid ins. (epoxy) silicon</td><td>NA (9)</td><td>24</td><td>NA</td><td>-25°</td><td>Proven</td><td>90 to 110 (10)</td><td>NA recycling needed</td></tr>
<tr><td>SIS w. earthed screen</td><td>NA (9)</td><td>17.5</td><td>NA</td><td>-25°C</td><td>Proven</td><td>90 to 110 (10)</td><td>NA recycling needed</td></tr>
<tr><td>Synthetic air & C_5-FK (7-14%)</td><td>95/90 (12)</td><td>24</td><td><1</td><td>-15°/-25°C (12)</td><td>Proven (13)</td><td>80 to 90</td><td>Mixture to be managed, end of life, closed cycle</td></tr>
<tr><td>Pure HFO1234zeE</td><td>100</td><td>36</td><td><1</td><td>-15°C (1.3 bar abs)</td><td>OK at. Lab.</td><td>~100</td><td>End of life, closed cycle</td></tr>
</table>

Notes related to table 6:

(1) Main alternatives to SF_6 for insulation based on existing products, prototypes and more promising researches.

(2) Dielectric withstand at power frequency at usual pressures used for MV equipment (typically 1.3 bar abs).

(3) Highest rated voltage as per chapter 7.2.1. for prototypes, pilots and first applications having similar footprint to existing SF_6 solutions

(4) GWP for 1 kg of gas or gas mixture according to IPCC methodology based on a 100 years' time period. GWP is the climatic warming potential of a gas relative to that of carbon dioxide (CO_2). The mass of the filled-in gas determines only part of the total carbon footprint of switchgear, which comprises the manufacturing of all its materials and its use and disposal. For solid insulation, GWP is not applicable, but Carbon Footprint is.

(5) Usual minimum operating temperatures reached with SF_6 and present alternatives as shown in section 7. This operating temperature may be reached with pressure different from the typical one of column (1)

(6) Indicative material compatibility between insulating medium and the most commonly used materials for MV switchgear.

(7) Indicative heat dissipation of the insulating medium itself with reference to SF_6 (assumed 100%).

(8) Global evaluation of the constraints relative to the gas handling process, when applicable. Solid insulation may have different constraints for handling & end of life which are not considered here. For SF_6 gas handling process is described by IEC 62271-4.

(9) Not Applicable because the architecture of the switchgear needs a mixed insulation, solid and gas or dry air.

(10). Direct comparison of heat dissipation between gaseous insulation and solid insulation may be not representative of the performance of the complete product because of different mechanisms of heat dissipation (different relative weight of conduction, convection and radiation). An indicative range of 90 to 110% has been considered like representative for conditions of existing product designs.

(12) Depending on ratio of C_5-FK in the gas mixture

(13) Development testing resulted in change of some materials versus SF_6; during piloting/installations up to now, no further material incompatibilities were reported

8.1.1.2 Arc interruption (switches and circuit-breakers)

With respect to arc quenching i.e. current interruption purposes, vacuum interrupters are an already existing and largely employed alternative. There's a tendency to use vacuum interrupters in SF_6-free solutions.

For load-break switches, required in particular for cost-effective MV secondary distribution equipment, the use of vacuum interrupters in alternative solutions implies that the typical functions (switching, disconnecting, earthing, interlocking) which is often provided by one device in SF_6 solutions, needs separate devices.

New emerging architecture using a vacuum interrupter in parallel with a 3-position disconnector and earthing switch or puffer-type load-break switches, enable to replicate similar operation habits and interface as SF_6 products load-break switches. This could enable a larger user's acceptance of the SF_6 free technology [19], [22].

8.1.2 Application by segments

8.1.2.1 Utilities

8.1.2.1.1 Primary substation (HV/MV)

AIS: In HV/MV substations, estimated 65 % of MV primary switchgear is ambient air insulated. SF_6 is used in 30 % of the MV circuit-breakers and vacuum interrupters is used in 70 %. General application of vacuum interrupters may suppress the use of SF_6 except in a few specific MV applications.

GIS: In HV/MV substations, estimated 30 % of all MV primary switchgear is GIS with SF_6 insulation. Vacuum interrupters are used in 90 % of the MV CB. Considering the already existing & emerging alternatives as described in chapter 7 and further developments, SF_6 alternatives should be technically viable in most of the MV applications still keeping the advantages of today's SF_6 technologies.

8.1.2.1.2 Secondary substation (MV/LV)

In MV/LV substations for utilities, GIS is predominantly used. The medium used for insulation and disconnecting switches is SF_6. Current breaking is predominantly performed by SF_6 switches and SF_6 switch-fuse combinations. Circuit-breakers offerings are available in Europe, based on Vacuum Interrupters, but are not often used. The switchgear assemblies are of sealed pressure type, therefore SF_6 leakages are very small (<0.1 %/year). For new substations, SF_6-free alternatives such as those presented in chapter 7 could be used with different limitations depending on the chosen solution, such as minimum operating temperature, size, purchaising cost, operating costs, regulation, operating complexity (separate devices vs. simple combined function load-break switches) and user's preference for standardized solutions. Due to limited size within existing secondary substation housings, replacement of SF_6 switchgear by switchgear using alternative technologies requires switchgear with similar dimensions and must be studied case by case.

A same detailed study needs to be done for any alternatives for pole-mounted outdoor switchgears, as the weight for pole installation is limited and climatic condition is different than inside secondary substation housing, so any alternative solution could be limited.

8.1.2.1.3 Switching substation (MV)

In MV switching substations, GIS is very often used. They consist of several functions, some with load-break switches and others with circuit-breakers. MV switchgears for switching substations typically have the same technologies as for MV/LV secondary substations. Therefore, the same principles and conclusions given in previous paragraph are applicable here.

8.1.2.2 Private substation

8.1.2.2.1 Primary distribution (Power-intense industry, oil and gas, Metallurgy, Mining, infrastructures (e.g. airport)

AIS and GIS technologies are both commonly used, depending on the choice of environmental conditions, technical parameters, and/or safety requirements. The conclusions on possible moves to alternatives are the same as for primary distribution for utilities (8.1.2.1.1)

8.1.2.2.2 Secondary distribution (Automotive, Food and Beverage, Hospital, Hotels, Airport, Data Centre & infrastructure.)

In medium industry and infrastructures, AIS and GIS technologies are commonly used, depending on the customer specification.

The conclusions on possible moves to alternatives are the same as for secondary distribution for utilities (8.1.2.1.2).

8.2 GENERATOR CIRCUIT-BREAKERS

Generator Circuit-Breakers are a niche application with a small number of devices all over the world, and thus representing only negligible quantities of SF_6 emitted into the atmosphere during all stages of its life cycle.

For Generator Circuit-Breakers below 50 MVA, vacuum Generator Circuit-Breakers is the most frequently used technology.

For Generator Circuit-Breaker above 50 MVA SF_6 is the most frequently used technology. Vacuum is an alternative to SF_6 below 400 MVA with severe limitations in term of asymmetry (or dc constant)

For higher performance, typically above 400 MVA, today there is no alternative to SF_6 Generator Circuit-Breakers. Considering the high technical constraints imposed by very high short-circuit currents & continuous currents, development of alternatives would be very long lasting and costly covering the complete range. SF_6 will likely continue to be used for high performance GCB for a long time.

8.3 HV APPLICATIONS

8.3.1 Common considerations

8.3.1.1 Insulation

With respect to electrical insulation i.e phase to earth, across open gaps of switches (disconnectors, earthing switches and circuit-breakers) & phase to phase for 3 phases encapsulated GIS, different alternatives to be considered are:

Existing alternatives (ref. to chapter 5):

- none

Emerging alternatives already used in pilots or first applications, as shown in chapter 7:

- Synthetic air (overpressure)
- CO_2 & O_2 (O_2 added in case of use for arc quenching)
- C_5-Fluoroketones (C_5-FK) in gas mixtures with CO_2 and O_2 (O_2 is added in case the gas mixture is used for arc quenching)
- C_4-Fluoronitrile (C_4-FN) in gas mixtures with CO_2 and O_2 (O_2 is added in case the gas mixture is used for arc quenching)

No other promising alternative in early stage of research activity as per chapter 6 is reported.

The simplified comparison in table 7 shows the difference between these alternatives and SF_6 with respect to the listed selection criteria:

Table 7 – Comparison of key characteristics for main insulating alternatives and SF_6 for HV applications

Gas or mixture (at 6 bar abs) (1)	Dielectric % (2)	Voltage available kV (3)	GWP of gas or gas mixture (4)	Minimum operating temperature °C (5)	Material compatibility (6)	Heat dissipation % (7)	EHS	Gas handling (8)	GIS foot print % (9)
SF_6	100	1200	22800	-40°	Proven	100	Additional to all technical and operational information, EHS topics are mandatory characteristics to highlight: T&D Europe has published a “Technical guide to validate alternative gas for SF6 in electrical equipment” [16] that shall be considered for EHS topics. Please contact individual manufacturer	Proven, end of life close cycle	100
Synthetic air	40	145	0	-60°	Proven	80 to 90		Proven	120
CO_2 & O_2	40	145	< 1	-40	Proven (11)	80 to 90		Proven Gas mixture to manage	120
C_5-FK (5%) & CO_2 & O_2	75 (10)	170 (GIS)	< 1	0° (10)	Proven (11)	80 to 90		Proven on pilots, end of cycle under development	120
C_4-FN & CO_2 & O_2 (12)	85 (10)	170 (GIS) 420 (GIB)	Less than 500 (11)	-30° (10)	Proven (11)	80 to 90		Proven on pilots, end of cycle under development	100

Notes related to table 7:

(1) Main alternatives to SF_6 for insulation based on existing products, prototypes and more promising researches.

(2) Approximate dielectric withstands at power frequency at usual pressures used for HV equipment (typically 6 bar abs).

(3) Higher rated voltage for prototypes, pilots and first applications as per chapter 7

(4) GWP for 1 kg of gas or gas mixture according to IPCC methodology based on a 100 years' time period. GWP is the climatic warming potential of a gas relative to that of carbon dioxide (CO_2). The mass of the filled-in gas determines only part of the total carbon footprint of switchgear, which comprises the manufacturing of all its materials and its use and disposal.

(5) Usual minimum operating temperature reached with SF_6 and present alternatives as shown in section 7. This operating temperature may be reached with pressure different from the typical one of column (1)

(6) Indicative material compatibility between insulating medium and the most commonly used material for HV applications

(7) Indicative heat dissipation of the insulating medium itself with reference to SF_6 (assumed 100%).

(8) Global evaluation of the constraints related to the gas handling process. For SF_6 gas handling process is described by IEC 62271-4.

(9) Approximate ratio based on the average footprint of GIS pilots presented in chapter 7 versus SF_6 design, typically based on comparison of bay width. The footprint of the AIS life tank, dead tank and instrument transformers is independant of the alternative gases.

(10) depending of C_5-FK & C_4-FN ratio in the gas mixture

(11) Development testing resulted in change of some materials versus SF_6; during piloting/installations up to now, no further material incompatibilities were reported

With this panel of alternatives, no major technical barrier is seen with respect to voltage insulation to develop SF_6 free products for all types of applications (GIS, DT, LT, GIL, IT) & all rated high voltages used in Europe from 72.5 kV to 420 kV. Products without interrupting capabilities with first applications are available up to 420 kV. However technical limitations might exist depending on a chosen specific alternative when compared to SF_6 products, for example minimum operating temperature.

8.3.1.2 Arc interruption (all types of circuit-breakers)

With respect to arc quenching and current interruption purposes, emerging technologies as per chapter 7 are:

- Vacuum interrupter;
- CO_2 & O_2 gas mixture;
- C_5-Fluoroketone (C_5-FK) & CO_2 & O_2;
- C_4-Fluoronitrile (C_4-FN) & CO_2 & O_2

The simplified comparison in table 8 shows the difference between breaking capabilities reached today with these alternatives and SF_6. Max. voltage and short-circuit current ratings reached with a single break interrupting unit are representative of the breaking capability.

Table 8 – Comparison of breaking capability reached today by circuit-breakers with alternatives and SF_6 for HV applications

Gas or mixture (1)	**Max single break voltage (kV) (2)**	**Isc (kA) (3)**
SF_6	550	63
VI	145	40
CO_2 & O_2	145	40
CO_2 & FK & O_2	170	40
CO_2 & FN & O_2	170	50

Notes related to table 8:

(1) Alternatives according to chapter 7

(2) Present situation for alternatives according to chapter 7

(3) Present situation for alternatives according to chapter 7

With this panel of alternatives, SF_6-free breaking prototypes or technologies are already available up to 170 kV and 50 kA.

With CO_2 & FK or CO_2 & FN mixtures which use the same interrupting principles as the last generation of SF_6 interrupting units, the extension to higher voltage is technically feasible though not yet proven. The extension to higher short-circuit currents for the alternatives using the same interrupting principles is likely possible but need to be further investigated extensively. Limitations exist depending on the alternative when compared to SF_6 solutions, for instance, in terms of minimum operating temperature for outdoor applications.

With regards to vacuum interrupter technology for HV, where the distance between contacts need to increase not linear with the voltage, products are available at time being up to 145 kV in operation. Above 145 kV first single break VI prototypes for 170 kV and 245 kV up to 63 kA current interruption were shown at Cigré exhibition in 2018. For voltages above 245 kV use of several interrupting unit in series with grading capacitors might be needed, influencing parameters of equipment like footprint, cost and complexity.

In all cases development of new HV circuit-breakers will imply major investments.

8.3.2 Perspectives for HV GIS

SF_6-free alternative technology for HV GIS is available for voltages up to 170 kV with footprint equal or slightly larger than SF_6 switchgear with similar performance. For circuit-breakers, SF_6 free alternative technology is available up to 170 kV and 50 kA.

Extending the technology to higher voltages and higher short-circuit currents seems technically feasible, but highly demanding in terms of investment and development efforts. For insulation purposes, the application of SF_6-free gases up to 420 kV has been demonstrated with a GIL.

However, completely replacing the SF_6, in particular for very low ambient temperatures below -30°C and very high short-circuit currents and voltages, is more challenging.

8.3.3 Perspectives for GIL

In gas-insulated line (GIL) the quantities of SF_6 may be quite high depending on the length of the line.

SF_6-free alternative technology is available today for 420 kV & a minimum operating temperature of -25°C. The technology can be extended to lower voltage and higher voltage.

Extension of operating temperature down to -30°C and even lower seems possible. In Europe, alternatives could cover most of the needs, likely around 90%.

8.3.4 Perspectives for HV AIS

Nearly all AIS S/S are applied outdoor and require a minimum operating temperature of -25°C or lower. Therefore, today not all the SF_6 alternatives described above are suitable to fulfill the requirements for this application.

8.3.4.1 HV AIS Life tank CB

Different SF_6 free technology exists for 72.5 kV voltage & 31.5 kA 145 kV and 40 kA based on synthetic air insulation and vacuum interruption and for CO_2 & O_2 as well as CO_2 & C_4-Fluoronitrile for both insulation and interruption.

For CO_2 & O_2 and CO_2 & C_4-Fluoronitrile mixtures, the same interrupting principles as used in the last generation of SF_6 chambers are used, but adapted to the characteristics of the specific gas mixtures. Until now no physical limitation has been found. It seems possible to extend these breakers to higher rated voltages and short-circuit currents. However, this would be highly demanding in terms of investments and development efforts.

8.3.4.2 HV AIS Dead tank CB

DT circuit-breakers have a very rare installation in Europe, therefore SF_6 free technology for Dead Tank circuit-breakers would not really impact the emission of SF_6 in Europe.

Alternatives considered for AIS Live tank circuit-breakers could also be applicable for dead tank circuit-breakers with similar perspectives and limitations.

8.3.4.3 HV AIS Instrument transformers

For AIS instrument transformers the external phase to earth insulation is made in air and the insulation phase to earth inside the porcelain or composite housing is made in oil, which is most commonly used, or in SF_6.

Technical feasibility of SF_6-free applications has been demonstrated with first applications up to 420 kV, the highest voltage used in Europe .

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ABOUT T&D EUROPE

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