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

T&D Europe Technical report on alternative to SF_6 gas in medium voltage & high voltage electrical equipment

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

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 first report issue 2017 is based on information made public before end of 2016.
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 2016)
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 present installed base and typical offers up to end of 2014 are considered
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 SF6 gas filled switchgear which occurred during the last 3 years: 2014, 2015 & 2016 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 SF6 gas filled switchgear; non-gaseous media for insulation are also considered.
"Alternatives" does not necessary mean that it will be able to replace SF6 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 2016 will be included.

2 - SCOPE

The purpose of this report is to provide a mapping of the status of alternatives to SF6 gas filled switchgear by the end of 2016. 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 intents to revise this mapping if and 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 SF6 based switchgear and SF6 free switchgear.
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

SF6 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. SF6 is neither toxic nor flammable and does not have any carcinogenic, mutagenic or repro-toxic (CMR) characteristics. On the other hand, SF6 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 SF6 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 SF6-free solutions, some alternative technologies already exist and are available for specific applications.

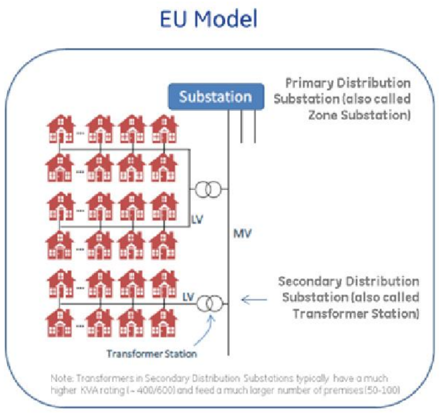
Gas mixtures partly based on SF6, partly using known gases and partly employing totally new gases are being researched and developed to reach electrical equipment having performances, dimensions and cost comparable to SF6 switchgear but with a much lower global warming potential.
In the following, the current situation, published SF6-free pilot switchgear applications, published recent moves in SF6-alternative technologies and future perspectives are presented.

4 - TERMS AND DEFINITIONS

4.1 Medium Voltage (MV)

4.1.1 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

4.1.2 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 20kA.

4.1.3 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 High Voltage (HV)

High Voltage: high-voltage above 52 kV.
HV is typically used for transmission of electrical energy from generation to distribution networks.

4.3 Types of switchgear:

AIS (Air Insulated Switchgear): MV or HV Switchgear in which the electrical insulation is mainly ambient air.
GIS (Gas Insulated Switchgear): MV or HV Switchgear in which the electrical insulation is mainly a gas within a metallic 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, required for specific insulation or current breaking 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.

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

		Utilities		**Private**
SECONDARY		**MV/LV substation**	**MV switching substation**	**Commercial and ind. Building (Supermarket, Hotel...), industry and infrastructure (Automotive, Food, Hospital, Airport, Data Centre...)**
	Main function	Switch for the ring, switch-fuse or CB for transformer protection	CB or switch	CB, switch and switch-fuse
	Feeder current	630A	630A or 1250A	630 A
	Short-circuit feeder	12.5 to 25 kA	12.5 to 25 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)
		HV/MV & MV/MV substation		**High power industry (Oil & Gas, Metallurgy, Mining, Cement...)**
	Main function	CB		CB, contactor

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PRIMARY	**Feeder current**	1250 to 2500A	630 to 4 000A
	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 substations
SECONDARY		**MV/LV substation** **MV switching substation**	**Commercial and Industrial Building (Supermarket, Hotel, …)**
	SWITCH **Insulating medium**	SF6: very high Air: low	SF6: medium Air: high Solid: low Liquid: very low (1)
	SWITCH **Breaking medium**	SF6: very high Vacuum: low Air: very low	SF6: high Air: low Vacuum: low
	CB **Insulating medium**	SF6: high Air: low	SF6: low Air: high Solid: low
	CB **Breaking medium**	SF6: low vacuum: high	SF6: low vacuum: high

Note: (1): Not investigated because of lack of sufficient public information.

An estimation of number of functional units is given in the table 3:

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
SF6: 45 % Ambient Air: 50% Solid < 5 % Dry air < 2 %	SF6: >90 % Ambient air < 5 % Vacuum < 5 %	SF6: 25 % Ambient Air: 75% Solid < 5 % Dry air < 2 %	SF6: 30 % Vacuum: 70 %	95% SF6

In CB functional units, mostly disconnector switches are also used which rely to a high percentage on SF6 insulation, so that finally estimated 95% of all CB functional units have some SF6 inside & only estimated 5% have no SF6 at all.
For switch functional units, less than estimated 10% of the units use no SF6 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 SF6 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 SF6 per functional unit is between 0.2 and 1kg.
Typical filling pressure of SF6 in MV switchgear compartments is 0.12 to 0.14MPa 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 Center...)
	SIS	No	No	low
	GIS	medium	medium	medium
	AIS	high	medium	medium

An estimation of number of functional units is given in the table 5:

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%	SF6: 100 %	Vacuum: 90% SF6: 10%	Air: 100%	Vacuum: 70% SF6: 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 SF6 quantities are between 2 and 3kg for GIS and between 0.1 and 0.6kg for AIS equipped with SF6 circuit breakers.

Typical filling pressure of SF6 in MV switchgear compartments is 0.14 to 0.18 MPa absolute

Since the 1980ies there is a trend to install more SF6 GIS switchgear. The higher is the rated operating voltage the higher is the share of SF6 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 SF6 GIS as shown in the table above.

Typical width of one functional unit is 500 to 1000mm 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 CRITERA

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 SF6 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% according IEC 62271-1.
Current offer for MV secondary and primary distribution switchgear using SF6 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 users 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 & SWITCHGEAR

Generator circuit breakers (GCB) are used to protect generators in power plants. These are medium voltage devices designed for operating with a high continuous current and high short circuit currents. Generator switchgear includes circuit breakers, disconnectors, earthing switches and instrument transformers.

Typical GCB:

The generator circuit breaker applications can be segmented into power generation units between 10 MW & 50MW per unit, between 50MW & 150MW & above 150MW.

For designs above 10MW, a specific IEC/IEEE standard for GCB is applicable (IEC/IEEE 62271-37-013).
In the low power segment below 50MW, applications are covered by both SF6 breakers with SF6 insulation or vacuum circuit breakers with air insulation.
Between 50MW & 150MW the use of SF6 insulation & SF6 breakers is by far the technology which is the most applied (typically 95%) and the vacuum technology with air insulation represents around 5% of the applications.
Above 150MW, 100% of GCB in service by end of 2016 use SF6 or air for interruption and insulation. Considering existing assets, an estimated split is likely around 95% for breakers relying on SF6 & 5% for air blast circuit breakers.

Respective ratings of SF6 & Vacuum technologies for GCB are:

Generator switchgear in the 10 to 2000 MW range with SF6 technology covers short-circuit ratings up to 31.5kV & 300kA, with continuous currents up to 50 000A.

For generator switchgear in the 10- to 250-MW range with specially designed vacuum generator circuit-breakers, 3-pole designs exist for power plants up to 170 MW with IEC ratings up to 24kV, 72kA, 6700A. Single-pole designs for power plants up to 250 MW exist with ratings up to 24kV, 100kA, 12500A. For the ANSI market designs up to 15kV, 63kA, 4000A are available.

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 SF6, VI & pressurized air technologies.
SF6 GCB installed base in Europe is estimated less than 1000 units.
Quantities of SF6 per unit is depending on performance. Typical range is between 40 & 200kgper unit.

5.1.3 HV APPLICATIONS

5.1.3.1 DIFFERENT TYPES OF APPLICATIONS:

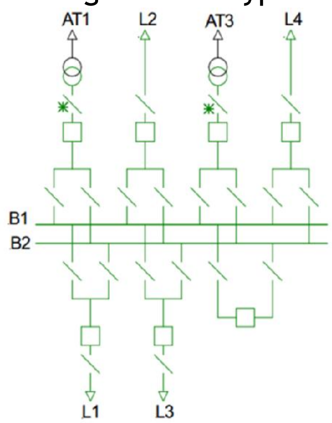
For rated voltage above or equal to 72kV i.e. high voltage, the switchgear is associated with so called “Gas Insulated Substations (GIS)” and “Air Insulated Substations (AIS)”:

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 SF6. 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 (SF6 to air bushings, cable ends, direct connections to transformers), and surge arresters.

SF6 is used for insulation, as well as for interrupting & making short circuit currents and switching continuous or induced currents.

Single line diagram of a typical substation (GIS or AIS):



Typical 145kV GIS arrangement – with all functions SF6 insulated:

A special application is the Gas Insulated Bus-duct which can be used instead of cables or overhead lines for connecting different parts of equipment such as the substation and power transformer or power generators. These connections are available at all rated voltages. The

quantity of SF6 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 80/20%) have been used in a couple of cases to cope with very low temperatures or to reduce the GWP by reducing the quantity of SF6 applied in the bus ducts. However, with typical GWP per kg around 15000, these gas mixtures have not been considered as real environmental friendly alternatives to SF6.

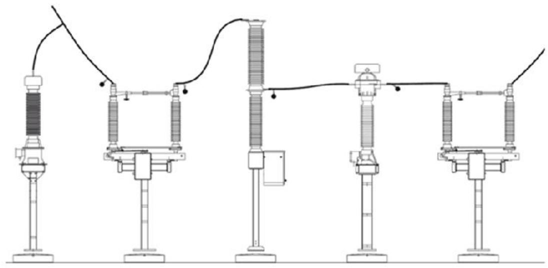
Typical 420kV gas insulated bus ducts:

5.1.3.1.2 Air insulated substations (AIS) and related switchgear:

In AIS, the phase to ground insulation is generally insured by atmospheric air. The parts intended to be operated at high voltage are supported by solid insulators made of ceramic or compound material. In AIS, SF6 is used mainly for interrupting purposes and internal insulation between open contacts or along insulating mobile rods in SF6 circuit breakers. Sometimes SF6 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 atmospheric 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 SF6 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 SF6 insulated. The bus bars are insulated by atmospheric air. Bus bars and overhead lines are connected to the SF6 insulated parts by SF6 to air bushings. When cables are used, they are connected to SF6 switchgear by direct interfaces, and when transformers are used they are generally connected through air insulated connections.

Typical 145kV 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 SF6.
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 SF6 or Nitrogen atmosphere. SF6 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 SF6, today the whole amount of SF6 used during manufacturing process of the insulating foam is reported as emission although - except of the part of SF6 consumed by the manufacturing process - all the SF6 is captured within the foam during the bushing's lifetime. Only in case of a damage of a bushing some SF6 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 SF6 will be recovered.

Typical power transformer with bushings & wall bushings:

5.1.3.2 EUROPEAN APPLICATIONS

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

5.1.3.2.1 GIS

GIS is exclusively using SF6 insulation technology in Europe. The first SF6 GIS has been put into service in the1970ties. 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 (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 SF6 banked in the switchgear are important. The order of magnitude for SF6 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 SF6 per bay of a recent GIS are in the range 30 to 1200kg normally increasing from 72 to 420kV. Typical filling pressure of SF6 in HV GIS is 0.5 to 0.75 MPa absolute.

Typical ratings available for GIS are:

HV SF6-gas insulated switchgear is used in Europe for substations up to 420kV, 63kA, and 6300A continuous current. Up to 170kV, 3-phase enclosures are commonly applied, whereas for higher voltages single-phase enclosures prevail.
For non-European applications, switchgear up to 1100kV 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 SF6 insulated.
Very few exceptions have to be reported for very low minimum operating temperatures with gas mixtures of SF6 & N2 or SF6 and CF4. However, with typical GWP around 15000 per kg, these gas mixtures have not been considered as real environmental friendly alternatives to SF6.

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 SF6. This is illustrated by an extract taken from the introduction of IEC standard 62271-100 on CB:

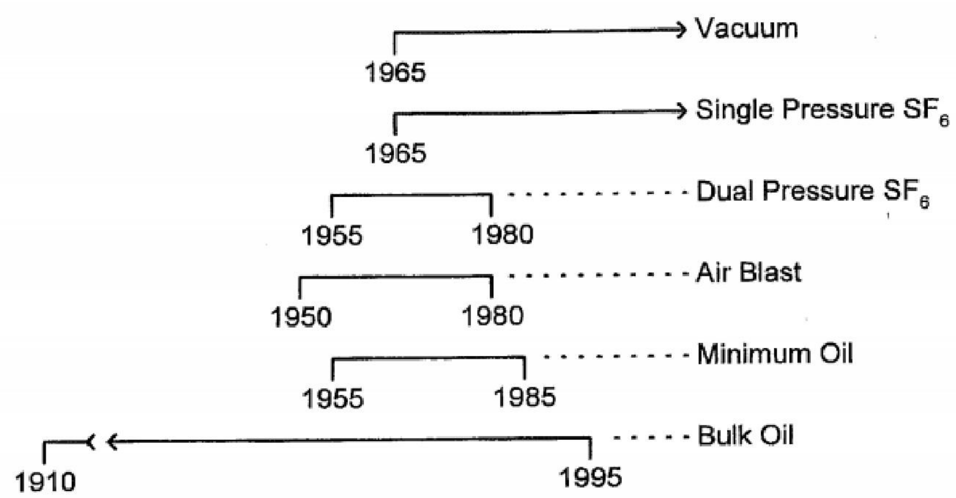


Figure 1 - Timelines for application of different circuit-breaker types. Solid lines indicate approximate or ongoing manufacturing periods

At time being all the HV AIS CB delivered in Europe are of SF6 type. Manufacturing of the other types has been stopped at the end of 1990ties or even before. The move to SF6 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 SF6 circuit-breakers are applied from 72.5kV up to 420kV in Europe and up to 800kV worldwide for short circuit currents up to 80kA and continuous currents up to 5000A. Up to 300kV one interrupter unit per pole is used, up to 550kV two, and above 800kV up to four interrupter units in series are applied. In addition, 72.5kV live tank circuit-breakers started using VI technology (in 2010).

IEC/ANSI HV dead tank SF6 circuit-breakers cover 72.5kV up to 550kV, short circuit currents up to 90kA and continuous currents up to 5000A. The breaker's enclosure is filled with SF6 and connection to overhead lines or bus bars is achieved by SF6 to air bushings.

In terms of existing assets, the number of non SF6 CB is estimated to be in the same order of magnitude as the number of SF6 breakers. Ageing equipment is now replaced by SF6 breakers. Therefore, the ratio is evolving to more SF6 equipment than pressurized air or oil filled equipment.

Typical quantities of SF6 per three poles in a “live tank” circuit breaker are between 2 and 50kg. Typical filling pressure of SF6 in HV Live tank CB is between 0.5 and 0.75 MPa 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 SF6 compared to the units with standard live tank design. For this technical report on SF6 alternatives, it will not be considered separately from the live tank circuit breakers application.

Instrument transformers:

Another use of SF6 in AIS in Europe is found in a limited number of instrument transformers, current, voltage & combined metering units. SF6 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 SF6.

Typical available ratings are:

HV instrument transformers using SF6 as the main insulation medium between high-voltage and earth potential are rated up to 420kV and 6000A concerning current transformers and up to 420kV concerning voltage transformers. The performance is equivalent to the performance of oil insulated instrument transformers.

The typical quantity of SF6 per pole of an instrument transformer is in the range of 10 to 60kg depending on the type & voltage rating. Typical filling pressure of SF6 in HV instrument transformers is 0.5 to 0.75 MPa 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 SF6-insulated power voltage transformers for AIS range from 72.5kV up to 420kV with an output power up to 125kVA (single-phase operation).

Disconnectors in AIS are always 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 SF6 encapsulated components and air-insulated devices is available with ratings up to 245kV, 63kA, 4000A.

This technology represents a limited part of the CB installed yearly in Europe and is estimated to 3% or less. Since his 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 SF6 per unit depends on the rated voltage and switchgear architecture (e.g. single or double bus bar) and may be considered being between 15kg & 60 kg of SF6 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 SF6 or vacuum interrupters) for transformer protection are of higher significance than in Europe where switch-fuse combinations are preferred (switching in SF6).
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.
Pad mounted arrangements for underground secondary distribution commonly use oil or SF6 for insulation purposes. Air-break switches are commonly used in overhead secondary distribution
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 the worldwide market are the same as in Europe for Generator Circuit breakers and switchgear.

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 SF6 are larger in “dead tank” breakers than in “live tank” breakers.
- For specific 72/84kV “dead tank” breakers in Japan, vacuum interrupters are frequently used. A few thousands of vacuum CB’s are in operation in Japan.

6 – RESEARCHES ON ALTERNATIVE GASES

6.1 Common requirements

Research has been ongoing to find a gas or gas mixture as alternative to SF6 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 behaviour 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 handling for filling and topping-up.

6.2 Available or recently developed technologies:

Natural occurring gases such as dry air, 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 SF6. 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 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.

CF3I – trifluoroiodomethane - 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 C5 perfluoroketones (C5-PFK, $C_5F_{10}O$) [8], C4 perfluoronitriles (C4-PFN, C_4F_7N[9] and hydrofluoroolefins (HFO1234ze). These pure substances have considerable lower global warming potential (GWP) than SF6 and C5-PFK even at the level of CO2. One disadvantage is that the pure substances show low liquefaction temperatures of 26.5 °C for C5-PFK and -4.7°C for C4-PFN at 0.1 MPa (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 0.1 MPa 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 SF6 has.

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 SF6 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 SF6 switchgear, however, with a much smaller GWP than SF6.

All alternative technologies 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 technology, it is desirable to develop and agree on standardized performance criteria to ensure a comparison of the currently discussed technologies with existing technologies 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 and recent moves in technology are presented.

7.2 EUROPEAN REGION

7.2.1 MV PILOT APPLICATIONS

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

Type	24kV GIS (Primary distribution)			
Insulation /GWP	C5-perfluoroketone gas mixed with dry air / <1			
Breaking /GWP	Vacuum interrupter / 0			
Rated performance	Ur (kV)	Ir (feeder) (A)	Isc (kA)	Min. op. Temp. (°C)
	24	2000	25	-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 SF6	Same			
Weight vs SF6	Similar weight			
Comments	Derating of Ir vs. similar SF6 switchgear			

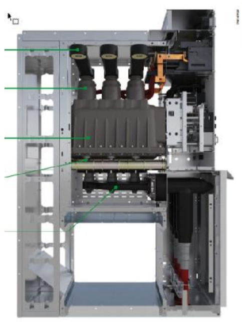

M2: 12 and 24 kV Ring Main Unit with vacuum interrupters

Type	12kV GIS for RMU (Secondary distribution)			
Insulation /GWP	Dry air 1.4 bar abs. also for disconnectors & earthing switch / 0			
Breaking /GWP	Vacuum circuit breakers & load break switches / 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 SF6 RMU	Same footprint as 12kV SF6			
Weight vs SF6 RMU	Slightly higher weight than 12 kV SF6			
Comments	Load-break function and load-break/fuse function realized by circuit-breakers			

Type	24 kV GIS for RMU (Secondary distribution)			
Insulation /GWP	C5-perfluoroketone gas plus 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. SF6 RMU	Same footprint as 24kV SF6			
Weight vs SF6 RMU	Slightly higher weight than 24 kV SF6			
Comments	Load-break function and load-break/fuse function realized by circuit-breakers			

M3: 17.5 kV Shielded solid insulation switchgear with vacuum interrupter

Type	17.5kV (Secondary and Primary distribution)			
Insulation /GWP (gas)	Air & Shielded Solid epoxy or EPDM, disconnecting by vacuum circuit-breaker, air earthing sw. / 0			
Breaking /GWP (gas)	Vacuum circuit breaker / 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, beginning of 2013			
Footprint vs SF6	Similar			
Weight vs SF6	Higher weight than a SF6 RMU & similar weight for CB functions			
Comments	Load-break function and load-break/fuse function realized by circuit-breakers			



7.2.2 GENERATOR CIRCUIT BREAKERS AND SWITCHGEAR

GCB1: GCB1 24kV, 12500A, 100kA Air & VI

Type	GCB 24kV			
Insulation /GWP	Air / 0			
Breaking /GWP	Vacuum 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 SF6	Similar			
Comments				

Source: Manufacturer’s brochure

7.2.3 HV APPLICATIONS

First industrial SF6-free prototypes have appeared recently for HV switchgear which can be split in 3 categories:

- Dry air insulation and using vacuum interrupters for breaking;
- Insulating and switching by use of a gas mixture of CO_2 & Fluoroketone, (C5 perfluoroketones (C5-PFK) [8]);
- Insulating and switching by use of a gas mixture of CO_2 & Fluoronitrile, (C4 perfluoronitriles (C4-PFN) [9].

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

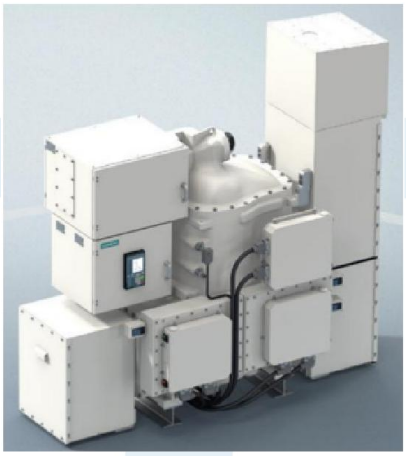
- For insulation: up to 420kV,
- For breaking by circuit breaker: up to 170kV, 40kA.

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: 72kV GIS« clean air » with vacuum interrupter.

Type	72kV GIS			
Insulation /GWP	air / 0			
Breaking /GWP	Vacuum interrupter / 0			
Rated performance	Ur (kV)	Ir (feeder) (A)	Isc (kA)	Min. op. Temp.(°C)
	72	1250	25	-30
Product first exhibition & year	Prototype shown in Hanover fair 2015			
Pilots & year of delivery/ service	No data			
Footprint versus SF6	larger			
Comments	Designed for offshore windfarm application (inside tower installation)			



Source: Cigre publication B3-108

G2: 145kV GIS “clean air” with vacuum interrupter.

Type	145 kV GIS			
Insulation /GWP	Air / 0			
Breaking /GWP	Vacuum interrupter / 0			
Rated performance	Ur (kV)	Ir (feeder) (A)	Isc (kA)	Min. op. Temp.(°C)
	145	<3150A	40	-50
Product first exhibition & year	Prototype shown at Cigre Session 2016			
Pilots & year of delivery/ service	No, at time			
Footprint versus SF6	larger			
Comments				

Source: T&D review October 5th 2016 & Manufacturer web leaflet

G3: 145kV GIS gas mixture of CO2 & Fluoronitrile for both insulation and interruption.

Type	145 kV GIS			
Insulation /GWP	CO2 and C4-Perfluoronitrile gas mixture / ~350			
Breaking /GWP	CO2 and C4-Perfluoronitrile gas mixture / ~350			
Rated performance	Ur (kV)	Ir (feeder) (A)	Isc (kA)	Min. op. Temp.(°C)
	145	2500	40	-25
Product first exhibition & year	Prototype shown at Cigre session 2016			
Pilots & year of delivery/ service	S/S in Switzerland & France for commissioning 2017 & 2018			
Footprint versus SF6	same			
Comments				

Source: Cigre session 2016

G4: 170kV GIS mixture of CO2, Fluoroketone & O2 for both insulation & interruption.

Type	170 kV GIS			
Insulation /GWP	CO2 and C5-Perfluoroketone and O2 / <1			
Breaking /GWP	CO2 and C5-Perfluoroketone and O2/ <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 SF6	larger			
Comments				


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

G5: 420kV GIB gas insulated bus-duct insulation made of CO2 & Fluoronitrile.

Type	420 kV GIB			
Insulation /GWP	CO2 and C4-Perfluoronitrile 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) / 2017			
Footprint versus SF6	Same			
Comments	3.4 tons of SF6 saved for Kilmarnock South installation			

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

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7.2.3.2 AIS APPLICATIONS

A1: 72kV LT with dry air and vacuum CB, Supplier 1

Type	72 kV live tank circuit breaker			
Insulation /GWP	Air / 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 (2 sites) & another European countries / 2012			
Footprint versus SF6	Same			
Comments				

Source: Cigre session 2016, publication B3-108

A2: 72kV LT with dry air and vacuum CB, Supplier 2

Type	72 kV AIS Live tank circuit breaker			
Insulation /GWP	Air / 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	1 in France / end 2012 and 1 in New Zealand / mid 2013			
Footprint versus SF6	same			
Comments				

Source: Cigre session 2012

A3: 72/145kV LT CO_2 & O_2 circuit breakers

Type	72kV 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	Deliveries of 72.5 kV CB started in 2014 Pilot (capacitor bank switching) of 145 kV CB in operation since 2010. No deliveries.			
Footprint versus SF6	similar			
Comments				


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

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A4: 245kV Current Transformers. CO2 & Fluoronitrile insulated

Type	245 kV AIS Current Transformer			
Insulation /GWP	CO2 and C5-Perfluoronitrile 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 2017			
Footprint versus SF6	same			
Comments				

Source: Cigre session 2016

A5: 72.5kV clean air Instrument Transformers

Type	72.5 kV clean air combined Instrument Transformer for AIS			
Insulation /GWP	air / 0			
Breaking /GWP	Not applicable			
Rated performance	Ur (kV)	Ir (feeder) (A)	Isc (kA)	Min. op. Temp.
	72.5	1200A	40	-50°C
Product first exhibition & year	Prototypes shown at Cigre session 2016			
Pilots & year of delivery/ service	NA			
Footprint versus SF6	Same than 123kV SF6 design			
Comments				

A6: 145kV Live tank – prototype

Type	145 kV AIS Live tank circuit breaker			
Insulation /GWP	CO2 and C5-Perfluoronitrile gas mixture / ~350			
Breaking /GWP	Circuit-breaker in CO2 and C5-Perfluoronitrile gas mixture / ~350			
Rated performance	Ur (kV)	Ir (feeder) (A)	Isc (kA)	Min. op. Temp. (°C)
	145	3150	40	-30
Product first exhibition & year	Type tests completed and presented during at Cigre session 2016			
Pilots & year of delivery/ service	no			
Footprint versus SF6	same			
Comments				

Source: Cigre 2016 A3 114

7.3 SIGNIFICANT MOVES FROM OTHER REGIONS

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	72.5kV AIS Dead tank circuit breaker			
Insulation /GWP	Dry air 0.15MPa/ 0			
Breaking /GWP	Vacuum interrupter / 0			
Rated performance	Ur (kV)	Ir (feeder) (A)	Isc (kA)	Min. op. Temp. (°C)
	72	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 SF6	Similar overall footprint but larger tank diameter			
Comments				

Source : Cigre session 2012

NE2 : DT 72kV from Japan

Type	72.5kV 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 SF6	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			
Pilots & year of delivery/ service	Unknown			
Footprint versus SF6	Unknown			
Comments				


Source : Cigre session 2016, publication A3-105

8 - PERSPECTIVES BY SEGMENT OR APPLICATION

The objective is to deliver an overview of perspectives by applications for alternatives to SF6 described in previous chapters.
This overview aims to:

- Compare the equipment respective main characteristics by segment of application.
- Deliver the best possible perspective from today, based on present alternatives, public researches & first pilots and applications known at end of 2016.

- 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):

- Ambient air;
- Solid insulation without earthed screen;
- Solid insulation with earthed screen;
- Dry air pressurized.

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

- Dry air (pressurised);
- New generation of solid insulation with earthed screen;
- Dry air with Perfluoroketones (C5-PFK) (pressurised).

T&D Europe estimates that another promising alternative in early stage of research activity (ref. to chapter 6) is HFO 1234zeE (pressurized);

Limitations might exist in terms of minimum operating temperature, for instance, when comparing the different alternatives to existing SF6 equipment.

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 SF6 with respect to major characteristics. Numbers are good estimations or based on published literature.

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Table 6 – Comparison of key characteristics for main insulating alternatives and SF6 for MV applications

Gas or mixture (at 0.13 MPa abs) (1)	Diel. % (2)	Voltage available kV (3)	GWP of gas (4)	Min. op. temp. °C (5)	Material compatib. (6)	Heat dissipation % (7)	EHS (8)	Gas Handling (9)	Foot print % (10)
SF6	100	40.5	22800	-40°	proven	100	proven	Proven, end of life closed cycle	100
Dry air	45	12	0	-50°	proven	80 to 90	proven	proven	160
Solid ins. (epoxy) silicon	NA (11)	24	NA	-50°	proven	90 to 100 (12)	Environtal Drawback flammable	NA recycling needed	120
SIS w earthed screen	NA (11)	17.5	NA	-25°C	proven	90 to 100 (12)	Environtal Drawback flammable	NA recycling needed	110
Dry air & C5-PFK	95/90	24	1	-15°/-25°C	Need use of specific mat.	80 to 90	Some data missing.	Mixture to be managed, end of life, closed cycle	100
HFO1234ze E pure	100	No product at time	6	-15°C (1.3 bar abs.)	OK acc. Lab. Tested	~100	Further investigations on flammability needed	Need more investigation for end of life	100

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Notes related to table 6:
(1) Main alternatives to SF6 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 0.13MPa 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. The value given in the table is the one considered by European regulation on F-gases dated on 2014. Other slightly different values can be found in the literature. For instance, the last value delivered by IPCC (International Panel for Climate Change) in AR5 report dated on 2013 is 23500. Practically comparison has also to be performed on the GWP of the complete product considering the quantity of gas used, the density and the GWP of materials used for the construction depending on the gas pressure and the size. GWP is not applicable ("NA") to solid insulation which may have other environmental drawbacks.
(5) Usual minimum operating temperatures reached with SF6 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 SF6 (assumed 100%).
(8) Global evaluation of EHS aspects.
(9) 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.
(10) Approximate ratio based on the average footprint of GIS pilots presented in chapter 7 versus SF6 design, typically based on comparison of bay width.
(11) Direct comparison between gaseous insulation and solid insulation may be not representative of the performance of complete product and has been considered like "not applicable" (NA).
(12). 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 100% has been considered like representative for existing product designs.

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. Recent moves are directed to a generalization of the use of vacuum interrupters.

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 SF6 solutions, needs separate devices. No public research is showing that alternative gases have been found for such a general purpose switch up to now. However, no technical reason should prevent investigating this function with some alternatives considered for insulating purpose like pressurized natural gases or natural gas mixtures with C5-Perfluoroketones or C4-Perfluoronitrile. HFO is not an alternative to SF6 for current switching.

8.1.2 Application by segments

8.1.2.1 Utilities

8.1.2.1.1 Primary substation (HV/MV)

In HV/MV substations, most (estimated 75 %) of MV primary switchgear is ambient air insulated, where SF6 is used in 30% of the circuit breakers and vacuum interrupters in 70%. General application of vacuum interrupters may suppress the use of SF6 except in a few specific applications.

Estimated 25% of all primary substations are GIS with SF6 insulation. Considering the already existing & emerging alternatives as described in chapter 7 and further developments, SF6 alternatives should be technically viable in most of the cases (typical 90%) still keeping the advantages of today SF6 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 SF6. Current breaking is predominantly performed by SF6 switches and SF6 switch-fuse combinations. However, circuit-breakers are rarely used mainly with vacuum technology. The switchgear assemblies are of sealed pressure type, therefore SF6 leakages are very small (<0.1%/year) with limited impact on SF6 emission into the atmosphere. For new substations, SF6-free alternatives such as those presented in chapter 7 could be used with limitations concerning the minimum operating temperature, size, cost, operating complexity (separate devices vs. general purpose switch) and user's preference for standardized solutions. Due to limited size within existing secondary substation housings, replacement of SF6 switchgear by switchgear using alternative technologies requires switchgear with similar dimensions and must be studied case by case.

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 switches and others with circuit-breakers. MV switchgear for switching substation typically implement the same technologies as 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 neglectable quantities of SF6 emitted into the atmosphere during all stages of its life cycle.
For operation of small generators, typically below 200 MW, air insulated breakers with vacuum interrupters are an existing alternative to SF6, which could be generalized and developed for higher performances. A 450MW generator vacuum circuit-breaker (GCB) has recently been launched as reported in chapter 7.
For higher performance, typically above 450MW, today there is no alternative to SF6 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. SF6 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. Due to their high GWP, gas mixtures such as SF_6 and N_2 or SF_6 and CF_4 are not considered as environmental friendly alternatives.

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

- Dry air (pressurized);
- CO_2 & O_2 (O_2 added for arc quenching purpose)
- C5-Perfluoroketones (C5-PFK) in gas mixtures with CO_2 and with addition of O_2 when also used for arc quenching
- C4-Perfluoronitrile (C4-PFN) in gas mixtures with CO_2

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 SF6 for HV applications

Gas or mixture (at 0.6 MPa abs) (1)	Dielectric % (2)	Voltage available kV (3)	GWP of gas (4)	Min. op. temp. °C (5)	Material compatib. (6)	Heat dissipation % (7)	EHS (8)	Gas Handling (9)	Foot print % (10)
SF6	100	1200kV	22.800	-40°	proven	100	proven	Proven, end of life close cycle	100
Dry air	40	145	0	-65°	proven	80 to 90	proven	proven	130
CO2 & O2	40	145	1	-65	proven	80 to 90	proven	Proven Gas mixture to manage	130
C5-PFK (%) & CO2 & 02 (%)	75	170 (GIS)	1	0°	Need use of specific mat.	80 to 90	Some data missing	Proven on pilots, end of cycle under development	120
C4-PFN (4-6%) & CO2	85	420 (GIB)	350	-30°C	Need use of specific mat.	80 to 90	Some data missing	Proven on pilots, end of cycle under development	100

Notes related to table 7:
(1) Main alternatives to SF6 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 0.6MPa 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. The value given in the table is the one considered by European regulation on F-gases dated on 2014. Other slightly different values can be found in the literature. For instance, the last value delivered by IPCC (International Panel for Climate Change) in AR5 report dated on 2013 is 23500. Practical comparison has also to be performed on the global warming impact of the complete product considering the quantity of gas used, the density, the gas and Joule losses and the global warming impact of materials used for the construction depending on the gas pressure and the size.
(5) Usual minimum operating temperature reached with SF6 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 SF6 (assumed 100%).
(8) Global evaluation of EHS aspects.
(9) Global evaluation of the constraints related to the gas handling process.
(10) Approximate ratio based on the average footprint of GIS pilots presented in chapter 7 versus SF6 design, typically based on comparison of bay width.

With this panel of alternatives, no major technical barrier is seen from insulation point of view to develop SF6 free products for all types of applications (GIS, DT, LT, HIS, IT) & all rated high voltages used in Europe and in the world, from 72kV to 1100kV. Products without interrupting capabilities with first applications are available up to 420kV, but limitations exist depending on this alternative when compared to SF6 solutions in terms of minimum operating temperature, for instance.

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 & O2 gas mixture;
- C5-Perfluoroketone (C5-PFK) & CO2 & O2;
- C4-Perfluoronitrile (C4-PFN) & CO2.

The simplified comparison in table 8 shows the difference between breaking capabilities reached today with these alternatives and SF6. Max. voltage and short circuit ratings reached with a single break interrupting unit are representative of the breaking capability. Perspectives of future extension of performance

Table 8 – Comparison of breaking capability reached today by circuit breakers with alternatives and SF6 for HV applications

Gas or mixture (1)	Max single break voltage (kV) (2)	Isc (kA) (3)
SF6	550	63
VI	145	40
CO2 & O2	145	40
CO2 & PFK & O2	170	40
CO2 & PFN	145	40

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, SF6-free breaking prototypes or technologies are already available up to 170kV 40kA.

The extension to higher voltage is technically feasible though not yet proven with CO2 & FK or CO2 & FN mixtures which use the same interrupting principles as the last generation of SF6 interrupting units.

This extension is much more challenging for vacuum technology where the distance between contacts need to increase not linear with the voltage. At time being, vacuum interrupters show a limit, particularly for capacitive switching, at 145kV. Above 145kV use of several interrupting unit in series with grading capacitors may be needed making the solution not competitive in terms of footprint and cost versus other alternatives.

Limitations exist depending on the alternative when compared to pure SF6 solutions, for instance, in terms of minimum operating temperature for outdoor applications. 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. In all cases development of new circuit breakers implements heavy investments.
capacitors may be needed which would most likely influence the equipment's footprint.

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

8.3.2 Perspectives for HV GIS

High voltage GIS is using larger quantities of SF6 than AIS HV equipment and MV equipment. In order to achieve a significant impact on SF6 emissions into the atmosphere, it is therefore required to focus on HV GIS.

SF6-free alternative technology for HV GIS is available for voltages up to 170kV with footprint equal or slightly larger than SF6 switchgear with the same performance. For circuit breakers, SF6 free alternative technology is available up to 170kV and 40kA.
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 SF6-free gases up to 420kV has been demonstrated with a GIL.
However, completely replacing the SF6, in particular for very low ambient temperatures below -30°C and very high short circuit currents, is not yet technically possible or proven.
In Europe, likely around 80% of the GIS SF6 equipment would be technically accessible with SF6-free alternatives.

8.3.3 Perspectives for GIL

In gas-insulated line (GIL) or gas insulated bus ducts (GIB), the quantities of SF6 may be quite high depending on the length of the line or duct.
SF6-free alternative technology is available today for 420kV & 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 seems possible. Extending to even lower operating temperatures might be difficult. 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 SF6 alternatives described above are suitable to fulfill the requirements for this application.

8.3.4.1 HV AIS Life tank CB

SF6 free technology exists for 72kV voltage & 31.5kA based on air insulation and vacuum interrupters and for 145kV and 40kA based on CO2 & O2 for both insulation and interruption as well as CO2 & C4-Perfluoronitrile for both insulation and interruption.
For CO2 & O2 and CO2 & C4-Perfluoronitrile mixtures, the same interrupting principles as used in the last generation of SF6 chambers are used, but adapted to the characteristics of the specific gas mixtures. It makes the possibility likely to extend these breakers to higher performance voltage and short circuit current), however this would be highly demanding in terms of investment and development efforts.

8.3.4.3 HV AIS Dead tank CB

DT circuit breakers have a very rare installation in Europe, therefore SF6 free technology for Dead Tank circuit breakers would not impact significantly the emission of SF6 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 SF6.
Technical feasibility of SF6-free applications has been demonstrated with first applications up to 245kV. Extension to the highest voltage used in Europe appears possible without major difficulty.

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

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