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Briefing paper: SF_6 and alternatives in electrical switchgear and related equipment

1 Introduction

Sulphur hexafluoride (SF_6) has been used as an insulating and circuit breaking medium in switchgear for decades. With a global warming potential (GWP) of 22,800[1], SF_6 is the most potent greenhouse gas known and its use in switchgear can produce toxic by-products. Regulation (EU) No 517/2014, Article 21(4), requests the EU Commission to assess whether cost-effective, technically feasible, energy –efficient and reliable alternatives exist, which make the replacement of fluorinated greenhouse gases possible in new medium-voltage secondary switchgear. This briefing paper provides preliminary findings of an assessment for the European Commission. In addition to all medium voltage (MV) switchgear, the paper also briefly covers high voltage (HV) switchgear as well as some related electrical equipment.

2 Status of alternatives to SF_6 in different types of equipment

2.1 Different types of switchgear

Switchgear can be distinguished based on:

(i) voltage level: up to 1 kV low voltage (LV); 1 kV - 52 kV medium voltage (MV); 52 kV - 230kV high voltage (HV); above 230 kV extra-high voltage;
(ii) application (e.g. transmission substations, distribution transformer cabinets, generator circuit breakers, etc.);
(iii) the insulation method and current interrupting device used

2.2 Medium voltage switchgear - general

In the medium voltage sector, primary power distribution refers to switchgear at the interface between (high voltage – medium voltage) substations and distribution networks.

Primary distribution is generally implemented in controlled environments such as substations of regulated or industrial network operators in closed buildings. Such devices are integrated directly into the networks of the final users.

Secondary power distribution refers to switchgear at the interface between medium voltage distribution networks and the (medium voltage – low voltage) distribution transformers, located in cabinets near the users' premises.

The dominating application of secondary power distribution are ring main units (RMU), in different configurations, integrated in MV/LV[2] transformer cabinets in regulated public networks. Compared to primary distribution, there are a number of additional constraints: installation space is usually very limited, environmental parameters like temperature or humidity are often not controlled and the equipment may be installed in public areas.

As regards insulation material, switchgear can be characterised as being air-insulated systems (AIS), gas insulated systems (GIS), or solid insulated systems (SIS)[3]. For the breaking function a distinction is made between switchgears using air, SF_6, vacuum and other gases (see Table 1).

1 IPCC Fourth Assessment Report: https://www.ipcc.ch/assessment-report/ar4/
2 MV/LV: medium voltage/low voltage
3 Switchgear using fluids (e.g. oil, ester) as insulating medium also exist.

Table 1: main insulating and switching media per segments for secondary switchgear with qualitative indication of share (e.g. high, medium, low) in installed asset base (based on T&D Europe: Technical report on alternative to SF6 gas in medium voltage & high voltage electrical equipment, Brussels, 2020)

		Regulated network operators	Private sector
		MV / LV substation, MV switching substation, MV overhead lines pole-mounted switchgear	Commercial and industrial buildings, 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
	Breaking medium	SF_6: very high Vacuum: low Air: very low	SF_6: High Air: Low Vacuum: Low
Circuit breaker	Insulating medium	SF_6: High Air: Low Dry air in sealed tank + solid (hybrid): very low	SF_6: Low Air: High Solid: Low
	Breaking medium	SF_6: Low Vacuum: high	SF_6: Low Vacuum: High

- Air-insulated switchgear (AIS) is mainly used in primary distribution. As the name reveals, it is using air as insulation. Vacuum or SF_6 is used for breaking. Compared to systems using SF_6 as the insulating medium, AIS tends to have a larger footprint[4] and electrical parts may be exposed to environmental influences. AIS have a significant market share in applications where these aspects are not critical, i.e. in rooms with controlled climate offering sufficient space. An example is **primary distribution** in industry. In the current market for **new secondary distribution** (RMU), AIS does not play any role of importance.

- Gas-insulated switchgear (GIS) (primary and secondary distribution): SF_6 is typically the gas used in conventional GIS today.

- Solid insulated switchgear (SIS) solutions for secondary distribution have been commercially available for decades. The footprint of products up to 24 kV currently marketed is equal to solutions using SF_6. Market share all over Europe is in the lower single digit percentage, partly due to the slightly higher investment compared to SF_6 products. In some member states and regions, however, final users adopted this technology and, hence, the market share locally is much higher.

  State of the art SIS designs combine solid insulation with air at ambient pressure in a hermetically sealed tank. Environmental factors like dust, dirt, salt, humidity do not affect the performance of the equipment.

In summary, SF_6-free alternatives have always been used in primary distribution; AIS with vacuum breaker are state of the art and represent about 50% of the existing asset base[5]. Also, different designs of switchgears for various applications in medium voltage distribution totally or partially replacing SF_6 have been traditionally used. There are however a number of limiting factors, in particular in secondary distribution, that restricted the choice of switchgear type, including initial investment needs, space constraints, required maintenance effort and environmental conditions (e.g. humidity, dust, salt, temperature).

2.3 Assessment of new alternatives for medium voltage switchgears

4 i.e. space requirement, size

5 T&D Europe: Technical report on alternative to SF6 gas in medium voltage & high voltage electrical equipment, Brussels, 2020

In addition to traditional existing solutions without SF_6, there are a number of new alternatives that have become available more recently, are already used in electricity distribution or are still being piloted. These are mostly GIS designs using alternative gases and blends of gases as insulating medium. Some gas blends consist of natural substances only (N_2, O_2, CO_2), others use synthetic substances (e.g. fluoronitriles or fluoroketones). **The solutions are designed to have similar properties to SF_6 switchgear with regards to use of space or reliability.**

The following table presents a selection of alternative solutions in MV secondary and primary distribution presented by manufacturers.

Table 2: Examples of alternative medium voltage switchgear (secondary and primary distribution)

Rated Voltage	**Type of application**	*Solution for insulation* **Solution for load breaking / circuit breaking**	**Status / comment**
Up to 24 kV	Secondary distribution	*Air* vacuum interrupter / vacuum breaker	Commercial product (applied for more than 5 years)
		Alternative gas using synthetic substances vacuum	Type tested and demonstrated with end users (less than 5 years).
		Alternative gas using natural substances Vacuum	Pilot presented in 2019 (12 kV).
		AIS load break switch with alternative gas (natural substances) at enhanced pressure in combination with vacuum interrupter	Commercial launch anticipated in 2020, GIS using same concept announced for 2021
36 kV		Various. Partly design extensions of existing 24 kV solutions.	Piloting / demonstration anticipated within 2 years
12 kV	Primary distribution	*Alternative gas (natural substances) at enhanced pressure*	12 kV pilot presented in 2019, next panel type to be presented in 2020
Up to 24 kV		*AIS* load break switch with alternative gas (natural substances) at enhanced pressure in combination with vacuum interrupter	Commercial launch anticipated in 2020, GIS using same concept announced for 2021
Up to 24 kV		*Alternative gas blended with synthetic substances*, design comparable to SF_6	Type tested, piloting and demonstration running for several years.
36 kV		*GIS alternative gas (natural substances, enhanced pressure)* Vacuum	Type testing and piloting ongoing, to be finalised in 2020
Up to 36 kV		*Various AIS* vacuum breaker	Variety of commercial products (applied for more than 5 years), larger footprint than SF_6

Summarizing assessment of alternatives in Table 2

Except where explicitly mentioned, physical dimensions and electrical ratings of these alternatives are identical to products using SF_6[6]. The weight of solutions using enhanced gas pressure may be slightly higher. Alternatives listed indicate that, in principle, there is no general technical barrier for using SF_6 free switchgear in new installations in the MV segment.

Regardless of the technology option and voltage levels, in the course of the consultations, manufacturer representatives reported **additional investment costs** after industrialisation in the range between 5% to 20%, with some conditional exceptions down to 0% and up to 30%. Of course, for new alternatives, cost information is based on manufacturers' claims and at this stage they can only provide indicative figures expected after full upscaling of manufacturing.

Differences of **operational efficiency** of existing switchgear and new alternatives are negligible. In particular in the case of RMUs, the average current running through the switchgears' components is far below rated values and hence operational losses on average are about one order of magnitude lower than rated losses.

Like SF_6 products, all new SF_6 free as well as some of the commercially existing alternatives are sealed for life, thus from a **maintenance** perspective, such alternatives are comparable to the GIS solutions using SF_6.

For those solutions using natural substances only, recovery of the gas at the **end of life** is not required. Thus, the costs at this stage of the life cycle is lower than for systems using SF_6 or alternative gas blends using synthetic substances[7]. However, it is not possible to reliably quantify this potential cost advantage[8].

Commercial availability of alternatives and, thus, potential market penetration will be affected by several additional steps:

- In particular in secondary distribution (RMUs), specific application configurations need to be developed and type-tested.
- A precondition for application by large end users (distribution network operators) is full homologation[9].
- Manufacturing processes for alternative solutions differ from products using SF6 in terms of tools and organisation. Manufacturers need to implement and upscale manufacturing to industrial scale.
- Manufacturers' investments in development and manufacturing of alternatives will depend on market expectations. Solutions for niche markets may become available later than large volume products like standard RMUs.

These steps take some time. The needed period may however be around 2 years for standard applications in primary distribution (MV switchgear in substations) and the most common RMU configurations, whereas other applications may need a few additional years for market readiness.

2.4 Assessment of new alternatives for high voltage switchgear

[6] A more representative and detailed overview is provided in T&D Europe: Technical report on alternative to SF6 gas in medium voltage & high voltage electrical equipment, Brussels, 2020

7 End-of-life treatment of gas blends with synthetic substances requires similar procedures like SF6.

8 From a climate policy perspective end of life emissions of SF6 are a crucial aspect. So far, only marginal shares of the existing SF6 asset base have reached end of life. Very little evidence-based data on end of life emissions are available. Estimates cover a range from 1% to 40% of emissions from scrapped equipment. In the worst case, 40% of the 1500 t SF6 annually filled into new equipment by European manufacturers (in MV and HV) will be released to the atmosphere at some moment in time. This corresponds to 1.5 Mt CO2 eq annually. The environmental impact of these emissions is potentially a multiple of current emissions in manufacturing and operation of electrical switchgear (MV and HV) in Europe.

[9] Homologation describes the process of integrating a particular solution in the companies' asset universe. As a result, in-house procedures and standards reflect the key characteristics of the solution This allows application without case specific assessment and evaluation.

High voltage switchgear is manufactured, type tested and assembled in components. This allows faster industrialisation than in case of mass product configurations like RMUs.

Switchgear for voltages between 52 and 145 kV

Gas insulated substations using gas blends with synthetic components (e.g. fluoronitriles or fluoroketones) are able to achieve similar ratings and footprint like equipment using SF_6. GIS using natural gases only (e.g. nitrogen, dry air, CO_2, etc.) requires larger dimensions and, hence, more material resulting in a cost increase of 20% to 30%. Future technology optimisation will allow deploying existing reduction potential.

Pilot installations for voltages up to 145 kV have been successfully implemented and operated using the different gases and gas blends. According to manufacturers, several hundred bays already have been ordered. Implementation of different technology approaches is expected in the next two years.

Also live tank breakers have been presented and piloted successfully by several manufacturers.

For offshore wind power plants, GIS for 72.5 kV has been commercially introduced. Substantial growth is expected (more than 1000 orders already placed).

Thus, from a technical point of view it is feasible to use SF_6 free solution for some uses in the HV voltage segment already now.

Switchgear for voltages higher than 145 kV

SF_6 free switchgear for 245 kV and 420 kV is under development. Depending on voltage and functionality (substation, live tank circuit breaker, dead tank circuit breaker), for various components scheduled development periods are 2 to 5 years. In general, the concepts are an extension of existing designs using higher pressures and / or adapted blends of substances.

2.5 Related equipment

Related equipment covers a variety of functionalities and respective products. Across the industry there is no agreed categorisation. The examples included here are focusing on passive high voltage applications.

- Gas insulated lines using a gas blend with synthetic substances have been demonstrated for voltages up to 420 kV.
- Bushings: in a number of applications alternatives are available for voltages up to 145 kV, with an extension to 245 kV being realistic in the medium term. Higher voltages still require fundamental research.
- Instrument transformers have been installed and operated at end users' sites at 245 kV. The offered range of technology options will be extended in the next 2 to 3 years. Development of selected solutions for specific technology approaches for up to 420 kV is close to completion, i.e. initialisation of pilots may be expected in the next two years. Diversification of technology approaches may take up to 5 years.

As for MV, instrument transformers rely on epoxy as insulating medium, but SF_6 is used during manufacturing. The final products contain only very low residues of SF_6. Further emission reduction in the manufacturing process is possible. Complete replacement of SF_6 may be possible for a limited number of applications (lower insulation levels) in the next 5 years.

3 End users' perspective on SF_6 free alternatives

Since most new alternatives have just recently been piloted, practical experience at the users' side for these new solutions is limited and the attitude of end users with respect to the future necessity of SF_6 is very diverse.

- Utility sector: Various network companies have a consistent history of using alternatives (in medium voltage AIS with vacuum switches in primary distribution; SIS in secondary distribution). Recently, some network companies have been actively investigating and piloting new options in collaboration with manufacturers. The majority of network companies has an observing attitude or does not yet pay dedicated attention to alternatives. Some stakeholders expressed reservations related to the lack of long-term practical experience with new alternatives and their proven reliability. There are national differences.

- Private sector (project developers, power plant owners / operators and private network companies): The majority of players, apparently, does not pay much attention to the subject. In the industrial sector, however, alternatives like AIS have always been part of the solutions.
- Manufacturers using OEM equipment in their products (e.g. wind turbine manufacturers) did not express a dedicated position nor clear concerns regarding restrictive policies addressing future usage of SF_6. There are first examples of application of SF_6 free solutions (GIS in offshore wind).

Some users express concerns regarding technical performance, cost and health and safety issues related to SF_6 free alternatives. However, whereas the initial investment costs are indeed likely to be somewhat higher (at least in the short term), manufacturers already have some experience with using SF_6 free solutions and they are performing tests on their new equipment that in principle should alleviate the other concerns related to space constraints and reliability.

It has to be mentioned that a variety of niche applications exist which cannot be served with standard products. Examples are end users that use differing frequencies (railway companies) or extraordinarily high currents in industry. In the near future, alternatives in these niche sectors may not be available, not least because niche markets are usually not the principal focus of manufacturers. Challenging requirements (e.g. extreme currents and temperatures) may justify an exceptional usage of SF_6.

Network companies and other asset owners emphasise the importance of the situation and boundary conditions for the applicability of alternative solutions offered by manufacturers:

Situation	**Description / example**	**Applicability of SF_6 free technologies**	**Remark**
'greenfield'	New MV/LV distribution cabinet to be placed as a consequence of network extension	After positive technology evaluation, alternatives may be equally applied.	Dominating part of total market potential in MV.
Complete retrofit	Exchange of defective RMU in an existing MV/LV distribution cabinet	Only solutions with the same or smaller footprint offer a realistic alternative. Manufacturers are addressing this aspect (no fundamental obstacle).	Market potential consisting of replacement of old AIS and GIS in existing building structures. The total volume now and in the near future is limited.
Partial retrofit / extension	Exchange of primary switchgear in a MV substation, addition of new primary switchgear in existing substation	Depending on the specific situation, identical footprint is not always a strict precondition. Nevertheless, manufacturers are addressing this aspect (no fundamental obstacle).	Looking at operation and maintenance, end users perceive the application of different gases / technologies at one site as unattractive.

4 Conclusion

Various types of SF_6 free switchgears have existed in parallel to SF_6 switchgear for a long time. Currently, SF_6 solutions are commonly used, certainly when there are special constraints such as space, as it is the case in secondary distribution. In primary distribution, SF_6 free solutions always have had a significant market share.

In recent years, the technological development of SF_6 free switchgear in GIS design for medium voltage switchgear in secondary distribution has made very good progress, providing alternative technologies that are comparable in many ways to SF_6 GIS systems.

The time period required for alternatives to be ready for large scale application depends, among others, on the level of voltage and application area. It may be quite short for standard applications in primary distribution (MV switchgear in substations) and the most common RMU configurations (secondary distribution). It is foreseen that SF_6 free switchgear can become technically feasible and associated with reasonable extra investments for nearly all segments of MV applications within 2 to 4 years.

However, in general such a shift may result in an initial cost increase of up to 20%, raising to 30% in exceptional cases, compared to systems using SF_6. On the other hand, the costs related to the treatment of the equipment at the end of life, is likely to be lower compared to SF_6 equipment.

The time needed for large-scale application in HV is longer, in particular for applications >145 kV where the scheduled development periods can last up to 5 years and the commercialisation can start only after this period.

At all voltage levels some exceptional applications exist, where adequate alternatives are not yet readily available. These applications have to be evaluated on a case by case basis.