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Author(s):

Franck, Christian ; Chachereau, Alise ; Pachin, Juriy

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SF₆-free gas insulated switchgear: current status and future trends

Christian M. Franck, Alise Chachereau, Juriy Pachin

The present article gives an overview of research on SF₆ replacement gases for electric power equipment, of existing SF₆-free technologies, and of worldwide developments in legislation to support these new technologies.

Introduction

Sulphur hexafluoride (SF₆) is widely used as electrical insulator and arc-quenching gas in equipment for the transmission and distribution of electric power. This includes various medium and high voltage applications, such as gas-insulated switchgear (GIS), gas-insulated lines (GIL), instrument transformers and bushings. SF₆ gas-insulated substations are very compact compared to air insulated substations and have less impact on the landscape, which makes them an attractive technology in densely populated areas.

However, the 100-year global warming potential (GWP) of SF₆ relative to CO₂ is 23'500 [1], and despite best efforts to reduce SF₆ emissions, a steady increase of its atmospheric concentration is still observed since 1995, as can be seen in Figure 1. The emission rate of SF₆ even increased, from 0.22 ppt/year over the period from 1995 to 2005 to 0.33 ppt/year over the period of 2005 to 2020. Additionally, SF₆ has a very long atmospheric lifetime, which makes its climate impact almost irreversible. The atmospheric lifetime of SF₆ is difficult to estimate precisely but would be about 850 years [2]. Therefore, the use of SF₆ raises environmental concerns.

Figure 1: Global mean of SF₆ atmospheric concentration since 1995 from the NOAA/ESRL Global Monitoring Division [3]. Two linear fits over periods of 10 years show that the growth rate of the SF₆ atmospheric concentration increased by 50 %, from 0.22 ppt/year during the period 1995-2005 to 0.33 ppt/year during the period 2010-2020.

Despite these concerns, the use of SF₆ could not be immediately banned in the electric power industry in the absence of alternative technologies. Instead, measures were taken to reduce the SF₆ emissions. However, with the emergence of SF₆-free alternatives for an increasing number of applications, bans of SF₆ for specific applications in the electric power industry are foreseeable in the near future.

A recent scenario analysis [4] has clearly shown that only a transition to SF₆-free technologies will lead to a continuing reduction of SF₆ emissions. Even the exclusive use of the most advanced technologies with minimum emissions would lead to steadily increasing SF₆ emissions (almost doubling today's emissions in the coming 80 years) due to the ever-increasing installed basis and with it the banked amount of SF₆. The legal frameworks must, thus, be urgently adapted and set to support and ensure a complete transition as fast as technically and economically possible. Due to the long development and even longer investment horizon, a dependable change is a mandatory requirement for manufacturers and users.

There are numerous requirements and selection criteria for gases to replace SF₆ as insulation medium. These include high electric strength, high volatility of the gas to enable the use of high pressures, low toxicity (ideally none), no ozone depleting potential (ODP), low global warming potential (GWP), and chemical stability over decades in the equipment. These requirements point towards fluorinated gases, although chlorinated gases would be suitable as well if they have sufficiently low ODP (cf. Figure 2, in which the boiling point and relative electric strength compared to SF₆ are plotted for a few recently discussed gases). So far, no pure gas fulfilling all these requirements has been found. However, if the high

volatility is disregarded, a large number of gases reasonably fulfilling the other requirements are available. Therefore, gas mixtures containing one fluorinated gas and one or more volatile gases could fulfill all the requirements. Amongst the gases shown in Figure 2, C4-PFN with the formula C_3F_7CN and C5-PFK with the formula $C_5F_{10}O$ are currently in use in SF_6 -free commercial products.

Figure 2: Electric strength relative to SF_6 and liquefaction temperature at ambient conditions of several insulating gases. The full line corresponds to the vapor pressure curve of SF_6 . Gases below this curve require higher operating temperature limit. GWP: very high global warming potential, tox: high toxicity, oxd: strong oxidizer.

In electric power equipment, SF_6 serves three main technical purposes: insulation of high electric field strengths, cooling (heat removal), and arc quenching (current interruption). These three functions must be fulfilled by any SF_6 -free system, which can also be non-gaseous alternatives, specifically solid, liquid or vacuum. Each of these SF_6 -free solutions has advantages and disadvantages compared to SF_6 , and is thus considered for different applications, e.g. oil insulation is used in transformers to support the convective heat removal, and solid insulation materials are indispensable for the mechanical support of voltage and current carrying components. The electric strength of the different insulation media is qualitatively shown in Figure 3. Gaseous insulation gaps show a linear dependence of the breakdown voltage with respect to pressure and gap length (at least in homogeneous electric field configuration, see section 0 for details). Different gases exhibit different breakdown voltages according to their different intrinsic electric strengths (i.e. at same gap distance and pressure) and obviously, those with high values are favored. Vacuum gaps show high breakdown voltages for small gaps, comparable to SF_6 at elevated pressures, but saturate at around 200kV and are usually applied only for gap lengths <1 cm and in medium voltage switchgear. Solid and liquid insulation systems in general show a high electric strength compared to gaseous insulation at ambient conditions, but of course, the quantitative value also depends on the insulation material itself. The insulation strength is

strongly reduced by contaminations, imperfections or humidity. Thus, qualitatively a sub-linear increase in breakdown voltage with increasing gap distance is observed, as an increasing volume inevitably contains a larger number of material inhomogeneities and imperfections.

Figure 3: Breakdown voltage of different insulation materials as a function of the insulating distance. Quantitative values are used for air and SF₆, but only qualitative trends are shown for the other (adapted from e.g. [5]).

Of the three technical purposes listed above (insulation, cooling and arc quenching), the focus of the present article is on the insulation capability. It is required in all apparatus and thus, it is the first characteristic that is investigated. If a gas (or gas mixture) should also be used as arc quenching medium, the large set of required properties listed above needs to be extended. In particular the fluorinated gas should have a low dissociation rate during arcing (as it will likely not recombine into its original form after arcing) and the dissociation products should have low toxicity (ideally none). For current interruption, the latest SF₆-free switchgear use either CO₂-based mixtures or vacuum.

The article is written with a wide audience in mind, not specialized in this particular field, but generally interested in electrical insulation and dielectric phenomena. We thus focus on the insulation characteristics in the fundamentals section, but for a more detailed assessment of the electric behavior of eco-friendly gases for electrical insulation we refer the reader to e.g. [6] or [75]. For a more detailed assessment of the interruption performance, e.g. [76] is recommended.

The present article is structured as follows: section 0 gives a general introduction into the fundamentals of gaseous insulation, sections 0 and 0 describe ways of identifying new alternative gases and how those are experimentally characterized. As shown in an overview

on the current status of SF₆-free technology in section 0, competitive solutions became increasingly available in the last decade. It is now a question of politics to support the change away from SF₆-technology and an overview on different legislation approaches is given in section 0. Section 0 concludes the article by highlighting a few future trends.

Fundamentals of gaseous insulation

A good insulation gas should prevent the undesirable electric discharges up to high electric field stress. Different regimes of electric discharges exist, such as electron avalanches, streamer and leader discharges and breakdown.

For an electron avalanche to occur two conditions must be fulfilled: the electric field must exceed the critical electric field strength of the gas, and at least one seed electron should be provided to initiate the discharge. Seed electrons may be provided by ionizing radiation, electron detachment from a negative ion or field emission, and their appearance cannot be avoided in general. Therefore, insulating gases are most often characterized by their electric strength, or critical electric field strength.

The motion of electrons in gases depends mainly on their collisions with neutral particles and on the applied electric field. Electrons are accelerated in the electric field and gain kinetic energy between collisions. During elastic collisions, electrons are scattered and lose only a very small fraction of their kinetic energy. In molecular gases, a large number of inelastic collision processes (such as rotational, vibrational and electronic excitations, and dissociation) enable a more substantial dissipation of the electron's kinetic energy. The collision frequencies associated with these processes are a strong function of the electron energy. Under steady-state conditions, an equilibrium electron energy distribution (constant in space and time) is established, and the electrons drift at constant velocity. The collision frequencies of binary collisions scale linearly with the gas pressure, whereas collision processes that involve also a third collision partner (three-body processes) have a more complex pressure-dependence.

The inelastic processes of impact ionization, electron attachment and electron detachment play a key role in electrical discharges, as they govern the evolution of the number of free electrons and ions. In an electron avalanche, the number of free electrons increases due to impact ionization of gas particles, and decreases due to electron attachment to gas particles. The number of free electrons varies exponentially with time [7]: $N_e(t) = N_e(t_0) \cdot \exp(\nu_{\text{eff}} \cdot (t - t_0))$, where ν_{eff} is the effective ionization rate, which is the difference between the ionization rate and the attachment rate. The critical electric field strength of a gas is the field strength at which the effective ionization rate is zero (at higher field strength, the effective ionization rate is positive).

An electron avalanche may grow into a streamer discharge. An empirical criterion to calculate the avalanche-to-streamer transition is that the integral of the effective ionization coefficient along the avalanche's path should exceed a certain constant K [8]: $\int \alpha_{\text{eff}} dx \geq K$. The effective ionization coefficient α_{eff} relates to the effective ionization rate ν_{eff} as $\alpha_{\text{eff}} = \nu_{\text{eff}}/W$, where W is the drift velocity of the electrons. The interpretation of this criterion is that if the electron avalanche grows sufficiently, the electric field of this charge distribution

becomes as high as the externally applied electric field, and enhances the discharge growth, leading to a streamer discharge.

If the electron density becomes sufficiently high, the insulating gas may transit into a conductive state, and an electric breakdown may occur. In homogeneous electric fields, the breakdown voltage coincides with the streamer inception voltage. However, in very inhomogeneous electric fields, the breakdown voltage may be much higher than the streamer inception voltage. There is, in general, no straightforward criterion for predicting the breakdown voltage in this case. For strongly electron attaching gases, a semi-empirical stepped leader model may be used [9], and empirical relations have been formulated for air [10].

The critical electric field strength divided by the particle number density $(E/N)_{\text{crit}}$ is constant for most gases. The consequence is that the breakdown voltage $U_{\text{bd}} = (E/N)_{\text{crit}} \cdot d \cdot N$ in homogeneous electric fields is a linear function of the gap distance d and particle number density N (and hence, pressure p). This linear dependency on $p \cdot d$ is called “Paschen’s law” and can also be seen in Figure 1 above. To be able to dimension electric equipment for practical insulation applications, the above-mentioned basic phenomena of electric discharges have to be understood in detail, and the most important properties of the gas have to be known quantitatively. However, even then, further complication originates from the manifold application scenarios that occur. The voltage stress on the insulation system can be continuous AC at nominal voltage or temporary AC overvoltage, it can be of shorter duration during lightning or switching impulses, or it can be DC (even in AC equipment, e.g. trapped charge voltage after disconnection). The above-mentioned role of provision of an initial electron can lead to substantial differences in measured breakdown voltage between these different voltage shapes. In general, longer voltage application leads to lower measured breakdown voltages. Naturally, the shape of the electrodes in the system (on high voltage and ground potential) varies greatly, and the resulting electric field distribution can be homogeneous (rarely possible), weakly inhomogeneous (targeted, e.g. coaxial cylindrical section) or strongly inhomogeneous (sometimes occurring, e.g. from particles and sharp protrusions). For gases with a high critical electric field strength and at elevated pressures, the surface roughness is also important to consider. Here, the above-mentioned integral of the effective ionization coefficient reaches the critical value K within a short distance on the scale of the roughness and the insulation strength is effectively much lower than the intrinsic electric strength of the gas. Besides all the above-mentioned complications, the interfaces between solid and gaseous insulation also need special consideration as these are particularly weak under tangential field stress and may accumulate charge carriers under normal electric field stress which, in turn, may change the electric field distribution on the electrode surfaces and/or in the gas gap. The charge accumulation or contamination with dissociation products on the surface of solid insulators may lead to a flashover, which is another important failure mechanism that needs to be considered. Identifying potential alternative insulating gases

Screening single gases

To identify new insulating gases, it is an option to screen large molecular databases. The ab initio calculation of phenomenological properties (such as electric strength, vapor pressure, GWP, ODP, toxicity, flammability, etc.) from the molecular structure is currently not

feasible. For this reason, semi-empirical screening methods are used to select the most interesting molecules for further investigation. These methods identify the functional relationship between descriptor variables and gas properties of interest. The descriptor variables are molecular properties, which can be computed by means of quantum-chemical methods. The most common descriptors are: ionization energy, electron affinity, polarizability, dipole moment, molecular mass and volume, electron number, area of molecule surface, molecule surface potential.

In the 1980s, systematic searches were performed to find an insulation gas superior to SF₆. A literature survey on approximately 400 gases and experimental data on roughly 50 gases were published in the EPRI-report EL-2620 [11]. J. C. Devins [12] investigated systematically the influence of the molecular structure, A. K. Vijh [13], [14] observed a correlation between electric strength and molecular size, and K. P. Brand [15] computed the polarizability and the ionization potential as descriptors.

The development of screening methods resumed after the turn of the millennium due to the necessity of GWP reduction. Functional relationships for the electric strength were suggested by N. Meurice et al. (2004) [16], A. Olivet et al. (2007) [17], J. Jiao et al. (2016) [18], L. Liang et al. (2019) [19], and Fan et al. (2019) [20]. This kind of screening is not specific to gaseous electrical insulation but common to other fields, e.g. research for new refrigerant gases. However, in the case of electrical insulation, the efficiency of screening methods is somewhat limited by the small number of molecules for which sufficient data is available (less than a hundred).

M. Rabie et al. (2013) [21]; [22]; [23], C. Zhang et al. (2016) [24], and X. Yu et al. (2017) [25] not only identified relationships for the electric strength and the boiling point, but also used these relationships to predict the electric strength and the boiling point of new molecules.

As of today, computational screening methods have only been reported for the electric strength and the boiling point, to some extent also for GWP and ODP. Other important parameters such as toxicity or material compatibility can only be determined experimentally (methods how to do this have been recently reported in [77]).

Gas mixtures

So far, none of the above-mentioned screening methods identified a pure gas, with a combination of electric strength, boiling point, GWP, (non-)toxicity and (non-)flammability, that is overall superior to SF₆. However, gases with superior electric strength but higher boiling point can be found. These gases could be mixed with a more volatile gas, such as N₂, O₂ or CO₂ to obtain a gas mixture with electric strength and boiling point similar to those of SF₆.

The electric strength of a gas mixture cannot be predicted solely from the electric strength of its components because it depends on the electron-molecule interactions in the gas mixture. A gas mixture is said to have a *synergy effect* when its electric strength is larger than the sum of the electric strengths of its components weighted by their mole fractions in the mixture [26]. This effect is obviously beneficial for the use of gas mixtures as electrical insulators. Furthermore, the electric strength of a gas mixture may even exceed the electric

strength of all its components, in which case, the gas mixture is said to have a *positive synergy effect* [27]. Synergy and positive synergy effects are illustrated in Figure 4, with the examples of SF_6/N_2 and $\text{SF}_6/\text{HFO1234ze}$ gas mixtures, respectively.

To the authors' knowledge, there is currently no available computational method to predict the electric strength of gas mixtures. Therefore, the investigation of synergy effects of high electric strength gases with buffer gases such as N_2 , O_2 or CO_2 must be carried out experimentally.

Figure 4: Electric strength of SF_6 mixtures with N_2 and with HFO1234ze. The electric strength is indicated relative to the electric strength of pure SF_6 : 355 Td. The data of SF_6/N_2 mixtures is calculated with Bolsig+ [28] using cross section data from Magboltz [29]. The data for $\text{SF}_6/\text{HFO1234ze}$ mixtures has been measured in a swarm experiment [30].

Experimental characterization of gases

Extensive series of tests must be carried out to measure the properties of prospective SF_6 alternatives. The properties of interest include the electric strength, the thermodynamic properties, the toxicity, the safety aspects and the environmental impact. Additionally, practical aspects must also be considered, such as the material compatibility of the new gas with other parts of the equipment and its chemical stability. The gas dissociation under partial discharges or arcing should also be studied. If substantial dissociation of the gas occurs, the gas composition is effectively changed. Therefore, the properties of the dissociation products should also be considered, in particular, the change in toxicity and electric strength. Each of the above-mentioned tests is time and resources consuming.

Characterization of the electric strength

To give an example of the complexity of the above-mentioned tests, the characterization of the electric strength of a gas or gas mixture is described here in more detail.

The ionization and attachment rate coefficients of a gas, and *à fortiori* its electric strength, can be measured using swarm experiments, such as pulsed Townsend experiments [31], time-of-flight experiments [32] or steady-state Townsend experiments [33]. The advantage of this approach is that the effective ionization coefficient is an important information for designing new equipment. The disadvantages of this approach are the complexity of the experimental setups and their rarity (they do not belong to the standard high voltage laboratory equipment). Moreover, if these setups are operated at too low gas pressures, some physical processes which are significant at operational pressures might go undetected.

An alternative approach is to measure the voltage at which an electric breakdown occurs, with uniform or slightly non-uniform electric field arrangements. The gases can then be compared with respect to their respective breakdown voltage. This approach is often preferred because of the availability of the equipment. However, its apparent simplicity can be deceiving. Several parameters such as the gas humidity, the surface roughness of the electrodes and the availability of seed electrons can significantly affect the results if they are not carefully controlled.

For both methods of experimental characterization, obtaining the electric strength of gas mixtures with different mixing ratios is useful to identify the optimal mixture composition, and to guide the design of new equipment. However, final tests in real equipment are still required to obtain the breakdown voltage in these complex conditions and geometry.

Tests in applications

The most promising gases or gas mixtures identified with experimental tests should also be tested under real operational conditions: using high pressure, various electrode shapes representing different field configurations in gas insulated switchgear, and various voltage waveforms representing different possible in-service fault scenarios. Heat dissipation tests are also required to verify the cooling performance of the new gas. Depending on the application, it might be possible to retrofit existing SF₆ equipment, or it might be necessary to design new equipment, *e.g.* to adapt to a different material compatibility or to a degraded insulation or cooling performance of the new gas mixture.

Current status of SF₆-free technologies

This section aims to give an overview on the current status of commercially available SF₆-free equipment for electric power transmission and distribution. A very good and detailed summary was already delivered in 2018 in [34], and only an updated overview is given here. The main use of SF₆ in electric power equipment is for gas insulated switchgear and thus, it is the focus here. Gas insulated lines, instrument transformers and bushings are also insulated with SF₆ or SF₆ gas mixtures but, in these applications, the arc quenching

capability is not required and it is most likely that SF₆-free technologies can be developed if gas insulated switchgear can be made SF₆ free.

Medium Voltage

A coarse distinction of medium voltage switchgear is in primary and secondary switchgear. Primary switchgear is installed at the interface between high and medium voltage networks and is predominantly equipped with circuit breakers (CB, interrupting fault currents). Secondary switchgear is installed at the interface between medium and low voltage networks and is generally equipped with load-break switches (LBS, interrupting nominal load currents) rather than circuit breakers. Classically, air insulated switchgear (AIS) and gas insulated switchgear (GIS) exist in medium voltage networks, the latter being more compact and independent of outside conditions (sealed from ambient air). Where space permits, AIS with vacuum circuit breakers (VCB) can be selected.

Alternatives to GIS in medium voltage distribution can be found not only with alternative gases, but also with solid (e.g. [35], [36]) and liquid insulation (e.g. [37]) and VCB. Some of these products have been on the market for more than a decade. With respect to alternative gases, technical air at elevated pressures up to 1.4 bar (up to 12 kV)[38] and air with C5-PFK at 1.4 bar (up to 36 kV)[39] are available as products with vacuum interrupters as primary equipment. In secondary switchgear, the LBS function is implemented today as a simple contact system embedded in SF₆ and can interrupt typically rated nominal currents of 630 A. This is, so far, not possible with non-SF₆ gases without special assistance, but can be solved technically with vacuum interruption technology as well. For some market segments of medium voltage primary and secondary switchgear, SF₆-free solutions have been developed and are available as products. Even though it is technically more difficult to extend certain solutions to higher rated voltage or current levels (e.g. challenge of thermal cooling for solid insulation), there is no technical reason why it should not be possible to develop SF₆-free solutions for all applications. Of course, it is an economic challenge to offer new products in smaller market segments, but it cannot be held as a solid argument against replacing SF₆ in MV equipment. Users should be flexible in substation layout and compare the benefits of purchasing SF₆-free equipment with the benefits of only accepting traditional layout and configurations. Regulations can support the transition with respect to economic arguments, as decade-old technology is most likely cheaper.

High Voltage

AIS in high voltage is (almost) exclusively used in outdoor applications due to extreme differences in size requirements. "CO₂ based" alternative Live-Tank breakers are available on the market up to 145 kV and 40 kA [40]. Using non-gaseous insulation and switching media is much more challenging in high voltage than in medium voltage switchgear. VCB technology is on the market up to 145 kV [41], and an announcement was made at the Cigre Session 2018 for a vacuum interrupter for 245kV and 63kA. Solid insulated high-voltage cables exist, but extrusion processes cannot be used for high voltage switchgear design. Paper-oil insulation is used for HV cables, power and instrument transformers, but is very unlikely to be used for HV switchgear. Thus, only gas insulated design is considered for insulation, and gas and vacuum technology for switching. The main market segment for HV GIS is the voltage level up to 145/170 kV, which is the first one addressed by main manufacturers. Several technical solutions are commercially available: compressed air with

VCB [42], air in combination with C5-PFK [43], and CO₂/O₂ in combination with C4-PFN [44]. For all these solutions, first installations exist, but development continues. An announcement was made to develop C4-PFN based solutions up to 420kV until 2022 [44], [45]. The refurbishment of a 380 kV SF₆ substation with C5-PFK based solutions was announced in two steps [46], and the substation is planned to be made completely SF₆-free by 2026. No technical reason is known why it should in principle be impossible to develop SF₆-free solutions for all high-voltage levels. The development is much more difficult than for medium voltage switchgear, but also here dependable regulations can economically support and speed up the transition to SF₆-free substations. From the users' perspective, a rethinking is required that not one single best solution is favored by all manufacturers (unlike SF₆) and, depending on the weight of different selection criteria (size, minimum ambient temperature, global warming potential, F-gas free, ease of gas handling,), different technical solutions will be preferred, or even be operated in parallel.

Current legislation and regulation on SF₆ for electric power equipment

In the Kyoto protocol [47], SF₆ was explicitly classified as one of six gases (Annex I) for which actions need to be taken to reduce its emissions. Since then, legal and regulatory measures have been taken in numerous countries. For many industrial applications, the use of SF₆ was avoidable and alternative solutions were already available, e.g. magnesium die-casting, filling for soundproof glass windows, vehicle tires and sports shoes. For these applications, SF₆ was banned or phased out in most countries. For the electric power industry, which is considered to be the largest emitter of SF₆ [48], alternatives did not exist for all applications and the regulatory focus was to reduce SF₆ emissions rather than banning its use. This picture has changed in recent years: SF₆-free alternatives have become available for an increasing number of applications (see section 4), and governments are intensifying the pressure on industry to refrain from using SF₆, or even phase out SF₆ completely. In the present article, the current status of regulations for many countries around the world is given. This overview cannot be complete and, due to the present rapid development, is only a snapshot in time. The overview is an extended update based on [6], [34], [49] (and references therein) and is structured in five items: i) regulations controlling the handling, containment and recovery of SF₆, ii) voluntary agreements between industry and governments or self-commitments to reduce SF₆ emissions, iii) taxes, iv) phase-out plans and v) bans.

Regulations controlling the handling, containment and recovery of SF₆

EU F-gas regulation

The present legally binding regulation on fluorinated gases for all member states of the European Union is No 517/2014 [50]. It makes statements about the gas containment (prevent emissions, detect leaks), user training, book-keeping of inventories and emission and recovery after use. Bans on the use of SF₆ for electric power equipment is currently only contemplated for specific applications and it is explicitly stated [51] that, by "1 July 2020, the Commission shall publish a report assessing 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 ...". To prepare this report of the Commission, the German Federal Ministry for Environment, Nature Conservation, Building and Nuclear Safety commissioned a study on the transmission and distribution of electrical energy without the use of SF₆ [34]. Based on this, as well as further written statements of industry associations (e.g. [4], [52]), the Federal Environment Agency is of the opinion that "there are adequate alternatives for SF₆ in new medium-voltage switchgear (≤ 24 kV), and it announced to advocate a ban on SF₆ in new medium-voltage secondary switchgear for these voltage levels with an appropriate transition period as part of the review of Annex III of the EU Regulation 517/2014". At the European level, the F-Gas Consultation Forum of the European Commission [53] is consolidating input from all member states and will give recommendations. It is likely that the new F-gas regulation will issue binding roadmaps to phase-out SF₆ for medium voltage applications, maybe even giving an outlook for its application at higher voltages.

China

In China, the country with the strongest growing electric network in the world and thus probably also the largest emitter of SF₆ [54], the use of SF₆ for electric power equipment is not restricted, but clear regulations from e.g. the State Grid Corporation of China (SGCC) are in place with respect to the supervision and management of SF₆ in electrical equipment [55].

Voluntary activities

Even though the F-gas regulation applies to all EU member states, the specific national implementations and goals for emission reduction vary greatly. Many countries have negotiated voluntary agreements with specific measures and envisaged reductions. In Germany, the latest voluntary agreement was negotiated in 2000 and signed in 2005 [56]. The goal to reduce the amount of SF₆ and to reduce its emission - whenever possible - was expressed, setting specific goals with respect to total emissions and emission rates. After a peak in 1998, the SF₆ emissions from electric power equipment dropped by almost 75% until today and the goals agreed in the voluntary agreement have been reached. A similar agreement was signed in France in 2004, but it expired in 2012. The emissions increased by 25% from 1990-1998, reduced by almost 80% until 2014 (compared to 1990) and remained constant since then [57].

Other European (non-EU) countries have also signed voluntary agreements. In Switzerland, a specific target for total SF₆ emissions in 2020 has been agreed upon [58]. After an increase of 50% in the period from 1998 to 2008, the emission from high- and medium-voltage equipment decreased by approx. 75% until 2018. In Norway, an agreement was in place from 2002-2010 with the aim to reduce emissions by 50% until 2010 compared to 2000 [59]. The agreement was not prolonged afterwards, but the related user group continues to operate with the aim to increase user awareness and training as well as reporting of use and emissions [60]. Absolute emissions in 2018 were on the same level as 2003 (though with a larger installed base) and in the peak year 2008 emissions were even up by a factor 2.6 [61].

In 1999, the SF₆ Emission Reduction Partnership for Electric Power Systems was started in the USA with the goal to identify, recommend, and implement cost-effective solutions to

reduce SF₆ emissions [62]. The average emission rates decreased from 14.2% in 1999 to 1.9% in 2013. Even more importantly, the total emissions decreased from 835 t to 259 t in the same period.

All this demonstrates that voluntary agreements can have a (very) positive effect, but only down to a certain level of emission. Further reductions or even complete elimination of emissions have not happened and are very unlikely to happen without further regulatory initiatives.

A few companies around the world have, thus, started to implement self-imposed emission reductions: The Korea Electric Power Corporation (KEPCO) started a systematic SF₆ recycling program in 2011 [63] and reduced most of its SF₆ emissions. However, as the majority of CO₂-equivalent greenhouse gas emissions in its transmission and distribution sector are still attributed to SF₆ emissions, KEPCO has started a development roadmap and introduction plan for a 170 kV SF₆ free GIS [64]. In the USA, PG&E is taking a very active approach in phasing in SF₆-free products [65], their medium voltage equipment has been completely SF₆-free for 15 years and purchasing SF₆-free equipment for higher voltage levels has been systematically evaluated and actively preferred [74]. Vattenfall also has a sustainability policy in their distribution business, and states “the ambition to adopt new insulation technologies for high voltage breakers to avoid the use of the greenhouse gas SF₆” [66].

Taxes

Some countries have started to tax the import and use of SF₆. In 2013, Spain enacted a law [67] that the first time fluorinated compounds with GWP >150 are put onto the market or into use, they are taxed based on a rate proportional to their GWP (15 Euro/t CO₂ equiv). A cap of 100 Euro/kg is given, i.e. at GWP of 6666, which obviously applies for SF₆. A transition period of 3 years was given, and the above-mentioned full rate was introduced linearly, becoming fully effective in 2017. With respect to total SF₆ emissions, a steep increase of almost a factor of 4 was reported between 1990 and 2008 and remained constant thereafter. It remains to be seen if the imposed tax leads to a decrease of SF₆ emissions in the future. Denmark issued environmental taxes in 2006 [68] for importing strong greenhouse gases, including SF₆. The tax level is in relation to the GWP with an upper cap of 400 DKK/kg (approx. 55 Euro/kg). The reported emissions in Denmark remained low between 2001 and 2010, sharply increased (more than quadrupled) between 2010 and 2014, and have been decreasing since then. The level in 2017 was still twice as high as in 2010. The effect of the tax cannot be related to this development.

Phase-Out Plans

One of the most extensive plans for specific phase-out is proposed by the California Air Resources Board (CARB). In August 2019, a discussion draft of “Potential Changes to the Regulation for Reducing Sulfur Hexafluoride Emissions from Gas Insulated Switchgear” [69] was published. It is proposed to prohibit to manufacture, purchase, import, transfer, sell, lease, or offer for sale or lease SF₆ gas insulated equipment for use in California or to convert non-SF₆ equipment to SF₆ equipment. The phase-out dates are differentiated by voltage level: ≤145 kV by 2025, 145 kV...245 kV by 2029 and > 245 kV by

2031. The dates are anticipations of the ongoing developments, but a technical infeasibility exemption is stated in case the commercial availability is not given by these dates.

Bans

To the authors' knowledge, SF₆ is currently not banned for use in medium and high voltage equipment in any country.

Future trends

The evolution of SF₆ gas insulated equipment since its first installation in the 1960s has been quite remarkable, and the latest generation of GIS is built much more compact, and thus requires much less SF₆ than the first generation of GIS. In addition, leakage rates have been dramatically reduced; during operation, but also during manufacturing, testing and commissioning. The first generation of SF₆-free equipment is far more advanced than the first generation of SF₆ equipment, but it can still be expected that the development advances and also this new equipment evolves, possibly also becoming more compact and most likely becoming more cost-efficient. In addition, when the market for SF₆-free products is growing, manufacturers will also develop equipment for a broader range of applications and for all voltage ratings. This includes gas insulated technology, but also others such as vacuum interrupters for higher voltages.

One noticeable difference is that, in contrast to previous years, where all manufacturers based their high-voltage insulation and interruption equipment on SF₆, the offered portfolio today is based on different concepts, different gas mixtures, but also fluid and solid insulation. Users will have to get used to the fact that many non-SF₆ technologies coexist. As mentioned above, the different solutions present different optimizations in the space of requirements, and the users have to make their choice with respect to size, environmental footprint, availability, ease of handling, cost, ... From a technological point of view, there is no single best solution today.

Besides the obvious trends of improving existing new products and extending the offered product range and covering all voltage levels, research for further non-SF₆ technologies continues and might one day also broaden the spectrum of used technologies. One of these future trends could emerge from the above described screening methods. If interesting candidate gases are identified, ideally backed up with measurements on structurally similar compounds [70], research on their synthetization and mass-producibility should follow. An often-heard argument against this pathway is that gases for which the electric power industry is the only user cannot be manufactured cost-effectively. Regardless if this is correct or not, research combining existing compounds in a favorable way to create synergistic effects, in particular, the above-mentioned positive synergy of the electric strength [30], is an important research track that should be followed.

To eliminate the emission of SF₆ completely, suitable alternatives need to be found also for the other applications that still use SF₆. SF₆-free alternatives are intensively researched and developed for example for airborne military radar systems [71], resistive plate chamber detectors [72], or industrial accelerators [73]. The experience and know-how of the development of SF₆-free GIS is transferred and applied also in these areas. The use of SF₆ in

many applications has been banned already, but due to the uncontrolled removal of soundproofing windows after their end of life, emissions from these applications are expected to continue for another 10-15 years, at times even dominating the emissions in some countries.

Overall, avoiding the use of SF₆ completely is the only way to further reduce its emissions in the long run and seems technically possible for the electric power industry from today's point-of-view. Governments should support and accelerate this transition by giving ambitious and dependable targets and incentives until all newly sold equipment is SF₆-free and old SF₆-equipment is removed from the field.

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Christian M. Franck (cfranck@ethz.ch) (SM'11) received the Diploma degree in physics from the University of Kiel, Germany, in 1999, and the Ph.D. degree in physics from the University of Greifswald, Germany, in 2003. From 2003 to 2009, he was with the ABB Swiss Corporate Research Center, Baden Dättwil, Switzerland, as a Scientist and a Group Leader for gas circuit breakers and high-voltage systems. He is currently a Full Professor of high-voltage technology with ETH Zürich, Switzerland. His current main research interests include gaseous and solid insulation systems and switching arcs.

Alise Chachereau (alisech@ethz.ch) followed preparatory classes to the French Grandes Ecoles at Lycée Descartes in Tours, France. She received her general engineering degree from the Ecole Centrale de Lyon in 2013, and her Ph.D. degree from the High Voltage Laboratory of ETH Zurich, Switzerland, in 2018. She now works at the High Voltage Laboratory as a postdoctoral researcher.

Juriy Pachin (jpachin@ethz.ch) received the M.Sc. degree in electrical engineering and information technology from Technical University of Munich, Germany, in 2015. In 2016 he joined the High Voltage Laboratory, ETH Zurich, Switzerland, currently investigating discharge mechanisms in environmental friendly insulation gas mixtures.