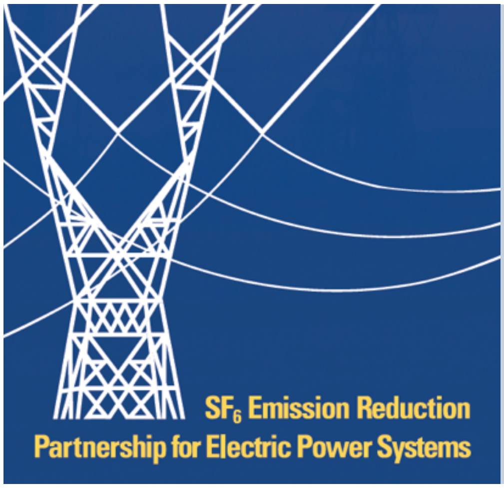

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Moving Toward SF_6-Free High Voltage Circuit Breakers:

Considerations for Adopting Vacuum Breaker and Fluorinated Gas Alternative Technologies

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https://www.epa.gov/f-gas-partnership-programs/electric-power-systems-partnership

Introduction

Over the last two decades, the SF_6 Emission Reduction Partnership for Electric Power Systems has offered utilities a platform to work together to reduce emissions of sulfur hexafluoride (SF_6), a very potent greenhouse gas. These efforts included adoption and dissemination of best management practices and, more recently, exploration of alternatives to SF_6. Although the industry has had success with non-SF_6 alternatives in low and medium voltage (up to 72.5 kV) equipment, alternatives for high voltage equipment have proven to be more challenging.[1]

New high voltage non-SF_6 gas insulated alternatives have recently become more promising, with early adoption both in the United States and abroad. Utilities may consider new options as they strive to meet their own voluntary commitments, respond to state or local requirements,[2] or manage their longer term plans for decommissioning first-generation SF_6 breakers or older oil-filled breakers. This document summarizes information about key alternatives for high voltage equipment, including recent developments and potential considerations for adopting SF_6-free insulated equipment. This work represents EPA's joint efforts with the industry to identify options for effective SF_6 emission reductions.

Objective

The focus of this overview is on two promising options to replace high voltage SF_6 equipment: (1) alternative vacuum circuit breaker technologies and (2) alternative fluorinated gas mixtures. This document does not cover all alternatives or manufacturers offering alternatives to SF_6 high voltage equipment, nor does it serve as an exhaustive list of current and future industry developments due to the dynamic nature of this topic. Mention of specific companies or products does not constitute endorsement by EPA.

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[1] In the United States, electric power systems are nationally classified according to the following voltage classes, per ANSI C84.1-2016:

- Low Voltage: 1,000 volts or less
- Medium Voltage: greater than 1,000 volts and less than 100 kV
- High Voltage: greater than 100 kV and equal to or less than 230 kV
- Extra-High Voltage: greater than 230 kV but less than 1,000 kV
- Ultra-High Voltage: equal to or greater than 1,000 kV

(Some states have different approaches to classifying electric power systems.)

[2] For example, the California Air Resources Board and Massachusetts Department of Environmental Protection have set mandatory emission rate maximums, reporting procedures, SF_6 gas recovery and recycling requirements, and, most recently, proposals in the State of California to phase out SF_6. At the local level, cities such as Seattle have reporting requirements that may incentivize utilities to reduce SF_6 consumption.

Properties of Alternative Mediums Used in SF_6-Free Technologies

To meet the operational needs of a circuit breaker, an alternative medium must fulfill dielectric requirements and arc interruption strength, perform at ambient and low temperatures, and perform at high voltages and high short-circuit currents. To reduce environmental impacts, alternative mediums or gases must have long-term stability (e.g., no chemical decomposition), minimal health impacts, and lower global warming potential (GWP). To achieve these effects in circuit breakers, original equipment manufacturers (OEMs) have used both dry air/vacuum and CO_2 and O_2 based mixtures with fluorinated Novec™ gases manufactured by 3M, some of which include a small amount of a fluoroketone or fluoronitrile gas to bolster the dielectric and interruption properties (Table 1).[3]

Table 1. SF_6 and Available Alternative Gases/Mediums

CHARACTERISTICS	SF_6	DRY AIR	CF_4–FLUORONITRILE	CF_5–FLUOROKETONE
Chemical formula	SF_6	N_2 and O_2	$(CF_3)_2CFCN$	$(CF_3)_2CFC(O)CF_3$
100-Year GWP (CO_2e) of Gas	22,800[a]	0	2,100	< 1
Typical Mixture Composition	100% SF_6	70–80% N_2, 20–30% O_2	3–5% $(CF_3)_2CFCN$, 95–97% CO_2 and O_2	10% $(CF_3)_2CFC(O)CF_3$, 90% mixture of O_2 and N_2, or CO_2
100-Year GWP (CO_2e) of Mixture	22,800[a]	0	< 500	< 1
Dielectric Strength of Mixture (with respect to SF_6)	1	0.43–0.77	0.87–0.92	0.7
Carrier Gases	N_2[b]	N_2 and O_2	CO_2	O_2 and N_2, or CO_2
Condensation Point of Mixture (°C)	–30[c]	–50	–30[c]	–5[d]
Arc Impact – Decomposition Products	HF, SO_2, sulfur compounds	O_3	CO, CO_2, HF, other F-gases	CO, CO_2, HF, other F-gases

Sources:

3M Novec™ 4710 Insulating Gas Health & Safety Bulletin, February 2020. Available online at: https://multimedia.3m.com/mws/media/1132124O/3m-novec-4710-insulating-gas.pdf

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Rak, T. January 2019. Protecting Our Environment with Clean Air Technology: PG&E Phases Out SF_6 Greenhouse Gas. *T&D World*.

[a] Countries that are parties to the United Nations Framework Convention on Climate Change (UNFCCC) have agreed to use consistent GWP values from the IPCC Fourth Assessment Report (AR4), based on a 100-year time horizon, although other GWP values and time horizon values are available. Therefore, EPA presents the AR4 value of SF_6 in this table.

[b] SF_6 can also be mixed with CF_4 to avoid condensation at low temperatures.

[c] Typical for high voltage but as low as -50°C for some products.

[d] Typical for high voltage but as low as -20°C for some products.

[3] 3M Novec™ Brand. July 2018. Demonstrated Uses of 3M Novec™ Insulating Gases as Alternatives to SF_6 in the Power Sector. Technical Bulletin.

SF_6-Free Technologies Under Consideration

While non-SF_6 equipment has long been available for low to medium voltage applications, alternatives for high voltage equipment are at the early stages of entering the market, including vacuum technology and other fluorinated gases with lower GWPs compared to SF_6. Below is an overview of two major technologies under consideration: vacuum circuit breakers (VCB) and fluorinated alternative gas breakers.[4]

Vacuum Circuit Breakers

Vacuum interrupter technology has been demonstrated to be highly reliable and is commercially available in medium voltage breakers. These circuit breakers use vacuum interrupters for switching functions and dry air, a mixture of N_2 and O_2, for the insulation medium. Currently, 72.5 kV VCBs are available from many providers, including Siemens, Hitachi, Mitsubishi Electric Power Products Inc. (MEPPI), Meiden America, and Shenyang Huade High Technology. The technology for 145 kV breakers has been under development for years; Siemens and Hitachi have commercially introduced this technology at this voltage rating, while MEPPI is expected to have this product available in the next few years. OEMs have indicated that scaling this technology to 245 kV voltage class and higher is difficult. Although all aspects of the interior and interrupter differ from the SF_6-free breaker, VCBs have similar bushings, current transformers, and control cabinets with relays. Also, VCBs generally require the same footprint at the 72.5 kV and 145 kV ratings and, therefore, a VCB can be a direct replacement of an SF_6 breaker (i.e., no retrofitting).

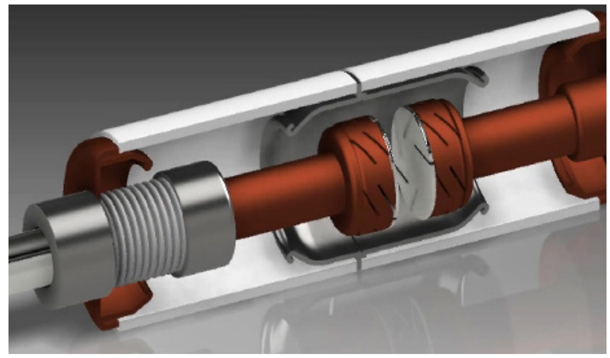

Figure 1. Cutaway of an Interrupter Utilized in Vacuum Circuit Breaker Technology

Source: Courtesy of Hitachi. Used with permission.

Fluorinated Alternative Gas Breakers

Some alternative CO_2 and O_2 gas mixtures have a small amount of a fluoroketone or fluoronitrile gas to bolster the dielectric and current switching properties and deliver the same performance as traditional SF_6 gas (Table 1), including at high voltages. ABB has made available live tank 72 kV breakers that use AirPlus™, which consists of fluoroketone, carbon dioxide, and oxygen. Additionally, GE offers 145 kV GIS, 145 kV live tank circuit breakers, 420 kV gas insulated lines, 245 kV current transformers, and a 123 kV combined metering unit using its Green Gas for Grid (g^3, pronounced "g cubed") technology, which relies on a gas mixture of fluoronitrile, carbon dioxide, and oxygen. OEMs have indicated that scaling this technology for dead tank circuit breakers to higher voltage classes up to 550 kV is possible.[5,6] High voltage alternative gas breakers have had numerous successful installations in Europe and Asia. Fluorinated alternative breakers are a direct replacement of an SF_6 breaker (i.e., no retrofitting).

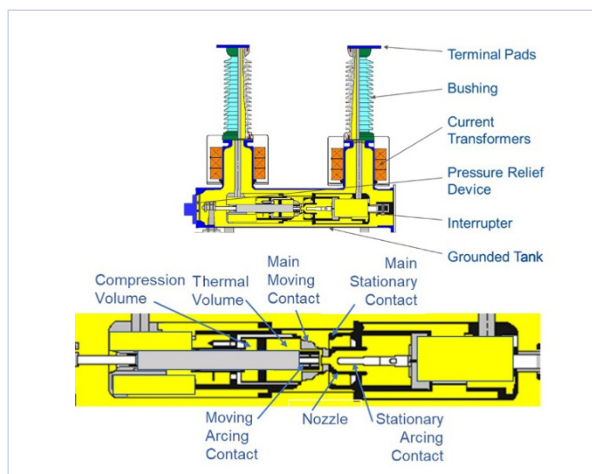

Figure 2. Schematic Diagram of Fluorinated Alternative Gas Circuit Breaker Technology

Source: Courtesy of GE Grid Solutions. Used with permission.

[4] The Partnership continues to monitor developments in other SF_6-free technologies that exist in the market.

[5] GE Grid Solutions. 2018. g^3 Technology – SF_6 Alternative for High Voltage Applications [brochure].

[6] GE Grid Solutions. 2019. g^3 Roadmap 2025 [brochure]. Available online at: https://www.gegridsolutions.com/products/reference/g3_roadmap_2025-Brochure-EN-2019-10-Grid-GS-1668.pdf

Considerations for Technology Adoption

As with any new acquisition or equipment upgrade, utilities will require capital and time investments, planning steps, and education, as well as a host of considerations to support their adoption.

Capital Costs

As alternative breakers begin to enter the market, utilities can expect that capital costs will be higher than for currently used SF_6 breakers. Several OEMs note that costs for alternative breakers can range from 10% to 50%, or more than that of a comparative SF_6 breaker. However, as volume commitments from utilities increase, utilities may see improved costs over time, as well as reduced time to market for new products.

Utilities can also expect to incur costs associated with the set-up of the new breaker. For example, ABB identified the possibility that a fluorinated alternative gas breaker may need additional tank heaters near it to prevent condensation, because the condensation temperature point for the fluorinated gases is higher than that of SF_6 (Table 1). The breaker may require additional castings and adjustments to the bushings. Normal pressures will likely be higher than required by SF_6 equipment. Additional measures for labelling may also be required if SF_6 and SF_6-free breakers are located in the same substation. Some OEMs use fill valves with different threads to avoid gas-filling mistakes. The warranty of alternative breakers is appreciably the same as SF_6 breakers, as stated by several OEMs.

Operational and Maintenance Costs

Regardless of technology, some level of maintenance applies to all equipment. As with any newer technology, operational and maintenance (O&M) costs may be higher in the beginning stages of implementation. New technologies require employee trainings on maintenance procedures and sensitivities of the equipment.

In the case of the alternative gas breakers, the core technologies are largely the same, and overall, gas handling and equipment maintenance practices are no different than those that technicians already utilize with SF_6 equipment. In addition, gas suppliers can provide alternative gas that is already mixed, so that no on-site mixing is needed. Some utilities have mentioned concerns with the homogeneity of the gas mixtures due to liquefaction of certain components at lower temperatures.[7] Manufacturers, such as GE, have ongoing testing programs to alleviate such concerns.

[7] Becker, G. 2019. Alternative Insulating Fluids to SF_6 Gas: Status and Strategy Considerations [presentation]. DILO 4th Annual SF_6 Gas Management Seminar. Available online at: https://us.dilo.com/fileadmin/dilo_us/8._Trainings_and_Seminars/2019_Seminar_Presentations/Becker-_Alt_Gas_Mixtures_Status_and_Strategy_Considerations_.pdf

Considerations for Vacuum Circuit Breakers

With a higher breaker interruption capability than SF_6, **VCBs** are inherently a more expensive technology, according to Hitachi. At the same time, VCBs do not require gas carts, because the dry air contained in the equipment is readily available with a GWP of zero relative to CO_2. Total cost of ownership is expected to create overall savings for the lifetime of the VCB.

Considerations for Fluorinated Alternative Gas Breakers

Adoption of **fluorinated alternative gas breakers** will require purchasing gas carts and gas analyzers that can work with the new gas. However, from an operational standpoint, these devices function similarly to those for SF_6 gas and should not pose a significant additional training burden. During equipment operation, leak tests and leak detection may be performed on similar equipment as used for SF_6 after recalibration. Total cost of ownership for fluorinated alternative gas breakers is expected to be approximately the same as that of SF_6 breakers, according to GE.

Life Cycle Assessment

Utilities can use a **Life Cycle Assessment** (LCA) methodology to consider the total cost of ownership, as well as the total environmental cost of various SF_6-free technologies. Rather than evaluating only the initial cost, this methodology considers costs and environmental impacts of production, installation, operation, maintenance, and end of life.

VCBs require significantly fewer inspections than SF_6 breakers. Without a fluorinated insulating gas, many maintenance costs are eliminated, such as the expenses associated with HAZMAT removal and personal protective equipment. For example, Southern Company and Pacific Gas and Electric (PG&E) found O&M costs associated with VCBs to decrease over time because gas handling with dry air is less intensive than with SF_6. Furthermore, Siemens estimates that the new vacuum technology can offer a lifetime of five times that of an SF_6 interrupter. For these reasons, these companies are finding it is cost-effective to replace their current SF_6 breakers with VCBs.

Nonetheless, training costs are an important consideration, particularly if multiple types of breakers (e.g., oil, SF_6, and alternative breakers) must be maintained. Having multiple technologies could be common in the early stages of adopting alternatives to SF_6 gas. Technicians must be able to differentiate between an SF_6 breaker, vacuum breaker, or fluorinated alternative gas breaker and maintain them accordingly.

Footprint

Most power system sites have finite space available for equipment and operations; therefore, the dimensions of the alternative equipment must be considered for the site. For fluorinated alternative gas breakers and VCBs, the footprint of the equipment is generally equivalent to SF_6 equipment at 72 kV and 145 kV. At higher voltages, however, the size of VCBs is expected to surpass that of the SF_6 equipment. Southern Company and PG&E explain that in their experience with 72 kV vacuum breakers, no significant energy or infrastructural changes were necessary.

Table 2. SF_6-Free Available Equipment

CHARACTERISTICS	VACUUM	G³	AIRPLUS™
Currently available products	- DTCB 72 kV, 40 kA - DTCB 145 kV, 40 kA - LTCB 72 kV, 40 kA - LTCB 145 kV, 40 kA - GIS 72 kV, 25 kA - GIS 145 kV, 40 kA - GIS 145 kV, 50 kA	- GIS 72.5 kV, 31.5 kA - GIS 145 kV, 40 k - LTCB 145 kV, 40 kA	- LTCB 72 kV, 31.5 kA - LTCB 145 kV, 40 kA
Size (DTCB) compared to SF_6 breaker at 72 kV and 145 kV	same	same	same
Size (DTCB) compared to SF_6 breaker > 145 kV	larger	same	same

GIS: gas insulated substation; DTCB: dead tank circuit breaker; LTCB: live tank circuit breaker; kV: kilovolts; kA: kiloamperes

Standards for Alternatives

Standards provide industry confidence in product performance and safety, which can be useful for equipment warranties in case of malfunction. Current industry standards, set by the Institute of Electrical and Electronics Engineers (IEEE), specify requirements for the performance of SF_6 breakers and VCBs. Standards for the fluorinated alternative gas breakers are in development under IEEE. International Council on Large Electric Systems (CIGRE) and IEEE working groups specific to this topic are already established or scheduled to take place in the next few years. Meanwhile, some utilities have requested ratings to be specified in the standards for SF_6 breakers to ensure the same performance of equipment from the OEM. OEMs that manufacture the fluorinated alternative gas breakers, including GE and ABB, have been conducting their research and development to achieve similar performance to that of the SF_6 breakers.

On-the-Grid Piloting

Utilities will need to develop a strategy for transitioning to alternatives. Some utilities have begun that process through pilot projects, which allow for a phase to test and vet the new technology before further adoption. It can take approximately four to seven years to design and pilot alternative equipment before being able to fully integrate it into the grid. Pilot projects require soliciting proposals, procurement, installation, field testing—particularly on-grid testing—and performance evaluation. These projects, and subsequent adoption of additional alternative breakers, will require capital investment planning.

Example Installations of Medium and High Voltage Alternative Equipment

Adoption of both VCBs and fluorinated alternative gas breakers has so far been more prevalent in Europe. In the United States, VCBs have experienced a greater market penetration relative to fluorinated alternative gas breakers thus far. Medium voltage VCB equipment has been installed in more than 35 states across the United States, as well as in Europe and Asia. Table 3 and Table 4 provide examples of installations of medium and high voltage vacuum and fluorinated gas breakers.

Table 3. Medium and High Voltage Vacuum Breaker Installations

LOCATION	YEAR	TYPE OF VCB
EUROPE		
Germany	2018	Siemens LTCB 123 kV
Kazakhstan	2018–2020	Siemens LTCB 145 kV
Norway	2017–2020	Siemens GIS 145 kV and 40 kA
Poland	2019	Siemens LTCB 123 kV and 145 kV
Romania	2018–2019	Siemens LTCB 145 kV
Sweden	2019	Siemens LTCB 145 kV
Switzerland	2019	Siemens LTCB 123 kV
United Kingdom	2019	Siemens LTCB 145 kV
ASIA		
Japan	2011	MEPPI DTCB, 72 kV and 84 kV
UNITED STATES		
More than 35 U.S. States	Since 2007	Hitachi DTCB, 72 kV

GIS: gas insulated substation; DTCB: dead tank circuit breaker; LTCB: live tank circuit breaker; kV: kilovolts; kA: kiloamperes
Sources: Representatives of MEPPI, Hitachi, and Siemens in February and March 2020

Table 4. Medium and High Voltage Fluorinated Alternative Gas Breakers

LOCATION	YEAR	TYPE OF FLUORINATED GAS BREAKER
EUROPE		
Denmark	2019	GE g^3 LTCB, 145 kV
	2017	GE g^3 GIS, 145 kV
France	2017	GE g^3 GIS, 72.5 kV
Germany	2019	GE g^3 LTCB, 145 kV
	2017	GE g^3 GIS, 145 kV
Netherlands	2017 and 2019	GE g^3 GIS, 72.5 kV
Spain	2018	GE g^3 GIS, 72.5 kV
Switzerland	2019	GE g^3 LTCB, 145 kV
	2015	ABB AirPlus™ GIS, 170 kV
United Kingdom	2018 and 2019	GE g^3 GIS, 145 kV

GIS: gas insulated substation; LTCB: live tank circuit breaker; kV: kilovolts
Source: Representatives of GE and ABB in February and March 2019

Conclusions

While the rollout of alternative technologies for high voltage equipment is still underway, utilities can begin to assess their 10- to 20-year replacement plans. Alternative breakers do not require significant changes to existing substations. However, utilities will first need to validate the pros and cons of each technology in terms of technical performance, footprint, costs to buy and operate, and training and policy changes necessary for safety and maintenance. Internal planning and circuit breaker purchases will require an implementation strategy, allowing time for steps such as permitting, piloting, and procuring the new technology. The utilities and OEMs interviewed for this paper provided insight on the recent developments and experiences in implementing these alternatives. Whether utilities are responding to state regulations to reduce SF_6 emissions or looking to replace SF_6 leaking breakers or equipment at end of life, alternative breakers offer a new option to the industry.

These innovative technologies and approaches are expected to further reduce or eliminate SF_6 emissions. In many cases, Partners of EPA's SF_6 Emission Reduction Partnership for Electric Power Systems have reduced SF_6 emissions to a very low emission rate—the average Partnership emission rate currently hovers below 2%.

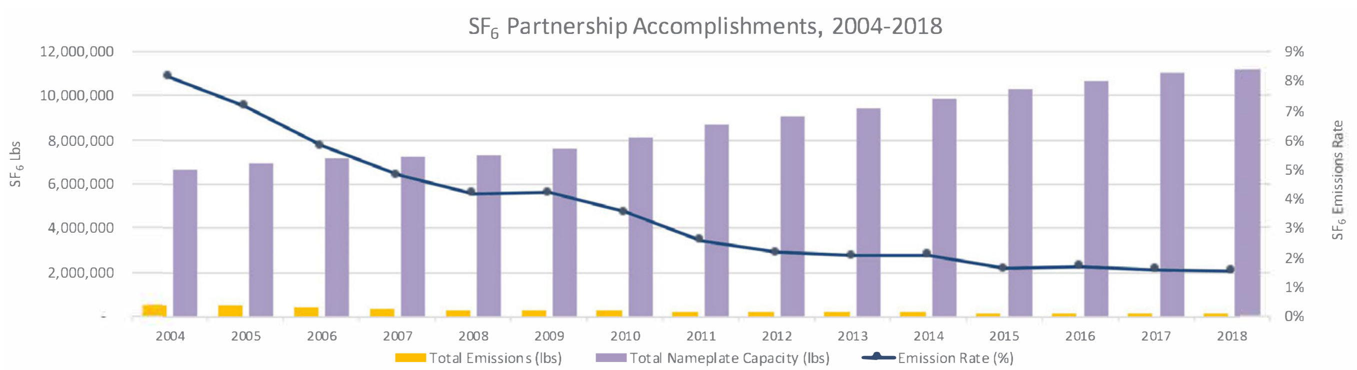

Figure 3. SF_6 Emissions and Emission Rate for Partners of the SF_6 Emission Reduction Partnership for Electric Power Systems

It becomes increasingly more challenging to eliminate SF_6 emissions without eliminating reliance on the gas entirely. Several utilities are embracing adoption of SF_6 alternatives, which provide an opportunity to address this challenge. For example, in California, companies are working together through the Electric Utility Industry Sustainable Supply Chain Alliance (EUISSCA) to advance the dialogue across the value chain from suppliers to utilities on this topic.

In general, as the market for SF_6-free equipment matures and the pace of technology adoption accelerates, the barriers for adopting the new technology also can be expected to come down.

Electrical Utility Industry Sustainable Supply Chain Alliance

EUISSCA is composed of member utilities and suppliers that aspire to minimize environmental impacts while addressing safety, cost, and functionality across the value chain. EUISSCA is engaging where appropriate to accelerate the development and adoption of SF_6 alternatives.

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