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Zero Emission F-gas-free 420 kV GIS for a Net Zero Carbon Future

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Abstract

Today SF_6 is most widely used as arc quenching and insulating gas in T&D equipment. Its properties have been proven in high voltage applications for more than 50 years. However, SF_6 is about 25,200 times more harmful than the greenhouse gas (GHG) CO_2 and has a lifetime of about 3,200 years in the earth's atmosphere. Thus, despite of leakage rates below 0.1 % per year in case of state-of-the-art-GIS, the SF_6 significantly contributes to global warming if it gets into the atmosphere.

It is known that the global average temperature has risen faster in just a few decades than ever before. Therefore, efforts are being made worldwide to reduce GHG emissions and even bring them down to zero to establish CO_2-free and net-zero economies.

Consequently, the replacement of SF_6 is essential to mitigate climate change and to reach a net zero carbon future. In this regard, SF_6 is the subject of intense discussions also at the regulatory levels. Hence the commitment to and demand for SF_6-free alternatives are continuously increasing. Today several F-gas-free alternative products are already available for specific voltage levels and the operational experience is growing rapidly [1, 2].

This article reports on the F-gas-free 420 kV / 63 kA GIS (including GIB) development status. The zero emission GIS is based on clean air insulation (synthetic air with 80 % nitrogen and 20 % oxygen) with a Global Warming Potential of zero (GWP = 0) combined with vacuum switching technology. In particular, the following aspects will be presented and discussed in detail in the paper in comparison to today's SF_6 designs:

(1) Technical Data and design aspects including dimensions and space footprint
(2) Life cycle stages considering product level assigned to value chain Scopes 1 – 3
(3) Expected lifetime and electrical endurance of clean air switchgear
(4) Status of research and development tests
(5) Results On-site installation and operational experiences
(6) Outlook and roadmap for clean air products

Keywords

GIS, AIS, SF_6 alternatives, synthetic air, clean air, vacuum interrupter, LPIT, GWP, LCA

Introduction

The UN Sustainable Development Goals point the way to the future and are the basis for strategic direction for companies. With this in mind, T&D equipment manufacturers have made huge investments over the last decade to develop more sustainable and zero emission products to gradually replace SF_6 at all voltage levels. The interest and efforts of T&D system operators to use and test SF_6 -

free products have also steadily increased in recent years, as awareness of health and environmental protection has also risen.

At a European level, the grid operator efforts have been significantly intensified after the announcement of the Green Deal [3] targets in December 2019. The EU aims to be net-zero by 2050. This objective is important to meet the EU's commitment to a global climate action under the Paris Agreement and mitigate the climate change. All sectors of the economy are called upon to invest in new, environmentally friendly technologies. Besides Europe, many other governments and companies worldwide have also committed themselves to this goal. And at the recent COP27 in Egypt F-gases emission reduction were unsurprisingly also topics of panel discussions aimed at exploring F-gas free alternatives globally.

Consequently, for electrical grids the replacement of SF_6 essentially supports the target of net-zero. More and more utilities worldwide commit themselves to cut CO_2 direct emission and start to specify and install gas insulated equipment with insulating gas of GWP < 1. Figure 1 shows the exponential increase of F-gas-free installations based on clean air with zero GHG emissions for high voltage applications.

In addition to climate protection measures and the reduction of greenhouse gas emissions, the EU Commission has adopted its sustainability strategy for non-toxic environment and chemicals [3]. This strategy proposes a comprehensive package of measures to regulate the use of per- and polyfluoroalkyl substances (PFAS). PFAS chemicals are connected to environmental pollution and health risks. There is a global trend towards PFAS phase-out and regulatory restrictions for these substances in discussion, where alternative solutions are available. As a reaction in the sense of sustainability one of the main market players 3M announced in December 2022, that it will exit (PFAS) manufacturing and work to discontinue the use of PFAS across its product portfolio by the end of 2025 including C4-FN insulating gas used as SF_6 alternative. An overview and summary of the latest regulatory information is shown in Table 1.

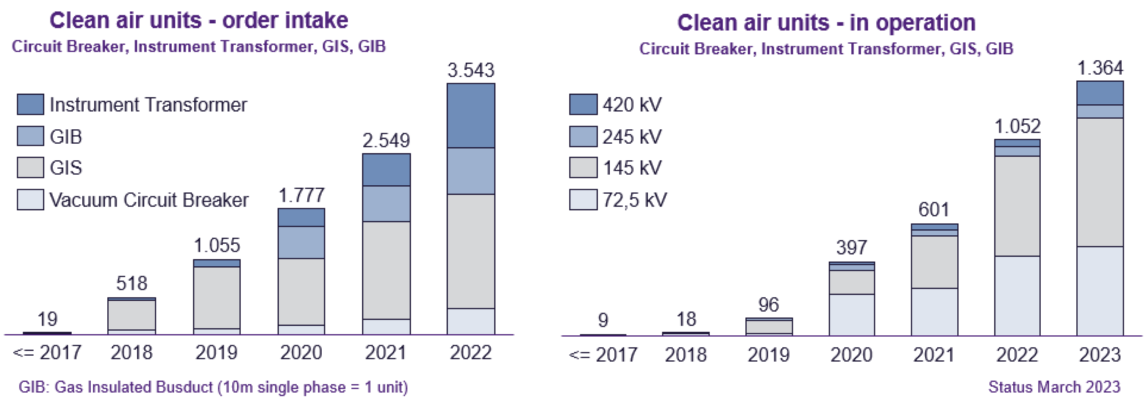

Figure 1 - Worldwide F-gas-free clean air references of a European Manufacturer

GHG / F-Gases	EU Revision of F-gas regulation in progress, the trialogue phase of negations between Commission, Parliament and Council started, the final decision is expected mid 2023. For switchgears stepwise bans of F-gases with **GWP > 10** or entire F-gas ban and restriction on F-gases as C4FN & C5FK expected, see COM (2022) 150 final, EU Parliament vote from 30.03.2023 and EU Council result from 05.04.2023. California: Stepwise SF_6 ban from 2025, F-gases with GWP > 1 are subject to reporting like SF_6
Chemicals PFAS	Europe: In order to improve the protection of human health and the environment, a ban on PFASs* has been initiated, unless there is an 'essential use'. The European Chemicals Agency (ECHA) submitted in February 2023 its restriction proposal for a comprehensive list of PFAS [4]. For PFAS F-gases used in switchgear, a ban is foreseen for voltage levels ≤ 145 kV in 2026/27 and for > 145 kV in 2033. USA: The Environmental Protection Agency (EPA) has established a PFAS-Council and in US state of Maine, the first PFAS-ban was announced effective from 01.01.2030 *Per- and Polyfluoroalkyl Substances inclusive F-Gases like C4-FN Fluoronitrile and C5-FK Fluoroketone
Grid Operators	Worldwide, more and more own commitments to climate neutrality and therefore specifications for T&D equipment with GWP < 1.

Table 1 - Summary and overview of main regulations in regard of sustainability including user trends.

(1) Technical Data and design aspects including dimensions and space footprint

In general, the technical ratings are comparable to a 420 kV SF_6 GIS with some improvements when it comes to numbers of short circuit interruptions and low temperature applications. Therefore, the clean air technology is suitable as replacement of SF_6 within the High Voltage AIS and GIS applications [5].

Rated Voltage	420 kV
Rated Frequency	50/60 Hz
Rated short circuit current	63 kA (3s)
Rated normal current (feeder / busbar)	5000 A / 6300A
Rated peak withstand current	2.7 x 63kA / 170kA
Rated filling pressure	1.1 MPa (rel)
Bay size (Double busbar cable bay)	7.4m / 3.6m / 6.3m (l / w / h)
Temperature range	-50°C to + 55°C

Figure 2 – F-gas-free 420 kV GIS: main ratings, cable bay (Option inductive CT, VT) and busduct

The physical size of the new technology is comparable to the size of a SF_6 gas insulated switchgear from the previous design generation (from around 2010). Therefore, a replacement of already existing equipment with a clean air solution will be possible within the available footprint. Furthermore, the new technology can be combined with existing SF_6 technology, which will enable several expansion options for already existing installations.

Figure 3 – Size comparison: previous SF_6 generation, current SF_6 generation, new clean air

(2) Estimated Life cycle assessment

This LCA shows a comparison of the existing SF_6 420 kV GIS and the clean air 420 kV GIS, based on current design, for the impact category "Global warming". The LCA is based on the principles and framework of life cycle assessment, ISO 14040.
The comparison of the GIS designs is based on the same functional units with the same single line diagram, namely a double busbar configuration.

The following essential life cycle stages of the GIS have been considered. Furthermore, these stages at the product level have been assigned to the corresponding corporate level showing the OEM and the TSO / Grid operators view. For assigning the different scopes across the complete value chain the relevant GHG Reporting standard was considered [6].

<table>
<tr><th colspan="2">Main GIS life cycle stages</th><th>GHG Protocol - OEMs View</th><th>GHG Protocol - Grid Operators View</th></tr>
<tr><td>Materials, Purchased goods of OEMs suppliers</td><td rowspan="2">Materials</td><td rowspan="2">Scope 3 (indirect) upstream</td><td rowspan="6">Scope 3 (indirect) upstream</td></tr>
<tr><td>Gas losses of OEMs Gassupplier</td></tr>
<tr><td>OEM Manufacturing & Assembly (Energy, Logistics)</td><td rowspan="4">Manufacturing</td><td>Scope 2 (indirect)</td></tr>
<tr><td>OEM Manufacturing Gas losses</td><td>Scope 1 (direct)</td></tr>
<tr><td>Transportation of product to site</td><td>Scope 3 (indirect) upstream</td></tr>
<tr><td>Installation & Commissioning on-site (Gas losses)</td><td>Scope 1 (direct)</td></tr>
<tr><td>Operation + Maintenance Gas losses</td><td rowspan="3">Operation</td><td rowspan="5">Scope 3 (indirect) downstream</td><td>Scope 1 (direct)</td></tr>
<tr><td>Transportation maintenance</td><td>Scope 3 (indirect) upstream</td></tr>
<tr><td>Operational Energy use</td><td>Scope 2 (indirect)</td></tr>
<tr><td>End of Life Gas losses (Deconstruction and demolition)</td><td rowspan="2">EoL</td><td rowspan="2">Scope 3 (indirect) upstream</td></tr>
<tr><td>End of Life Recycling (Waste transport, Disposal)</td></tr>
</table>

Table 2 - Life cycle stages considering product level assigned to value chain Scopes 1 – 3 in line with Greenhouse Gas (GHG) protocol reporting standard [6]

Materials and Manufacturing

Based on the requirements for our suppliers, respectively secondary material share for the different materials was considered as available.

For the manufacturing, the GIS factory in Berlin with its renewable energy consumption was considered. Gas handling losses were considered for both solutions with 0.5% of the gas volume.

Operation

A lifetime of 50 years was assumed for the analysis. Within the lifetime, 2 maintenance procedures were considered for all solutions as a visual inspection and a large inspection. As a handling loss for gas work, 0.4% of the residual gas volume has been set as a loss. As spare parts 0.15% of the switchgears weight was taken into account in the lifetime phase of the products, as well as transport by truck and a distance of 500 km. According to the type test, a leakage of 0.1% / year was considered over the lifetime. The current losses during operation over the lifetime were taken into account by 25% of the nominal current. Power loss of the anti-condensation heater used in the components for the secondary components was considered. For the operation renewable energy, considering wind energy onshore, was chosen as the electricity mixture with 19 g CO_2 / kWh.

Allocation

For setting the system boundaries, the cut off approach was used in this study. The cut-off model is also known as “Recycled Content”.

The system boundary is drawn between “product one” (GIS) and “product two” for new application at the point where the user of product one hands the product over to recycling.

The waste remains at the producer's responsibility, so the life cycle of product one includes activities like waste transport, incineration (without thermal recovery) and landfilling at the end of life, but not recycling, recovery or re-use.

Software

The LCA software used is SimaPro with the Ecoinvent 3.7 database. The data sets used are ‘Cut-Off, S’ (system process) or ‘Cut-Off, U’ (unit process). The LCA method used is ReCiPe 2016 following a midpoint characterization approach (midpoint (H)).

LCA Conclusion

The total CO_2 emissions are reduced by 81% applying clean air instead of SF_6.

Main lever for CO_2 emissions is SF_6 Gas. Only 22% are dedicated to all materials, power losses, logistics and manufacturing. In the future the CO_2 emissions of material share of 86% for clean air GIS will be further significantly reduced since climate neutral power is aspired and beneficial for material manufacturing and logistic.

From the TSO perspective the Scope 1 direct emission are eliminated applying by clean air.

LCA Results

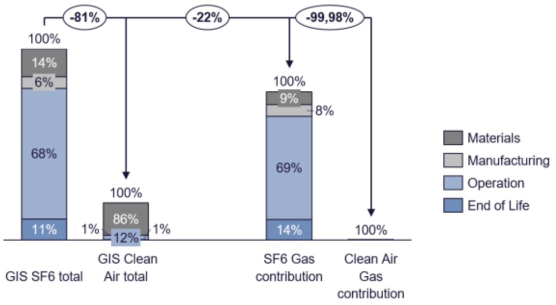

Figure 4 – Comparison of 420 kV GIS SF_6 vs clean air, LT 50 years, Contribution of gas CO2e over the life cycle

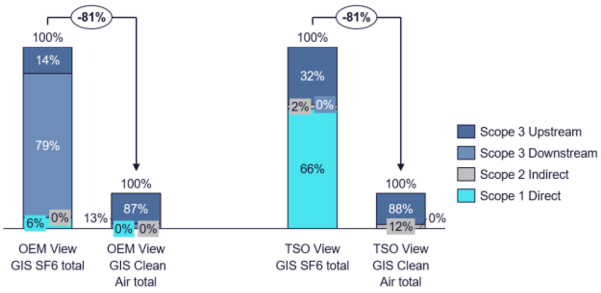

Figure 5 – Comparison of 420 kV GIS with SF_6 vs clean air, LT 50 years, considering "Scope 1-3 setting" from OEM and TSO perspective

(3) Expected lifetime and electrical endurance of clean air switchgear

The life expectations of GIS generally range from 40 to 50 years. This is valid for classical SF_6 insulated GIS and can be also considered for alternative insulation gases like clean air or dry air. The overall used materials for enclosures, insulators, conductors and contacts are equal or similar compared with SF_6 installations. Most exterior components are identical or very similar: drives, supports, secondary equipment, earthing etc. The sealing materials reach a similar performance compared with SF_6 while the permeation for smaller molecules like O_2 and N_2 is higher. The measurement of tightness with clean air can be done using a tracing gas such as He.

There is no difference in the mechanical endurance of circuit breakers, disconnectors and earthing switches.

The electrical endurance of circuit breakers with Vacuum Interrupter are significantly higher than any gas circuit breaker. Gas circuit breakers reach typically 6 to 12 full rated short circuit interruptions while vacuum interrupters can reach 30 to 50. With this performance it is unlikely to reach the end of life for the electrical endurance during service life of the vacuum circuit breaker. The main reason for this is no erosion of contacts and no ablation of nozzle material.

(4) Status of research and development tests and results

The technological basis for the new zero emission and F-gas-free 420 kV GIS was laid by the investigations performed in the public-funded project ECO-BREAK-420. The dimensions of the future GIS are comparable to the previous generation of 420 kV SF_6 switchgear. As an example, the following test duties according to IEC 62271-102 have been successfully passed by a clean air insulated disconnector demonstrator for U_r = 420 kV:

- TD1 (U_{source} = 267 kV_{AC}, U_{load} = -377 kV_{DC})
- TD3 (U_{source} = 242 kV_{AC}, I_{load} = 0.5 A)
- Bus transfer current switching for I_r = 5000 A (U = 25 V, I = 3000 A)

In addition, the following dielectric ratings according to IEC 62271-203 were successfully demonstrated:

- Switching state **"Closed"**
  - U_{AC} = 650 kV
  - U_{LI} = 1425 kV
  - U_{SI} = 1050 kV

- Switching state **"Open"**
  - U_{AC} = 815 kV
  - U_{SI+AC} = 900 kV + 345 $kV_{AC,peak}$
  - U_{LI+AC} = 1425 kV + 240 $kV_{AC,peak}$

The investigations on the circuit breaker design are being continued based on a series-connection of two vacuum interrupter units. It is expected to fulfil all test duties related to the switching performance according to IEC 62271-100.

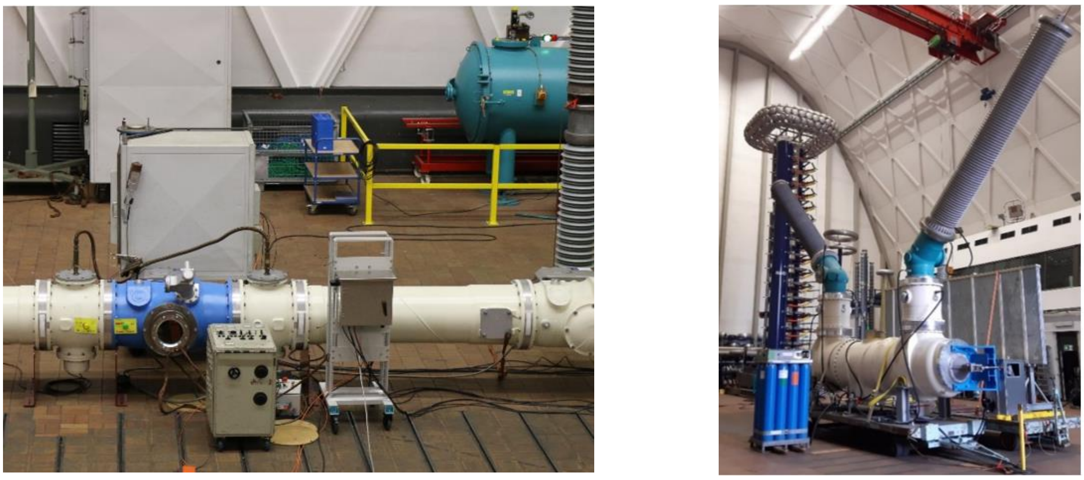

Figure 6 – Demonstration of clean air insulated equipment for the new zero emission and F-gas-free 420 kV GIS from ECO-BREAK-420 (left: disconnector, right: circuit breaker)

Status of the type tests of the clean air GIB for 420 kV

The type tests of the clean air Gas Insulated Busduct (GIB) for 420 kV have been completed successfully by end of March 2022. Customers of first installation projects were present, personally and via remote access for the main type tests such as the dielectric tests, temperature rise tests, short time & peak withstand current tests and internal arc test. Examples of the test set-up arrangements are shown in Figure 7.

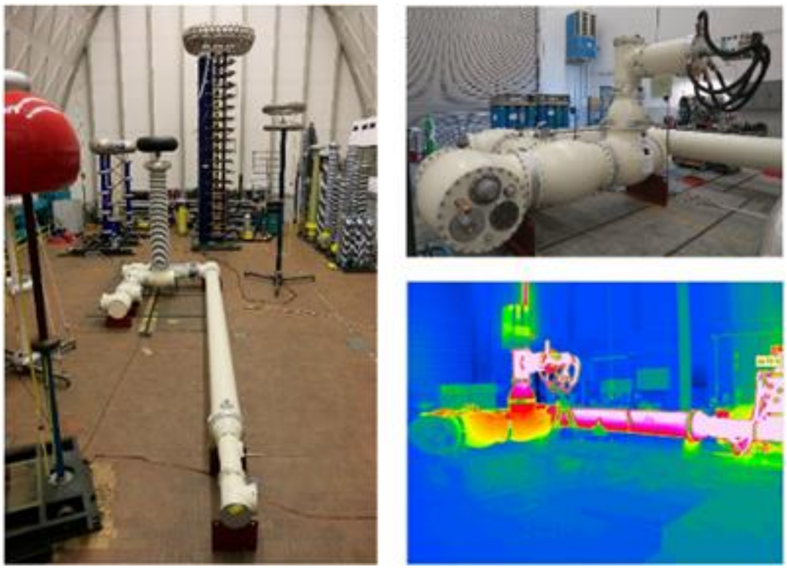

Figure 7 – Clean air 420 kV GIB – Dielectric type test and temperature rise type test including thermal camera observation.

(5) Results On-site installation and operational experiences

The installation & commissioning works of the first installation in Scotland for a 420 kV clean air GIB are in progress (approx. 500 m, single phase), see figure 8. The energization of the GIB is expected in spring 2023:

Figure 8 – First installation of a 420 kV clean air GIB – OHL feeder bay

A new method is used for the leakage test on site, the so-called "vacuum method". Already with SF_6 gas installation it always was a challenge to detect leakages under windy weather conditions with the conventional sniffing method. The new vacuum method will work in the opposite direction in which the detection gas Helium will be injected outside a flange connection by means of a plastic cover. A leakage detector with a vacuum (turbomolecular) pump and a mass spectrometry will measure the Helium particles inside the vacuum of the module as per

Figure 9. Under outdoor conditions this new method showed better results than the conventional sniffing method. The achieved measuring values were < 10-6 mbar l/s.

Figure 9 – Principle and test arrangement of the vacuum method

(6) Outlook and roadmap for clean air products

It is mandatory to comply with the UN sustainable goals. Zero emission for switching products is not only the future but proven reality with delivered products and major positive test results in higher voltage levels. Based on over 20 Mio hours (2,300 years) in operation for switching and non-switching products in HV the reliability of this technology has been proven.

Figure 10 marks available SF_6 free products in blue. An important milestone was the introduction of the SF_6 free Dead Tank breaker 145 kV and 63 kA as worldwide first product with VI and clean air technology. As described in this article, the development of 420 kV GIS is under work with positive test results. Supported by the new F-Gas regulation, the main Switchgear and Circuit breaker portfolio elements up to 550 kV will be developed until 2028.

Insulation coordination of clean air for 420 kV is proven by the finished development and installation of GIB for 420 KV. The switching capability of 63 kA has been proven by finished type test for 63 kA @ Dead tank breaker of 145 kV at 60 Hz. The Vacuum interrupter technology for switching, combined with clean air insulation, can be applied up to 550 kV.

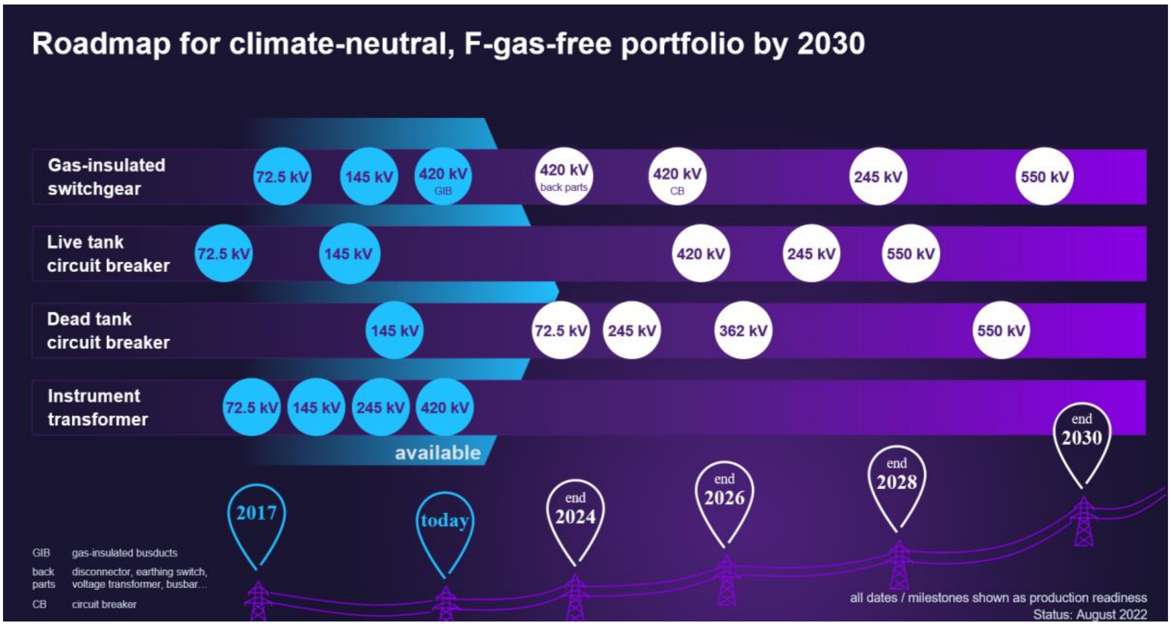

Figure 10 – Actual roadmap of SF_6 free zero emission clean air products

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