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A3 – PS 2 - TRANSMISSION AND DISTRIBUTION EQUIPMENT
Decarbonisation of T&D equipment

# Experience with F-gas-free High voltage equipment for On- and Offshore applications

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## SUMMARY

In Europe, the efforts of utilities have significantly intensified after the announcement of the Green Deal targets in December 2019 to reduce net greenhouse gases (GHG) for 2030 to at least 55% compared with 1990 levels [1]. The EU aims to be climate-neutral by 2050. Within the UK, the government has announced their "Net Zero" by 2050 initiative. Germany aims to become climate neutral in 2045. In other continents and countries other specific targets are being defined. Therefore, transmission system operators, have taken the initiative and increased the introduction of F-gas free equipment to support their target of moving towards $CO_2$ neutral grids. It is expected that the use of F-gases, like sulphur hexafluoride ($SF_6$), the most potent greenhouse gas with a GWP of 25.200 [2] will be more restricted also for high voltage (HV) switchgear equipment. For Europe, the F- Gas Regulation (EU) No. 517/2014 applies, which is currently under review with an update planned for 2022.
This paper presents the experience with equipment using the combination of Clean Air (CA), which consist of 80% $N_2$ and 20% $O_2$, as insulation gas with a GWP of 0 and vacuum interrupting technology. This covers specific applications like the installation of the 145 kV Live Tank Circuit Breaker at SPEN, the 420 kV Voltage Transformers at Amprion and the 72,5 kV GIS for Wind Turbine Generator (WTG) installed at Offshore Windfarms.
Furthermore, an example of an incentivising mechanism deployed by Ofgem to encourage SF6 – free installations in Great Britain is described and a comparison of alternatives to $SF_6$ is provided.

## KEYWORDS

High voltage circuit breaker, GIS, instrument transformer, vacuum interrupter, $SF_6$ alternatives, net zero, F-gas free, PFAS,

# 1. INTRODUCTION

Transmission System operators have already started the transition to $CO_2$ neutral grids by a stepwise phasing out the application of $SF_6$ for On- and Offshore installations.
By the combination of Clean Air (CA), which consist of 80% $N_2$ and 20% $O_2$, as insulation gas with GWP = 0 and vacuum interrupting technology (VIU), the manufacturers can provide sustainable high voltage solutions for circuit breakers, instrumental transformers and gas insulated switchgears.
In order to achieve the target of $CO_2$ neutral grids, the application of a $CO_2$ neutral gas with GWP < 1 like Clean Air is required.
In this paper the return of experience with the installation of the 145 kV vacuum circuit breakers installed in Great Britain, the 420 kV Clean Air Voltage Transformer installed in Germany and the 72,5 kV Clean Air GIS for Wind Turbine Generator (WTG) installed at different Offshore Windfarms in four countries is described in general and for the specific application in the grids. The enhancement of the equipment is also described.
Beside climate action and the reduction of greenhouse gas emissions, the EU Commission adopted its sustainability strategy for non-toxic environment and chemicals [3]. In this strategy, a comprehensive package of measures to regulate the use of per- and polyfluoroalkyl substances (PFAS) listed by the Organization for Economic Cooperation and Development (OECD) is proposed. The OECD list contains over 4700 substances including F-gas-based products and gases, which are currently used in different mixtures as alternatives to $SF_6$. CA does not fall under the PFAS classification. More information is available in [4].

## 1.1 Statistics on worldwide commissioned equipment with Clean Air (CA)

The quantity of the installed equipment using CA is growing as shown in figure 1.

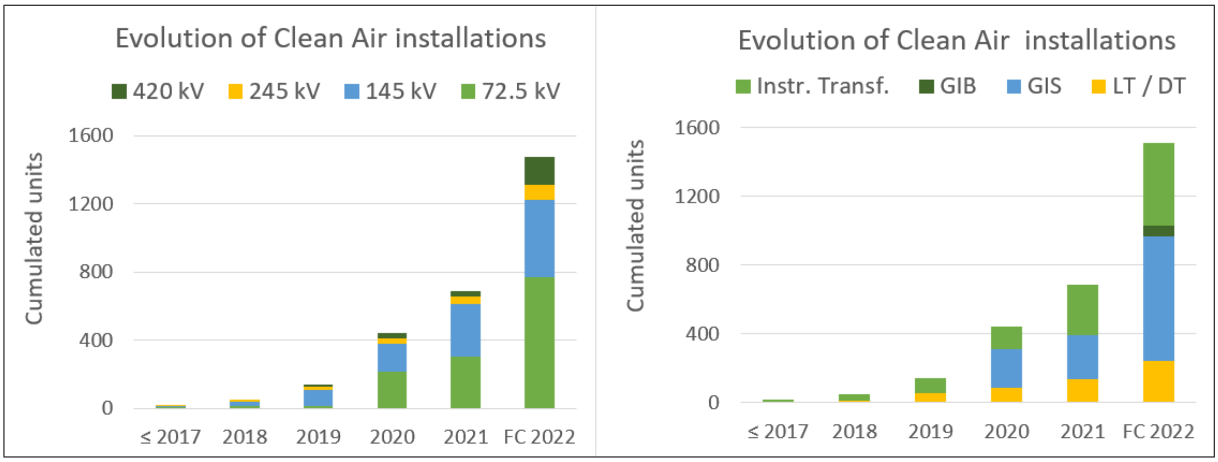


Figure 1: Cumulated CA installations according to voltage level (left) and type of equipment (right)

# 2. CONSIDERED EQUIPMENT

## 2.1 General

### 2.1.1 Comparison of switchgear technology and consequences on application

Table 1 is based partly on field data and summarised evaluations of properties and impact of $SF_6$, fluorinated alternative gas mixture based on heptafluoroisobutyronitrile (C4-FN) and Clean Air. This covers circuit breakers based on gas - and vacuum interrupting technology and passive (non-switching) applications. A general comparison of technologies from operator views regarding technical, regulatory- and commercial aspects for $SF_6$ alternatives technologies in HV circuit breakers has also been considered in the evaluation [5].

| | | | | Circuit Breaker (LT & GIS) | | | Applies for Instr. Transf., passive GIS | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Property | Consequence / Impact | $SF_6$ | C4-FN-Mix | VIU + CA | $SF_6$ | C4-FN-Mix | CA |
| A) Switching / breaking | 1 | Arcing times | Fault duration | 0 | 0 | + | n.a. | | |
| | 2 | Mechanical endurance | Challenge, costs | 0 | 0 | 0 | n.a. | | |
| | 3 | Electrical endurance | More interruptions | 0 | - | + | n.a. | | |
| | 4 | Outlook > 245 kV | Product portfolio | + | 0 | 0 | n.a. | | |
| | 5 | Outlook > 50 kA | Product portfolio | + | 0 | 0 | n.a. | | |
| B) Life Cycle aspects | 1 | Service experience of technology, MTTF, MTBF | Reliability | + | 0 | + | + | 0 | + |
| | 2 | Insulating medium stability | Asset management | + | - | + | 0 | 0 | + |
| | 3 | Low temperature applications including handling | Special measures | 0 | - | + | + | - | + |
| | 4 | Footprint | CAPEX, Civil Cost | + | 0 | -* | - | + | 0* |
| | 5 | Internal arc failure | Contamination | - | - | + | - | - | + |
| | 6 | Gas handling, repair, end-of-life | OPEX | - | - | + | 0 | - | + |
| | 7 | Lifetime ohmic losses | OPEX, CO2e emissions | 0 | 0 | 0 | - | 0 | 0 |
| C) EHS | 1 | Leakage to environment | CO2e emissions | - | 0 | + | - | 0 | + |
| | 2 | GHG reporting/monitoring and regulations | OPEX | - | - | + | 0 | - | + |
| | 3 | Toxic decomposition products | Safety measures on site | - | - | + | n.a. | | |
| | 4 | X-Ray in open position due to HV test voltage | Safety measures factory | n.a. | n.a. | 0 | n.a. | | |

Table 1: Overview comparison of switchgear technology and application aspects provided by Clean Air (CA) equipment manufacturer (+ positive, 0 neutral, - to optimise, n.a. not applicable)

**Remarks & explanations to table 1 concerning differences between gas mixtures with C4-FN and VIU+CA**

A1: VIU+CA: Compared to gas breakers the arcing time is significant lower (< 50%) because for VIU it is sufficient enough to have an adequate contact distance. For gas breaker additionally a sufficient gas pressure built up and an adequate gas flow for deionisation is required. Additionally, the VIU offer a very fast dielectric recovery compared to gas breakers (sensitivity for dU/dt variation) [20], [21].

A2: C4-FN; VIU+CA: More than 10 000 times operation.

A3: C4-FN: Gas circuit breaker shows contact wear and nozzle burn out and therefore limited to typically 10 times fully short circuit interruptions. Nom. current switching typically up to 6000 switching operation.
VIU+CA: Typically, 30 times rated short-circuit breaking current interruptions due to negligible contact wear [17], [23], [24]. More than 10 000 times operation at nominal current switching [21], [22], [24].

A4: C4-FN; VIU+CA: With today's technology for voltages above 245 kV multi-break approach is needed at least for VIU+CA. (For VIU+CA, see chapter 4)

A5: VIU+CA: MV VCBs are existing up to 100 kA, HV VCB breaker for 63 kA are successfully tested [6].
C4-FN: Applications for 63 kA and higher expected to be challenging since the breaking performance of C4-FN is mainly influenced by the background gas $CO_2$. $CO_2$ is a small molecule compared to SF6 and its thermal breaking performance is lower than that of $SF_6$ [7]. Development of 63 kA CBs are announced.

B1: VIU+CA: Accord. CIGRE reliability survey 2020, VIU applied at both MV distribution and HV transmission levels generally show excellent service experience [25].
C4-FN: No published reliability survey available.

B2: C4-FN: Various species after current interruption are produced, no recombination to original gas molecule. Minor long-term experience. Solid by-products may be formed, also without switching [8],[9]
VIU+CA: Extremely stable, no hazardous by-products or chemical reactions based on long term experience for switchgear application [10].

B3: VIU+CA: Applicable to lowest temperature down to -60 °C without liquefication and special measures.

B4: C4-FN: Equivalent footprint of GIS up to 145 kV is reported. For higher ratings exceeding 63 kA and ≥ 245 kV, the footprint of the first generation may be larger due to multi-break design.
VIU+CA: ≤ 245 kV: LT: No impact on footprint expected; GIS: Slightly larger footprint.
VIU+CA: > 245 kV with a multi-break design footprint could be larger compared to $SF_6$.

*AIS: LT and Instr. Transf., no significant impact on footprint (see figure 7)

B5: C4-FN: In case of internal arc and opening of the burst plate contamination (including toxic decomposition products) of environment needs to be cleaned with special safety procedures as applied to arced $SF_6$. [11]
VIU+CA: In case of CA insulation the main decomposition products are ozone and NOx. Ozone (O3) is recombining to O2 within 1-2 h. NOx is slowly disappearing.
Metal vapour appears for all applications depending on design with minor impact.

B6: C4-FN: Multiple gas mixtures with 3 different gases require special mixture techniques to ensure a ratio verified in type tests and in use. Gas needs to be evacuated. Recycling is not clean; it is expected to be as with $SF_6$. Handling/analysis equipment is commercially available from third parties. Uncertain whether multiple mixtures are adopted even by a single OEM.
VIU+CA: Natural-origin gases are needed in different branches and can be easily and cost efficiently; sourced from different suppliers, it can be released to the atmosphere

B7: VIU+CA: Vacuum interrupters have one contact system for continuous current conduction and (short-circuit) current interruption. Because of the low contact wear the contact resistance keeps stable with time and current interruptions. This leads to comparable resistance to gas breakers.

C1: GWP differences considered

C2: C4-FN mixture with GWP >500, for C4-FN concentrate > 5% (accord. IPCC (AR6) values GWP 2750 [2]) may become accepted, Duty for reporting expected accord. upcoming revision of EU-F-gas regulation since C4-FN shall be included in Annex II [12]. Ofgem regulation (Office of gas and electricity markets) for UK requires reporting and penalty for GWP ≥1. In the new CARB regulation for Reducing Sulfur Hexafluoride Emissions from Gas Insulated Switchgear (released 01.02.2022) [13] C4-FN is defined as "Other fluorinated GHG" and therefore the same reporting requirements apply as for $SF_6$.
C4-FN listed as PFAS gas within the Organisation for Economic Co-operation and Develop. (OECD).
VIU+CA: Acceptable without discussion about duty for reporting and monitoring. Very low environmental impact with natural gases.

C3: C4-FN: During arcing phase decomposes to toxic by-products [11].
VIU+CA: non-toxic and no decomposition products and chemical reactions in VIU [11].

C4: VIU+CA: X-radiation only in open contacts above the operation voltage possible (applies only in type and routine tests). VCBs must fulfil the limits in the standard (e.g., IEC 62271-1) for a safe operation. For on-site tests with operating voltage no safety measures necessary.

## 2.2 145 kV Vacuum Live Tank Circuit Breaker with Clean Air (CA) insulation

The first installations were carried out already in 2010 for 72,5 kV applications. Based on that experience the 145 kV vacuum circuit breaker was introduced in 2018 [14] and more than 100 CBs are installed. The design is approved for a rated short-circuit breaking current of up to 40 kA, a rated current of up to 3150 A, operating temperatures from -60°C up to +55°C without any additional heating systems and up to 30 full short-circuit interruptions. Further advantages are easier handling during transport, installation and in operation - as well as during maintenance and when recycling. No maintenance efforts of the sealed-for-life VI units are required. After the first introduction in 2018 the following enhancements were achieved:

**Qualification for 60 Hz applications according to IEC 62271-100:**
The 145 kV vacuum circuit breaker is released also for 60 Hz, 145 kV, 40 kA.

**Shunt reactor switching in accordance with IEC 62271-110:**
One solution for shunt reactor switching is based on RC filter circuits. The selection of appropriate parameters for the RC filter depends on the individual system configuration (e.g., cable connection or overhead lines). It can be expected that the multiple re-ignition phenomenon will be considerably influenced by the RC filter circuit. In addition, the published analysis was able to show that a satisfying damping characteristic can be achieved for a large variety of system parameters [15]. Typical RC parameters have been predefined to serve different grid configurations to avoid extended system simulation work.
The application of RC filter circuit was successfully tested and qualified for GIS und LT Vacuum interrupter applications. First Pilot installations are planned for 2022.

**Switching of tertiary windings at transformers up to 36 kV:**
For this AIS application the 145 kV vacuum circuit breaker can be used without any additional mitigation measures to switch tertiary windings. 10.000 electrical operations with up to rated current

can be ensured. Therefore, the maintenance interval will be the same as for standard line circuit breakers. Applications are in service since 11-2019.

## 2.3 420 kV Voltage Transformer with Clean Air (CA) insulation

Instrument transformers with CA insulation are based on the same design principles as $SF_6$-insulated devices. The biggest challenge when using CA insulation is the electrical strength, which is 2 to 3 times lower than that of $SF_6$ depends on pressure [19]. To compensate the lower dielectric strength of CA, either an enlarged electrode gap and or a higher gas pressure must be applied.
While the first 123 kV devices represent "downgraded" $SF_6$ devices with larger electrode spacing and same insulating pressure as for $SF_6$, the subsequent developed 245 and 420 kV voltage transformer were specifically designed for CA insulation, i.e., for a higher service pressure and with very similar dimensions and same footprint as $SF_6$ designs (see figure 7). The filling pressure was increased to 12.5 bar rel. which is approx. 2 times higher compared to $SF_6$. The increased filling pressure requires a reinforced housing design with new housing technology.

| | **Clean Air VT 420 kV** |
|---|---|
| **AC [kV]** | 630 |
| **BIL [kV]** | 1425 |
| **CW [kV]** | 1640 |
| **SIL [kV]** | 1050 |

Table 2 : Electric parameters of Clean Air VT 420 kV

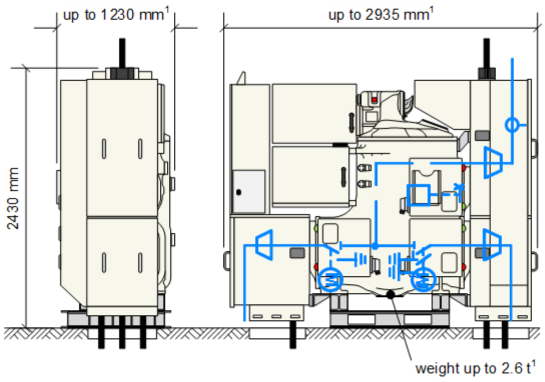
All ITs developed have been type-tested in accordance with IEC 61869. There are no restrictions for VTs with CA compared to corresponding $SF_6$ units with regards to the technical parameters, such as service conditions, insulation levels, mechanical loads and arc fault protection level. Moreover, there is a benefit for ITs with CA insulation in respect to low temperature application even below -50°C since there is no liquefaction of CA. Applying gas insulated technology with explosion proof housing, composite insulator and rupture disk an explosion proof design can be realized which fulfils the highest protection class II and protection stage 2 according to IEC 61869. For CA technology the rupture disk design was adapted to the higher filling pressure and faster and higher pressure-rise compared to $SF_6$ gas. The higher and faster pressure rise is related to different gas dynamics and power dissipation of the arc discharge in CA. The arc fault behaviour of the 420 kV VT was proven by an internal arc test with an arc current of 80 kA.

Figure 2: 420 kV VT after internal arc fault test with 80 kA and properly triggered rupture disk.

## 2.4 72,5 kV GIS with Clean Air (CA) insulation and VIU for Wind Turbine Generator

In cooperation with the manufacturer of the wind tower generator equipment the clean air GIS is continuously enhanced. The main improvements from the initial installation in 2017 [16] are as follows:

- 31.5 kA qualification including cable compartments accord. to IEC 62271-200 for the Internal Arc Qualification (IAC) fault current with a duration of not less than 1 s.
- 60Hz qualification
- Implementation of view ports according to IEEE markets.
- Seismic qualification for Asia Pacific accord. to IEC 62271-207




| | | |
|---|---|---|
| Rated voltage | up to | 72.5 kV |
| Rated frequency | | 50 / 60 Hz |
| Rated short-duration power-frequency withstand voltage (1 min) | up to | 140 kV |
| Rated lightning impulse withstand voltage (1.2 / 50 μs) | up to | 325 kV |
| Rated continuous current | up to | 1250 A |
| Rated short-circuit breaking current | up to | 31.5 kA |
| Rated peak withstand current | up to | 85 kA |
| Rated short-time withstand current (up to 1 s) | up to | 31.5 kA |
| Internal arc classification of HV cable compartments | | IAC A FLR 31.5 kA, 1 s (acc. IEC 62271-200) |
| Leakage rate per year and gas compartment (type-tested) | | < 0.1 % |
| Driving mechanism of circuit-breaker | | stored energy spring |
| Rated operating sequence | | O-0.3 s-CO-3 min-CO |
| Interrupter technology | | vacuum |
| Insulation medium | | clean air |
| Weight of $SF_6$ or other fluorinated greenhouse gases | | 0 kg |
| Global Warming Potential (GWP) | | 0 |
| $CO_2$ equivalent | | 0 kg |
| Rated filling pressure | | 0,56 MPa abs |
| Ambient temperature range | | -30 °C up to +45 °C |
| Installation | | indoor |
| First major inspection | | > 25 years |
| Expected lifetime | | > 50 years |
| Standards | | IEC / IEEE |

Other values on request

Figure 3: Technical data of 72,5 kV GIS with clean air insulation and VIU for wind tower installation

## 3. ON-SITE INSTALLATIONS AND OPERATIONAL EXPERIENCES

### 3.1 SPEN: Installation of 145 kV Clean Air (CA) Vacuum Live Tank Circuit Breaker (CB)

Ofgem (Office of gas and electricity markets) act as the independent energy regulator in Great Britain and its role is to protect energy consumers by ensuring they are treated fairly and benefit from a cleaner, greener environment. RIIO-T2 is Ofgem's second set of price controls implemented under the Electricity Transmission price control model for the period from 1 April 2021 to 31 March 2026 (called RIIO-T2). They incentivise Transmission Operators (TOs) to reduce emissions of harmful greenhouse gases. This includes emissions of $SF_6$ and other insulation and interruption Gases (IIGs) to support the transition to low greenhouse gas alternative IIGs. TOs must report annually on their $CO_2e$ emissions due to leakage of IIGs and receive a reward or penalty for the deviation from their baselines. This is applicable to any IIGs with a Global Warming Potential (GWP) of 1 or greater. The cost of greenhouse gas (carbon) emissions associated with dielectric gas leakage over the lifecycle of the equipment is based on the current UK Government Greenbook, set an annual carbon price at £248/t$CO_2$ in 2022, rising to £378/t$CO_2$ by 2050. It is intended to push the market towards a lowest overall cost solution, which accounts for the social and environmental impacts of greenhouse gas emissions.

SPEN have decided to adopt a global leadership position as part of its sustainability strategy to be Net Zero in Europe by 2035.

The reduction on the use of $SF_6$ is an important part of the RIIO-T2 Business Plan and implicates a commitment that every opportunity is used to apply alternatives and $SF_6$ equipment will only be added to the asset base where there is no other alternative. In case of 145 kV equipment, SPEN have declared that all new switchgear installed shall be $SF_6$ free. At higher voltages, SPEN also committed to employ $SF_6$ free switchgear when this becomes commercially viable. This commitment is expected to avoid installing an additional 9.700 kg of $SF_6$ during the period of RIIO-T2.

To date SPEN have commissioned 12 vacuum circuit breakers 145 kV at six sites across Scotland, England and North Wales after a successful trial of first installation in Scotland in 2019. The physical dimensions and mass of the vacuum circuit breakers are similar to the existing designs of $SF_6$ and air blast live tank circuit breakers in the network so the construction work involved to replace existing circuit breakers with vacuum circuit breakers is minimal. In many cases it is possible to utilise the existing foundations or structures. Figure 4 shows an example where this vacuum circuit breaker has been used to replace an older air blast circuit-breaker in the distribution network operator (DNO) business area in North Wales. The vacuum circuit breaker was mounted on the existing concrete structure and no additional civil works were required. The existing CTs on site were re-utilised without having to be relocated. This was the first deployment of $SF_6$-free 145 kV circuit-breaker by a UK DNO.

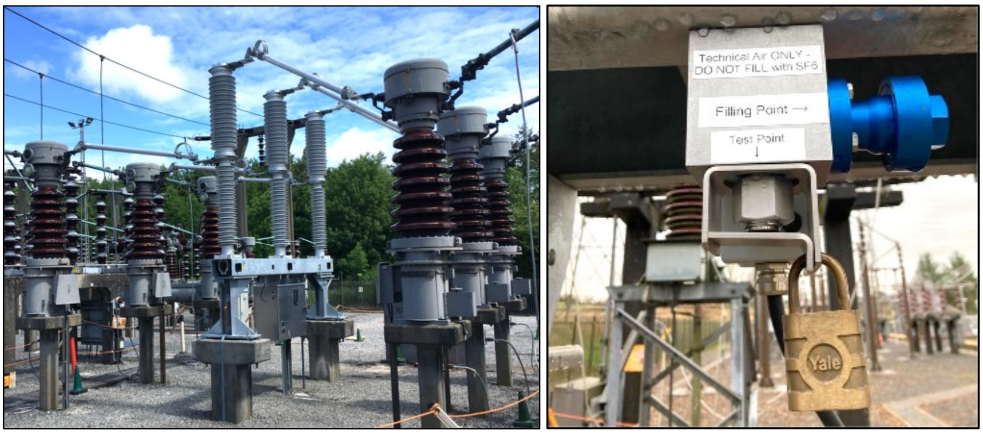



Figure 4: Left: Installation of  vacuum CB on existing foundations; right: Unique filling flange for CA

The UK DNOs and TOs have agreed a standard for sizes and identification of gas filling vales for $SF_6$ and alternative IIGs. These are fitted to equipment to avoid operators using the incorrect gas when gas handling operations are being carried out. In case of CA, the valve type used is a DN20 with M50 thread in anodized blue aluminium with a cap (see figure 4). The UK IEC NC proposed to consider that approach to standardize within TC 17. Preparation of a proposal is planned for the end of 2022.
The commissioning tests carried out on the vacuum circuit breaker are practically identical to those employed for $SF_6$ types.  This includes, main contact resistance, timing tests and gas alarm tests. The purity and moisture content of the clean air is checked using similar methods to that used for $SF_6$ checks and is carried out using readily available instruments. Gas handling precautions to ensure the safety of personnel are similar to those that are employed when handling $SF_6$, so there is no re-training of personnel who already are certified to handle $SF_6$.
The EU F-Gas Regulations 517/2014 is not applicable to products using CA. Unlike $SF_6$, CA does not need to be recovered and can be released directly into the atmosphere. Since DNOs and TOs only need to report gas emissions where the GWP of the IIG used is 1 or greater, there is no requirement to report emissions for clean air equipment.
SPEN have over 40 years' experience in the use of vacuum interrupters at medium voltages up to 36 kV and their use at voltages in this range is well established. Field experience of vacuum interrupters demonstrates high reliability, and they are considered to be "maintenance-free". Extension in application of vacuum interrupters at high voltage range is considered to be a natural progression.
In figure 5 an example of a fault record is shown caused by a single earth fault at an overhead line. The fault current of approx. 8 kA was interrupted after 80 ms by the protection system based on digital distance protection and CB. The break time of the CB was approx. 45 ms [17]. This fault record of the 145 kV CA vacuum live tank circuit breaker shows no difference to an interruption with a SF6 CB.

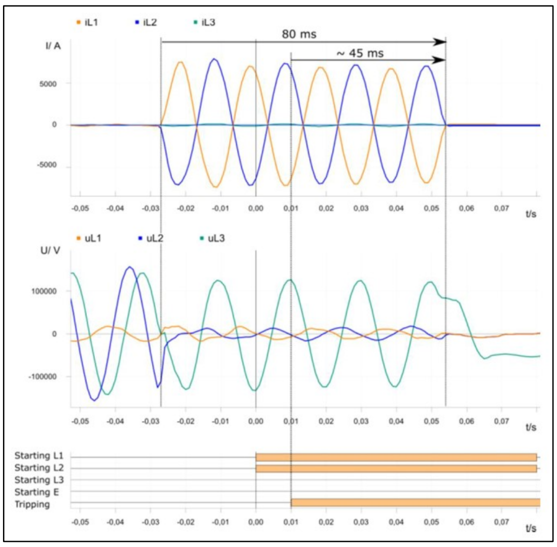



Figure 5 : Example for fault record ; Tracks: Currents, line to earth voltages, binary signals [17]

### 3.2 Siemens Gamesa Renewable Energy (SGRE): Installation 72,5 kV Clean Air (CA) GIS

SGRE is the manufacturer of wind tower generators (WTGs). For offshore applications, looking into the area of High Voltage equipment, it is a natural step to consider improvements of the switchgear design and the reduction of $SF_6$. Therefore, the use of $SF_6$ - alternatives, such as CA introduced for 72,5 kV GIS motivates to use that type of equipment in offshore wind turbines, to reduce the use of greenhouse gases.
The main requirement to the manufacturer of WTGs is to minimize the time for installation of the WTG. In contrast to onshore application the planning complexity is much higher. Weather conditions and the availability of installation vessels (ships) are the main factors for planning and executing the installation. To realize the tight installation time window the manufactured equipment, must be available on time at the pre-assembly. The design of the equipment needs to be suitable to withstand offshore conditions and being easy to handle.
The application of CA in the GIS brings the benefits, as CA is easier to handle without restrictions, compared to $SF_6$ gas that has limits on the amount of $SF_6$ gas you can transport, how to store and handle this and how to register the use. This improves the logistical work on site, when handling CA.

In order to achieve the requirements, the following aspects were considered to qualify the GIS:

- Fully tested GIS, ready to be installed w/o any additional testing offshore, except minor commissioning steps at final installation site
- Compact design: All functions are integrated in one gas compartment (see figure 3)
- Suitable design for installation: Cable terminal box with outer cone design suitable for cable T-plugs, which are fast and easy to install, with good access (see figure 7) and enables also a compact design, since up to three T-plugs can be attached to one bushing
- GIS is designed in accordance with IEC 60502-2 and can be VLF (very low frequency) tested.
- Vibration and shock tests according to IEC 62271-203/207 Class 2M1, respecting the loads from transportation on land and on ship from the harbor to the wind park (wave effect), and the vibration from operation of the WTG
- Corrosion class C4 high accord. to ISO 12944, since saline environmental condition
- Sea Packaging with drying agent to ensure moisture less than 60% for transport and storage

For offshore GIS installation there are two scenarios that are usually used for wind turbine application.

- GIS installed in transition piece (TP) (see figure 6)
- GIS installed in wind turbine tower

Both solutions come with advantages and disadvantages, but the main target from manufacturer of WTG perspective is to handle the Gas filling in the TP or Tower, while this is located at land at low level.

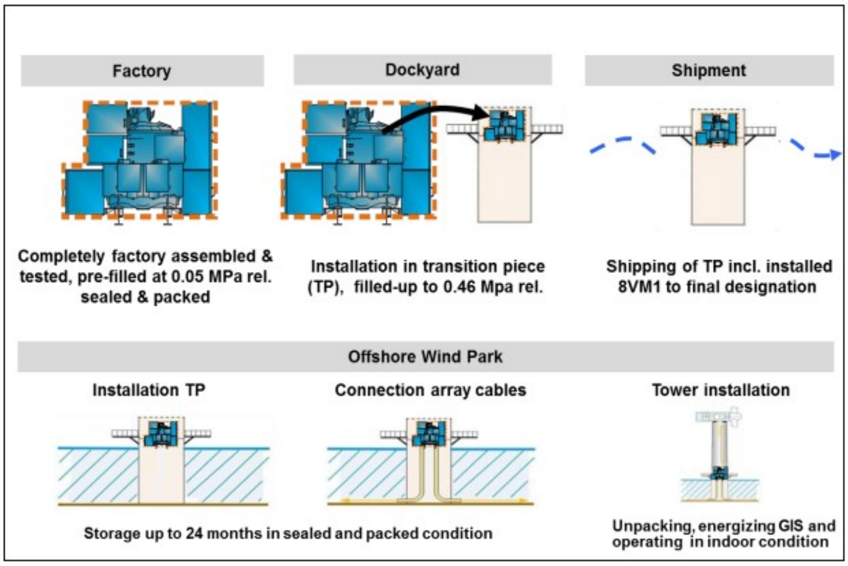


Figure 6: Left: Schematic sequence of transportation and installation of GIS in transmission piece (TP); Right: Lower area - mounted sea cable T-plugs, upper area – mounted surge arresters T-plugs

SGRE have installed the 72,5 kV Clean Air GIS unit worldwide in four different countries from the beginning of the first 66kV project in Denmark in 2017 and based on that experience the equipment has to date proved to be stable, with next to no operational issues and no major failure occurred.

### 3.3 Amprion: Installation of 420 kV voltage transformers with Clean Air (CA) insulation

Amprion is one of four German transmission system operators (TSOs).
Due to the network expansion, an increase in gas-insulated equipment and switchgear and the associated gas volume is expected, and a long-term corporate strategy to reduce the amount of $SF_6$ is pursued. Part of this strategy is the sensible use of alternative insulating gases with a Global Warming Potential (GWP) $\leq 1$ where it appears to make strategic and technical sense.
Since $SF_6$ has been used for many years, expertise has been built up in the company in the filling and maintenance of $SF_6$-insulated equipment as well as in the handling of this insulating gas, this generates requirements for the use of alternative insulating gases.
The availability of 245 kV and later 420 kV voltage transformers with CA insulation provided the opportunity to gain initial experience with this alternative insulation technology in line with its corporate strategy.
This includes compatibility and usability in existing and planned substations with regards to electrical characteristics and mechanical dimensions and weights. Furthermore, the same normative requirements and existing specifications and internal standards were applied. In addition, the transport and installation on site should not be different from a $SF_6$ filled device. Finally, the filling process as well as the control of the insulating gas should be comparable to the $SF_6$ filled equipment.
All these requirements were successfully implemented in the initial application of the 245 kV voltage transformers with CA. After passing all the requirements and tests stipulated by the specification and standards, which must also be met by every $SF_6$ filled equipment when it is first approved. A uniform gas handling system was further coordinated with the manufacturer and the other German TSOs. The existing and proven filling and test systems were introduced with unique connections for filling and maintenance to avoid any confusion or use of incorrect gases. DN20 filling connections with M50x2 thread (see also Figure 4) has been specified for CA and DN8 with M30x1,5 thread couplings for the maintenance and test connections. Filling onsite is carried out by trained internal personnel in consultation with the manufacturer, and the existing equipment was expanded to include filling fittings for CA and adapted measuring devices for pressure and dew point.
The commissioning tests are carried out according to the same procedure as for $SF_6$-instrument transformers. Here, the measured filling overpressure and the displayed value on the density monitor are compared, the alarm values are checked, and the gas humidity is determined.
Since the first procurement in 2018 and initial installation in 2019 more than 24 units for 245 kV have now been successfully in operation since 2019 without any abnormalities.
The 420 kV voltage transformers were also successfully qualified and tested in 2020 according to the described procedure and the first units have been in operation in the substation “Meckenheim” since spring 2021.
The company’s long-term goal is to have alternatives with an insulating gas with a GWP of less than 1 available for the entire portfolio in use, particularly the 245 kV and 420 kV combined transformers.

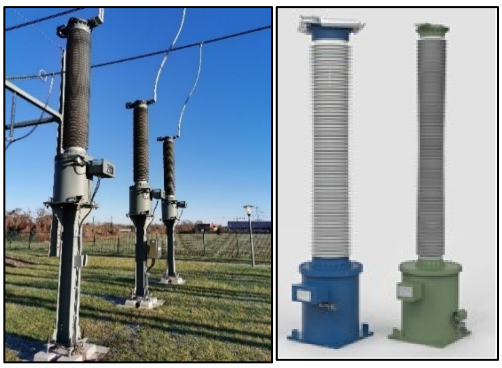


Figure 7: Left: 245 kV Clean Air VT at substation Wambel (source Amprion); Right: Comparison of Clean Air (blue) und $SF_6$ (green) 420 kV VT

## 4. TECHNOLOGICAL OUTLOOK

**Clean Air vacuum circuit breakers:** Vacuum switching technology combined with CA insulation yields a highly performant, environmentally benign and maintenance free solution replacing $SF_6$. For rated voltages up 245 kV (170 kV already available at the market) single break VIUs are under development. For rated voltages up to 550 kV and beyond multiple break concepts are under consideration. This principle can e.g., be used for metal enclosed and live tank circuit breakers [18].

**Clean Air GIS busducts:** 420 kV busduct design is successfully type tested. First 3 projects will be executed in 2022 including the biggest substation Daxlanden in Germany (GIB length 4000 m) [19].

**Clean Air instrument transformers:** 245 kV CT and 245 kV Combined CT / VT were type tested. 420 kV CT and 420 kV Combined CT / VT to be type tested in 2022.

## 5. CONCLUSION

There is an increasing number of Clean Air installations in grids worldwide. No major failures have been reported. Portfolio enhancements with continuous user feedback were performed. Future applications are under development.

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