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PS2 Impact of Net Zero on the Lifetime Management of SF_6 filled equipment

Dual-gas concept and design compatibility between SF_6 & SF_6-free GIS products

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SUMMARY

Replacement of SF_6 in high voltage equipment has accelerated in the last years. C4-FN gas mixture has shown the ability to replace SF_6 for GIS applications up to the highest ratings.

Some regulations have started to consider threshold on GWP to define which solution is the most suitable to replace SF_6 and mitigate climate change. While GWP is a correct criterion when considering the sole gas contribution to the global warming, a HV switchgear is much more than just a gas and all other impacts related to the complete HV switchgear components must be considered. These uncertainties on regulations are questioning users when making decisions. Some are delaying they shift to SF_6-free solutions, others are continuing investment in SF_6 switchgears, putting additional tons of SF_6 on their assets for the next 40 years!

To cope with these uncertainties and various users' expectations, authors have developed a dual-gas concept, meaning products able to be operational under SF_6 or C4-FN gas mixture whatever the gas.

New products with specific design rules are today available or under development to propose such a solution, from 72.5 kV to 550 kV levels, including switching devices. C4-FN gas mixture has similar behaviour than SF_6, allowing to achieve same ratings with same size of GIS. This paper is introducing this dual-gas concept and present the ability of new products to be filled in SF_6 or C4-FN gas mixture It is giving latest update on regulation and their impact of SF_6-free GIS developments, it explains how the dual-gas concept works and its main advantages. It also explains the different steps to follow when switching from SF_6 to C4-FN gas mixture.

KEYWORDS

GIS, gas-insulated substation, GIL, gas-insulated Line, SF_6 alternative, dual-gas, C4-FN, fluoronitrile, regulations, retrofit

1 Introduction

Replacement of SF_6 in high voltage equipment has accelerated in the last years and C4-FN gas mixture is confirmed as best candidate to replace in a short term period SF_6 on all complete range of GIS (from 72.5 kV up to 550 kV).

Some regulations have been recently put in place (like CARB in California) or are under revision (like F-gas in Europe). This creates some uncertainties and raises some questions to the users when making decisions. Some are delaying their shift to SF_6-free solutions, others are continuing investment in SF_6 switchgears, putting additional tons of SF_6 on their assets for the next 40 years. Fortunately, a growing number of users are not waiting for regulations to be settled and they are shifting right now to SF_6-free solutions, as developed today by manufacturers.

In order not to delay all these strategic investments and to get prepared to this important change and switch from one gas to the other when users are operationally ready, the authors have developed a dual-gas concept, meaning products are able to be operational under SF_6 or C4-FN gas mixture whatever the gas.

This concept is detailed in this paper, with a special focus on the 420 kV GIS which takes benefit of this solution.

2 Latest update on regulation and their impact of SF_6-free GIS developments

Regulations handling SF_6 and its alternatives are usually included in global regulations addressing a broad range of equipment and not considering the specificities of high voltage switchgear.

Therefore, some regulations have started to consider threshold on the gas global warming potential (GWP) to define which solution was the most suitable to replace SF_6 and mitigate climate change. GWP is a correct criterion when considering the sole gas contribution to the global warming, but a HV switchgear is much more than just a gas. As the gas is acting as insulation medium, it is having significant impact on its size and its embedded carbon. Several papers based on Life Cycles Assessment analysis have evidenced that, indeed, having the lowest GWP for the gas is not leading the lowest CO2 emissions when considering the equipment lifetime from cradle to grave [1], [2].

One of the main regulatory move in this field is under discussion in the European Union. In April 2022. EU Commission issued a proposal of regulation to limit, if not ban when alternatives are available, the use of SF_6 for medium and high voltage switchgear.

This proposal has included a criterion based on the sole GWP to define which type of gas shall be selected. A threshold at 10 was introduced without considering the impact of this choice on the complete switchgear and not considering the global carbon footprint.

Feedbacks were given by the main stakeholders on EU portal in June 2022. This proposal of threshold at 10 was not welcomed by associations of users like ENTSO- E recommending to keep only the GWP limit <2000, or Eurelectric asking to "Revise the GWP (Global Warming Potential) threshold from 10 to 1000 for voltage levels above 24 kV".

In addition, manufacturers of MV and HV switchgear, via their association, T&D Europe, reminded that the climate change benefits of any alternative shall be considered taking into account the full product and not only the gas contribution via its GWP: "… Life Cycle Assessment (LCA) method according to ISO 14040/44 is the state-of-the-art tool to evaluate the impact of products and systems on the environment. The GWP of the gas alone does not enable to assess the global carbon footprint of the electrical switchgear …"

At the time we are writing this article the process of revision of the European regulation on F-gases is still on the way. It is expected to be finalised by the end of the year 2023.

3 Dual-gas concept, what is it and how it works

To cope with these uncertainties and various users' expectations, authors have developed a dual-gas concept, dual-gas concept GIS means that these gas-insulated products can be operated with either SF_6 or SF_6-free gas mixture.

Therefore, GIS is considered as dual-gas if it can be used in the same conditions either with SF6 or its substitute, and if it can be switched from one gas to the other without any dismantling of main components (like active parts, switching elements, sealings, enclosures, etc). Only secondary components linked to gas managements (typically filling valves and adsorbers) have to be changed and adapted to the corresponding gas. As an example, a TSO can buy the SF_6 version today and can easily switch at later stage from SF_6 to SF_6-free solution. This change can be made during project execution or even after its installation at site.

This is today achievable (except for circuit breakers) if we use alternative gas having similar insulating behavior as SF_6 and similar pressure. It means that we can achieve same ratings with same size of GIS. From the authors perspective, C4-FN gas mixtures are today considered as the good candidates to allow dual-gas concept in next generation of GIS.

The following figure shows the scalability of C4-FN for all voltage range of GIS applications. It confirms that the gap with SF_6 is small and can be managed in a reasonable way as detailed later in the paper. It also shows that this dual-gas concept cannot be implemented with other SF_6-free solutions based on dry air insulation media. This scalability phenomena and technology difference was detailed in CIGRE 2022 paper [3]

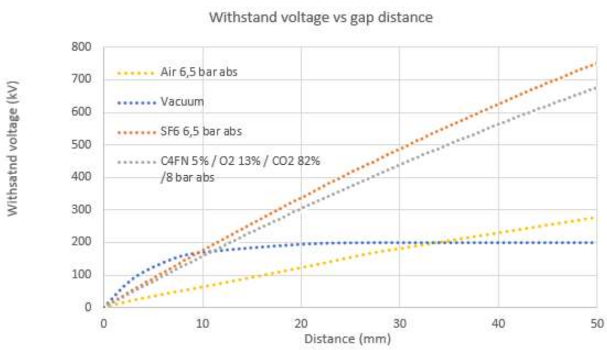


Figure 1 – Dielectric withstand with SF_6 and C4-FN mixture

From design point of view, dual-gas concept adds some constraints that need to be considered from the beginning of the development and that lead on specific technical choices.

GIS products performances are widely depending on the insulating properties of the gas. Changing the gas, especially from SF_6 that is considered as an excellent gas for HV performances, is significant.

Designing dual-gas GIS products requires to update or define new design rules, in order to manage insulating, thermal and switching performances.

This is for example key aspect to achieve some specific performances for induced current switching on earthing switches, bus transfer current switching on disconnectors, or continuous current tests.

More details on performance demonstration with dual-gas product are shown for 420kV GIS in CIGRE 2023 paper n°130 [4]. In this paper, we can see that dual-gas products require the validation of the performances for both gases. This is generally made during the same type tests campaign to optimize the R&D project efficiency.

The figure below shows how tests could be handled on a disconnector to manage both gas performance demonstrations during a type test campaign

Figure 2 - Dual-gas three-phase disconnector arrangement during a type test campaign with SF_6 and C4-FN gas mixture, during power test (left) and during dielectric condition check (right)

Globally dual-gas GIS product based on C4-FN gas mixture will use similar design concept as for SF_6. Some optimisations on the shapes, on material selection or on other parameters are needed to insure reliable behaviour of the product in all conditions. This specific design approach is described hereafter for the major GIS components.

3.1 Design of dual-gas passive elements

GIL up to 420kV filled with g^3 (a C4-FN mixture) are existing since 2016. This first generation of SF_6-free GIL was using SF_6 designed GIL product. The same components and therefore same diameter of enclosures were kept and to reach same level of performances (dielectric and continuous current), only the pressure of the insulating gas was increased [5].

The following figure shows the comparison of dimensions between first SF_6/C4-FN (4%) GIL with new dual-gas GIL SF_6/C4-FN (5%) and also with dry air (technical air) solutions [6], Dimensions of dry air solutions are 50% higher than SF_6 solutions and therefore 50% bigger than C4-FN solutions.
New generation of dual-gas GIL SF_6/C4-FN (5%) propose much lower filling pressure than its first generation, and even lower than a typical Dry Air GIL.

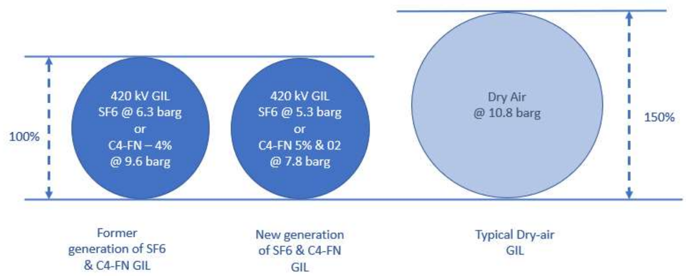


Figure 3 - Comparison of 420 kV GIL related to the type of gas.

This dual-gas approach with same dimensions and "reduced" pressure will help to better manage the reliability of the product under site operating conditions (tightness, cleanliness, temperature…).
For example, studies [7] already demonstrated in SF_6 that increase of pressure within HV equipment will increase the dielectric withstand in clean conditions but also increase the sensitivity to particles that could be introduced during site erection operations. Higher pressure can lead paradoxically to lower voltage withstand in polluted conditions in SF6. The same was observed (Figure 4) during investigation tests in C4-FN mixture. Meaning that a compromise is to be selected for dual-gas products to well manage the mix between dielectric withstand in clean conditions with both types of gases, SF_6 and C4-FN gas mixture, and the sensitivity to potential particles present in the HV equipment with the same gases.

The following figure shows the effect of pressure with some particle intentionally introduced in a mock-up using C4-FN gas mixture as insulating gas.

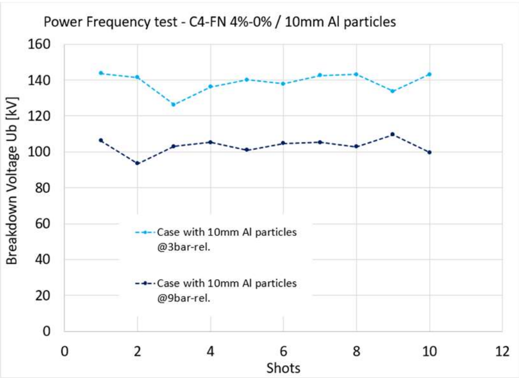


Figure 4 - Influence of pressure on dielectric withstand in polluted conditions.

3.2 Design of dual-gas disconnectors and MID

As for the other components, dual-gas disconnectors are using similar design concept as for SF_6.
Only specific solutions on arcing area are today needed to withstand bus transfer current switching performances at high voltage level during the lifetime of the disconnectors. These solutions are fully compatible with SF_6 and allow standardisation to reach the goal of dual-gas approach when using either SF_6 or C4-FN gas mixture.

The following figure show simplified design used in current SF_6 solution and in dual-gas solution. Same principles are used to design the mobile side, the fixed side and the arcing contacts of the disconnector.

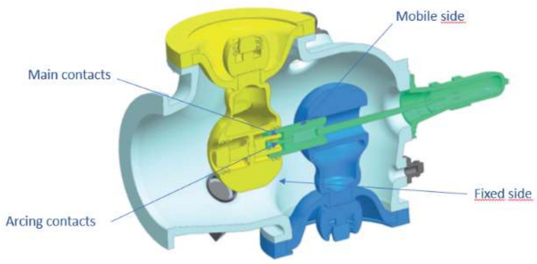


Figure 5 - SF_6 or dual-gas disconnector arrangement

For Maintenance Isolating Device (MID), dual-gas concept is also applicable considering that with new design rules, same elements can reach the required performances both with SF_6 and C4-FN gas mixture.

The MID design is integrating the dielectric gap of the disconnector, and as it has no switching performances requirements (no bus transfer performance), it is a pure dielectric design with no need for the specific arcing contact.

The performances of disconnector have been validated for both SF_6 and C4-FN gas mixture at 420kV voltage level according to IEC 62271-102 standard [8]. For instance, bus transfer performance of 3000A and 25 V has been achieved for both SF_6 and SF_6-free gases. More details on results of tests on disconnectors for both gases are given in [4]. Figure below show the test in dielectric laboratory of the capacitive switching test.

Figure 6 - Bus charging test in laboratory performed on both gases.

3.3 Design of dual-gas earthing switches

Dual-gas earthing switches is following the same standardisation principle. Compared to classic SF_6 design, a small device to improve gas flow around the arcing contacts, is today needed to meet induced current switching performances with C4-FN gas mixture. This adapted design is fully compatible with SF_6 and allows us to standardise the solution for both gases.

Performances are today validated for both SF6 and C4-FN mixture at 420kV voltage level with induced current and voltage values higher than IEC 62271-102 standard [8] to cover specific country specifications. More details on tests results and tested performance are given in [4].

Figure 7 - SF_6 or dual-gas earthing switches arrangement during induced current test in laboratory

3.4 Design of dual-gas voltage transformers

Dual-gas GIS product based on C4-FN gas mixture is also able to use the same voltage transformer for both gases. Tests were performed on a classic SF_6 designed voltage transformer to check compatibility with C4-FN up to 420kV as show on next figure.
The complete IEC test sequence was successful, and 1st flash-over occurred only during research limit at +1575kV (instead of 1425kV required by IEC), meaning more than 10% extra margin.

Figure 8 - SF_6 or dual-gas voltage transformer arrangement in test laboratory

Standardization of RCVD and LPIT for both gas solutions is still under review and will need additional time to confirm or not the dual-gas concept for these devices.

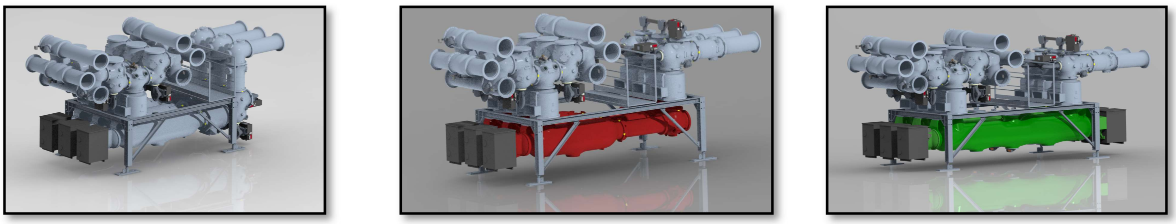
3.5 Specificity of circuit breakers and consequence on full bay arrangements

Circuit-breaker is a major component of the bay for which the replacement of the gas from SF_6 to C4-FN with only minor design modifications is not possible. The equivalence of dielectric performances between the gases is not sufficient to cover a full equivalence in switching. Fortunately, the dedicated C4-FN circuit-breaker design offers the possibility for an easy change with SF_6 circuit-breaker in the GIS bay, using a "convertible" configuration as detailed later in the paper.

The consequence of this specificity of circuit breaker for dual-gas concept is that 3 main bay arrangements are needed to handle all request of users.

The figure below shows examples of typical bay arrangements with dual-gas GIS product.

- Combined version is the most compact one. SF_6 circuit-breaker is combined with a bay that can be filled with SF_6 or C4-FN mixture. Switch from one gas to the other for the bay elements (except CB) is possible at any time with dual-gas products.
- Convertible version allows the user to start with full SF_6 bay or combined principle, and will allow to switch later to full C4-FN version.
- Full C4-FN version is entirely filled with C4-FN gas mixture. Switching back to full SF_6 is unlikely to happen, but possibility exists, considering the convertible configuration.



Combined version | Convertible version | Full C4-FN version

Figure 9 - Different possible bay designs at 420kV, with mixed SF_6 and C4-FN elements or with full C4-FN elements, including circuit-breaker

Dual-gas GIS products are today available or under development to propose such a solution, from 72.5kV to 550kV levels, including switching devices.

4 Main advantages of dual-gas products

4.1 Benefits of standardized product with both gases

We are facing a period of transition between SF_6 model and SF_6-free model. Manufacturers, users and regulators are moving progressively to SF_6-free solutions but at different pace.

Dual-gas concept mean standardization of a product for both SF_6 and SF_6-free applications. The advantages for such standardization are:

- Same GIS elements except circuit breakers
- Same gaskets
- Same enclosures
- Same accessories except valves (but could be mounted on service module to ease the change)
- Same densimeters (digital sensor could be used to switch from one gas to the other without dismantling)

At the end, this approach offers lots of advantages to users and manufacturers especially during this period of transition.

4.2 Benefits for users

For the users the identified main benefits are:

- Regulation evolution management: risk is reduced by the fact that initial decision can be made based on one gas (like SF_6) and then decision for alternative gas can be made at later stage during the course of the project.

- Operational maturity management: new gas mixture means new knowledge for operators, new trainings and new tools. Therefore, some additional investments are in the balance. Dual-gas concept allow user to manage this important adaptation in parallel with their project roadmap. For instance, training to the equipment like switching device is done once and valid for both gases (except for the CB).

- Overall footprint of the GIS (see figure 10): some projects are planned long time in advance and changing the overall footprint of a substation to include SF_6-free solution may not be possible in the timescale of a project planning. This dual-gas solution gives some flexibility in the decision process and is not compromising choices made previously based on one or the other solution. A simple fallback solution exists without impacting the planning approval process.

- Delivery model and quality insurance: dual-gas GIS product allows the same delivery model up to 420 kV as done today for SF_6 products. Meaning that the size of the GIS is the same and that the delivery in full bay assembly is still possible (see figure 10). So, quality check at factory is still done before delivery and gives the benefit already observed for all SF_6 GIS products up to 420kV. Figure below shows that the overall footprint of a fully assembled dual-gas GIS bay (green) is comparable in terms of dimensions with the current SF_6 420kV GIS bay.

- Spare-parts: standardized components for SF_6 or C4-FN applications allow user to reduce their own stock of spare-parts and allow a better reactivity from supplier to procure spare in case of urgency.

- Extension of existing GIS equipment of similar design and refurbishment of GIS sections: some operations like replacement of busbar sections can even be envisaged to reduce the carbon footprint of the GIS substation at later stage. For instance, some 420 kV elements (typically complete busbars with common points) of current SF_6 type GIS can be replaced by new dual-gas elements as they are compatible in terms of footprint.

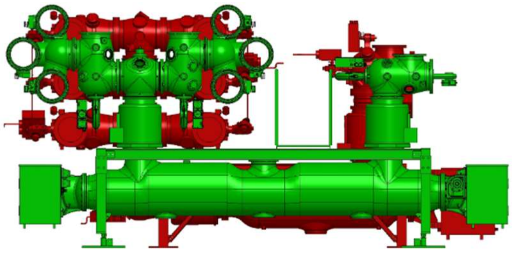


Figure 10 - Comparison of current 420 kV SF_6 bay (red) and dual-gas 420 kV SF_6/g[3] bay (green).

4.3 Benefits for the manufacturing unit

For the manufacturers the identified main benefits are:

- Keep efficient industrial processes and at the end ensure same quality level as SF_6 products, same lead time and same competitive advantage for the benefit of the users
    - Same parts for SF_6 and SF_6-free products, means that thanks to standardization, they can optimize logistic flow
    - Same parts for SF_6 and SF_6-free products, means that they benefit from scale effect during procurements
    - Same product for SF_6 and SF_6-free products, means that they can produce GIS using the same tools, assembly processes, routine test equipment, production lines
    - Same product for SF_6 and SF_6-free products, means that they can use the same packing and delivery model at each voltage level

5 Steps to follow to switch from SF_6 to SF_6-free gas mixture with a dual-gas product

Dual-gas concept means that we can switch from one gas to the other without big constraints. We are detailing here, based on the example of the 420kV GIS product, how it is possible to switch from SF_6 to C4-FN gas mixture (most logical evolution with such dual-gas products).

5.1 Starting from "Combined" version of GIS

The "combined" version of 420 kV bay is the most compact design available in full SF_6 that could offer the possibility to switch later to C4-FN for the bay components, but not for the circuit-breaker.

By using dual-gas GIS at 420 kV, we remove 15% of SF_6 in the typical bay shown below compared to current SF_6 solution

When doing the switch from SF_6 to SF_6-free solution with a dual-gas GIS at 420 kV, we remove 60% of SF_6 in the typical bay shown below. This is not considering GIL element on the feeder side (for instance busduct elements going to the gas bushings or to the power transformers). It means that this reduction of SF_6 mass could reach 95% for example for the same bay with linear 300m of GIL

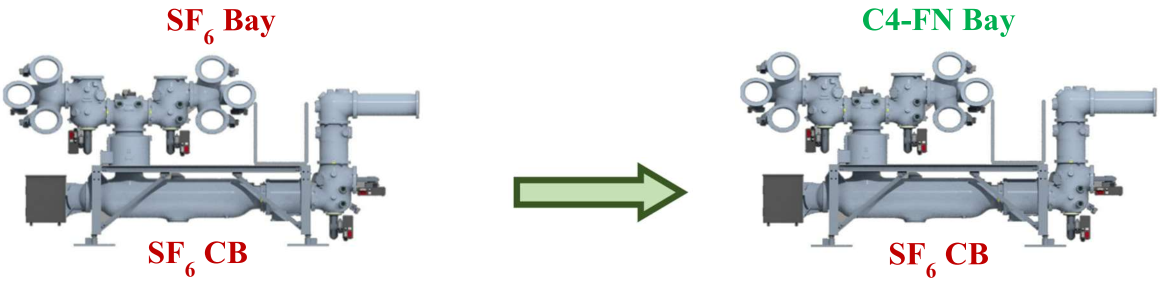


Figure 11 - Combined GIS switched from SF_6 to C4-FN gas mixture

Operations to be done to switch from SF_6 to SF_6 free:

- Outage of the substation
- SF_6 gas treatment (removal)
- Change of some accessories linked to gas management:
    - Filling valve according to discussions in progress at IEC TC17 [9] (poka yoke defined to prevent gas operation mistake)
    - Molecular sieves
    - Conventional densimeters (if digital sensors are not used to monitor the gas)
- Gas monitoring digital system setting
- C4-FN filling and retrofill commissioning

5.2 Starting from "convertible" version of GIS

The "convertible" version of 420 kV bay, with a limited initial impact on the SF_6 bay size, offers the possibility for an easy change at later stage to full C4-FN GIS.

Thanks to C4-FN properties and strong R&D efforts, the 420 kV C4-FN circuit-breaker could be designed with the same width as the SF_6 circuit-breaker. Based on initial "convertible" bay SF_6 design, the change of the breaker to C4-FN is transparent for the bay: only the circuit-breaker itself is replaced, with no change on the support structure for instance. The accessibility of the breaker allows the removal of the SF_6 version to the C4-FN version with no dismantling or removal of bay elements.

When doing this switch, we remove 100% of the SF_6 contained in the typical bay shown below.

The figure below shows how the "convertible" solution is the only known technical solution available that has so minimal impact on the GIS substation, to move from SF_6 to an alternative gas offering much lower carbon footprint.

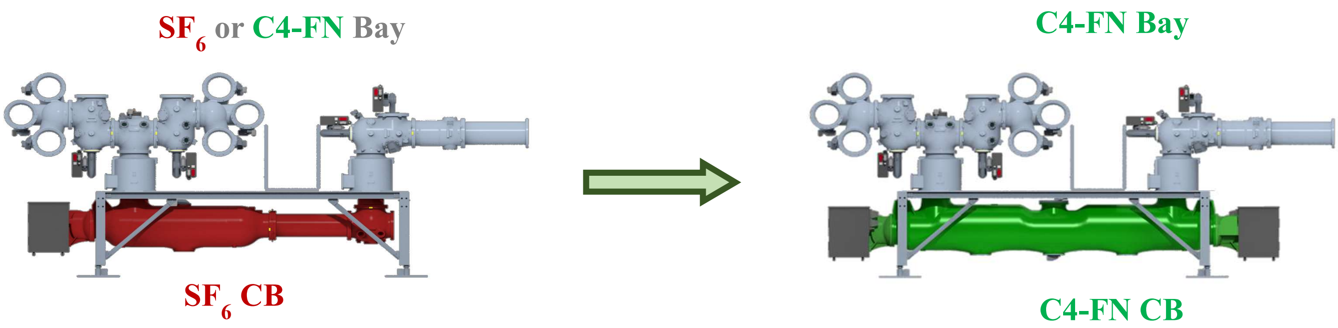


Figure 12 - Convertible GIS switched from SF_6 to C4-FN gas mixture

Operations to be done to switch from SF_6 to SF_6-free:

- Outage of the substation
- SF_6 gas treatment (removed)
- Change of Circuit Breaker
- Adaptation of low voltage control cubicle for circuit breaker purpose
- Change of some accessories link to gas management:
    - Filling valve according to discussions in progress at IEC TC17 [9] (poka yoke defined to prevent gas operation mistake)
    - Molecular sieves
    - Conventional densimeters (if digital sensors are not used to monitor the gas)
- Gas monitoring digital system setting
- C4-FN filling and retrofill commissioning

6 Conclusions

Time is running to limit the global warming effect on the planet and quick shift to SF6-free alternatives is of prime importance.

For GIS equipment below 170 kV, the shift started already some years ago and different technologies exist, giving the choice for the users to select one or the other.

When dealing with voltages equal and above 170 kV, only C4-FN has demonstrated the capability to cover full scope of performance of current GIS product range. GIL projects at 420 kV and up to 63 kA have been implemented with this technology since 2016. New projects are in progress for full scope of GIS.

However, some regulations are on the move and not all users are willing to select SF6-free solution right now.

The dual-gas GIS concept offers them the possibility to start right now their investment while keeping the choice to move to C4-FN gas mixture at later stage (during contract execution or even later in service).

This paper is describing the advantages such solution offers and gives some key indications how to manage projects for a smooth but secured transition to SF6-free solution using C4-FN gas mixture with a dual gas GIS product.

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