Paper No: 130
A3/B3 Colloquium 2023
PS1 - Emerging Substation & HV equipment strategies to deliver the transition to a low carbon future

Update on the development of 420 kV GIS Substations switchgear using environment friendly C4FN / O_2 / CO_2 gas mixture

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SUMMARY

245 kV and 420 kV substations represent more than 65% of the installed SF_6 gas [1] on the grid in Europe. A large plan in Europe and in the United Kingdom consists in refurbishing existing substations and installing large number of new assets to support the integration of renewable energy. A successful elimination of SF_6 can only be done by applying SF_6 alternatives at these voltage levels.

Following the successful completion of the LIFEGRID project aiming at the development of a 420 kV 63 kA Circuit breaker, the demonstrated ratings of the circuit-breaker and corresponding performance will be described.

An outlook on the bay and circuit-breaker architecture will be introduced to underline the benefit and robustness of the design.

An update on the type tests and performance available with the bay elements will also be exposed.

Disconnector bus transfer and bus charging current switching characteristics will be detailed with a comparison between the existing SF_6 and the g^3 (C4FN based gas mixture) versions.

Then, the available performances of the fast-earthing switch for induced current switching beyond IEC standard requirements will be detailed.

Finally, an outlook of the progress of the first installation of the complete 420 kV GIS substation installation will be shown.

The 420 kV GIS g^3 Bay and Circuit-Breaker developments are now completed and type-tested. This opens the way to an eco-friendly, complete, economical, viable and immediate SF6 abandon.

KEYWORDS

Substations, HV Equipment, High Voltage – Circuit Breaker – Disconnector – Earthing switch – SF_6 alternative – Decarbonisation – 420 kV – Europe – EU LIFE program – Switchgear – C4FN – g^3 - Fluoronitrile

1 Introduction

SF_6 elimination from transmission systems is today a major concern for system operators to limit the climate impact of the grids.

The energy transition together with the need for existing assets replacement is generating a large demand for new substation equipment installation.

To be consistent with the emission reduction targets set in most regions of the world, the low carbon generation shall also come together with low carbon emission grids.

In Europe (including UK), especially the massive introduction of renewables requires the development and reinforcement of the grid. The backbone of the system is the 420 kV voltage level and at this level new and upgraded substations are flourishing at a never seen before pace.

245 kV and 420 kV voltage rating network represent an overall 15% of the installed number of assets, however they contain up to 65% [1] of the installed SF_6 gas.

It is planned that by 2030 the overall banked SF_6 amount could double without SF_6-free solutions. Up to 67% of the 245/420 kV will be new equipment [1] and will be in energised for several decades.

Therefore, a true transition away from SF_6 can only happen if higher ratings are addressed with complete solutions especially for GIS substations which require large quantity of insulating gas. These solutions have to be ready now to avoid a massive additional SF_6 installation.

C4FN-based gas mixture called g^3 is used in HV electrical equipment that have proven to be scalable and viable SF_6-free solutions. They represent the lowest carbon footprint possible [2] [3] with best compactness, reaching SF_6 performances for insulation and arc interruption [4] and have proven to be applicable for all 420 kV substation component [5].

The purpose of this paper is to update on the availability of the fully type-tested g^3 420 kV GIS substation solutions which included Gas Insulated line (GIL), Bay components (Busbar, Disconnector and earthing switch) and Circuit-Breaker.

2 420 kV Circuit Breaker:

To achieve a complete solution applicable at all European transmission voltages levels, 420 kV 63 kA switchgear (circuit-breaker, earthing switch, and disconnector) is the main chain-link to accomplish the demonstration that C4FN equipment can substitute SF_6 across the whole grid.

To accelerate the development of high voltage SF_6-free switchgear, the European Commission has partially funded the development of the C4FN based 420 kV 63 kA GIS Circuit-breaker under its LIFE Climate action program called LIFEGRID (LIFE18 CCM/FR/001096) [6] aiming at the completion of the 420 kV 63 kA GIS interrupter in 2022. The research program initiated in 2019 reached its objectives as planned end of 2022 demonstrating all required performances. The prototype used during the research phase [5] was industrialised and the final version of product is now type-tested.

This final update will detail the comprehensive set of tests and performances executed allowing for a full elimination of SF_6 in 420kV networks allowing a true transition towards low carbon grids.

2.1 Performances

2.1.1 Circuit-breaker ratings

The standard requirements from IEC 622271-1 [7], IEC62271-100 [8], IEC62271-101 [9] IEC 62271-203 [10] and IEC62271-110 [11] were applied.

The executed type-tests have been performed in accordance with IEC standards basic requirements applying the following standard ratings:

U_r =420 kV, 63 kA, 50 Hz, k_{pp} =1.3, k_c = 1.4, k_{op} = 2, M2 & C2 class

The g^3 gas mixture that was used has the following composition: 5% C4FN, 13% O_2, 82% CO_2.

A double chamber circuit-breaker has been developed. One chamber of this double break is being implemented in the 245 kV bay and will shortly be available.

2.1.2 420 kV Circuit breaker type tests:

Covering the 420 kV IEC standard, the development and testing phase in C4FN was conducted and successfully achieved the following type tests: T10, T30, T60, T100s, T100a, L75, L90, OP2, LC/CC.

The double-chamber architecture gives solid strokes synchronisation all along the opening or closing operation, and this in several arcing conditions (including full $63kA_{RMS}$ fault).

Low current faults such as T10 or T30 with strong du/dt and high TRV peak are covered with margin thanks to the double break architecture. Hot gas management was optimized to maintain high compactness and ensure voltage withstand to the ground for the highest current faults and voltages.

Figure 1: GIS 420kV Circuit-breaker C4FN at CERDA test Laboratory

The apparatus is equipped with internal grading capacitors for voltage repartition between the two chambers. Grading capacitors for C4FN double chamber are the same as for SF_6 double-break in terms of value and tolerance.

In addition to an equal voltage distribution, they assist the interruption process of short line faults. Therefore, these faults known for being severe for the gas circuit-breaker aren't a major threat for this architecture which demonstrated significant margin.

A comparison between the type tests executed on the full pole of the 420 kV C4FN product with the existing SF_6 state-of-the-art circuit-breaker arcing window range is proposed.

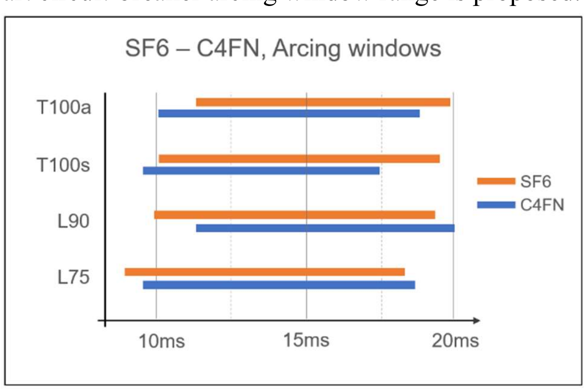

Figure 2: C4FN & SF_6 – 420 kV Arcing windows

It confirms that little difference exists between the existing arcing windows known for years in SF_6 and what is demonstrated with C4FN mixture.

2.1.3 GIS 420kV – Voltage condition check after breaking

The voltage conditions check after making and breaking tests was conducted on a prototype including additional shots during the test sequence (erosion at least 25% higher than the required one by IEC standard). The pole was subject to 8 times L90 (56.7 kA) interruptions prior its voltage condition check.

Test was first carried out as per IEC sequence, with 80% of the rated switching impulse withstand voltage (SIL) with five impulses of each polarities withstood. The dielectric investigation continued and even reached the full SIL value (100%) with a complete demonstration (5+/5- shots), under heavily worn conditions with the corresponding arced gas.

This confirms again the robustness of the technology overtime and regarding the electrical endurance. It also confirms again that the lifetime limit of a C4FN circuit breaker will never be reached with the gas composition change but as in SF_6 on the arcing contacts or PTFE parts wear. Therefore, no specific maintenance plan is required regarding gas quality rather than equivalent to what was already existing in SF_6.

2.1.4 GIS 420kV – Depollution stage

The apparatus presents a strong electrical endurance after complete L75 & T100a single phase test sequence, including additional shots. The commutation contacts show clean surface without advanced wear and neither abnormal roughness, in addition of neat and controlled erosion on arcing contacts (smooth surfaces), even from an apparatus performing 14 interruptions of L75 & T100a 63 kA.

Figure 3: After complete L75 & T100a test sequence - Arcing contacts

A limited amount of solid by-products is observed at the bottom of the tank and the majority of which being collected in dedicated particle traps.

2.2 420 kV Bay Layout

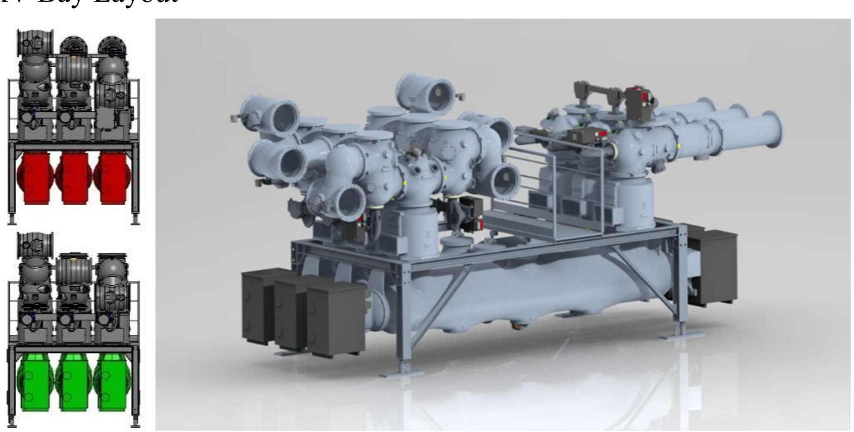

Figure 4: Left: same bay width (SF_6(red) and C4FN (green)) – Right: full 420 kV / 63 kA C4FN bay layout

2.2.1 Circuit-breaker design

With SF_6, it is common to have single interrupting unit designs for 420 kV / 63 kA ratings. But it took decades to reach this level of mastery. In the 2020s, time-to-market is shortened with C4FN mixtures in comparison with early years of switchgear development with SF_6. The knowledge of SF_6 design rules is partially reusable. Also, even if C4FN is relatively new, the other gases composing the mixture have already been experienced in switching and dielectrics.
Nevertheless, it remained very challenging to develop a 420 kV / 63 kA breaker with C4FN within a few years, meaning simultaneously facing the stresses from high voltage and from high short-circuit current level.
Based on the progresses observed recently in switching performances with C4FN, there is no doubt it is achievable to reach 420 kV / 63 kA ratings with a single break interrupter design. The decision was made to use first a double break technology, as it was the best option to propose an alternative to SF_6 in the shortest possible time. And it also offers synergies with 245 kV ratings.

2.2.2 Double chamber interrupter

Multiple break designs with grading capacitors are very common, and they are still mandatory when going up to very high voltage levels where no other solution exist. Double break interrupters have proven their reliability in AIS and GIS.
One main concern of multiple breaks versus single breaks is not really the reliability, but the size. For sure, the circuit-breaker itself with double break C4FN is longer than its equivalent in SF_6 with single break design. But thanks to its optimized architecture [5], the full GIS bay is not bigger than the current SF_6 420 kV bay. C4FN 420 kV bay is not only as compact, but also as accessible as the SF_6 bay.

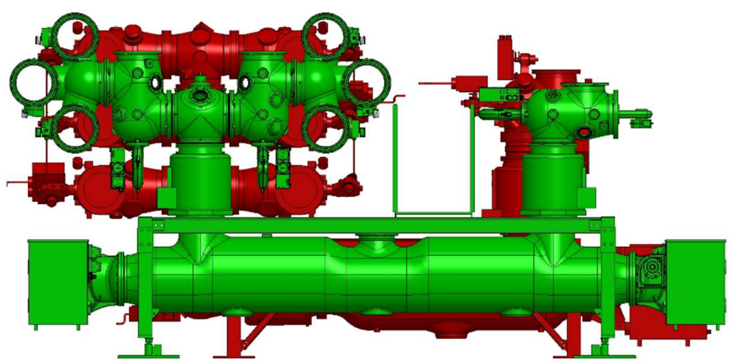

Figure 5: Comparison of SF6 bay (red) and full-C4FN bay (green)

The C4FN bay is not only as short in length as SF_6 bay (Figure 5), but also as narrow in width, which is a key parameter for a shipment perspective. Indeed, keeping the same baywidth (Figure 4) as the SF_6 solution allows a full bay shipment, synonym of higher quality thanks to a reduced amount of site erection activities. As for the SF_6 variant, the C4FN breaker is fully routine tested and sealed at factory with its tight partition insulators, and not reopened at site.

2.2.3 Double drive solution

What is noticeable in the 420 kV C4FN breaker design is the use of two drives per phase. Breakers with multiple drives have existed on the market for decades. There are various reasons for such choice.
When the technology is high energy demanding, like with puffer-type breakers, one single drive may not be sufficient to provide enough power for several chambers. But this is not the case for the double-break C4FN, where each chamber is not requiring more energy than a usual 245 kV / 63 kA SF_6 breaker. So, the energy for double-break C4FN is not more than of usual SF_6 double-breaks of same range.

A reason for using a double drive can also be a matter of space and mechanical efficiency. For instance, at 800 kV and above in AIS, there are several chambers in series, and the motion inlets of each column are distant of several meters from each other. For a 4-break (2 times T-shape design) at 800 kV (Figure 6) in terms of energy it would be achievable to use one single operating mechanism, but it would not be optimal for a mechanical aspect.

Using a single drive would mean adding several meters of rigid linkage between the columns, in addition to the already long insulating rods. Risk of buckling leads to the need for big cross-section linkage, meaning heavier parts with more inertia. In the end, using one single mechanism instead of two can require much more than two times the energy of each mechanism. And the bigger they are, the less reliable the drives are. The drives used on double-break C4FN have low energy levels and are already widely used on existing SF_6 HV switchgear. The return of experience on performance, reliability, interrupters synchronisation and site operability is very positive.

Figure 6: example of an 800 kV Live Tank AIS 4-break design with 2 drives

Another reason for the use of a double drive arrangement (Figure 7) is compactness and accessibility. Single drive design does not offer so many options. The mechanism is either connected to the middle point (in between the two chambers), or at one end.

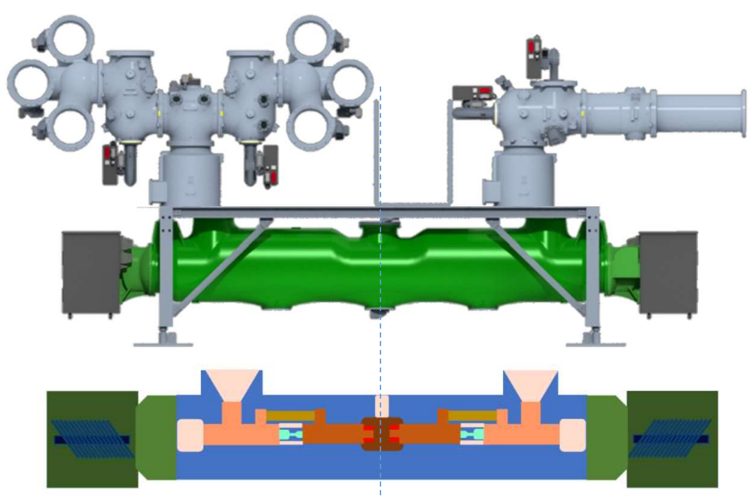

Figure 7: double break double drive chosen design with symmetrical arrangement

For obvious mechanical efficiency and reliability (as said above with buckling issue), a drive has to be connected as close as possible to the motion inlet.

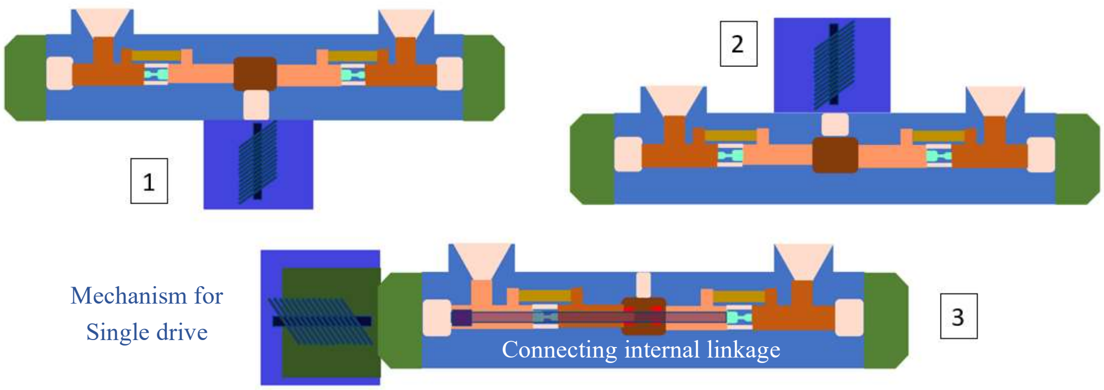

Figure 8: Alternative Circuit-breaker architecture - 1: double break design with drive connected at middle point, above enclosure - 2: double break design with drive connected at middle point, below enclosure - 3: double break design with single drive connected at one end

With a middle point inlet, it means a drive either above or below breaker enclosure.
Above drive as per Figure 8-1 is interfering with drive and bay accessibility, by condemning the catwalk.
Drive below enclosure as per Figure 8-2 means much higher bay and building. It also renders the full bay shipment impossible.

In-line single drive connected to one end of the enclosure means not only bigger mechanism, but as well additional internal mechanical linkage to operate the distant chamber. As it can be seen on Figure 8-3, such design is not symmetrical anymore regarding middle point. The distant chamber may not have exactly same behavior as the chamber close to the drive. Asymmetrical design may lead to different behavior depending on the terminal at which a fault is located.
Last but not least, internal linkage to operate distant chamber leads to unavoidable larger enclosure. Such linkage needs space and shielding. Either inside or outside the active part with its exhaust volumes, it makes the chamber bigger which means larger enclosure.

Double drive design is mandatory to keep same bay width as SF_6 solution, and to keep the quality benefits of the full bay shipment.

2.2.4 Performances with double drive.

Double drive design was fully tested as per IEC and fulfills the requirements. Each operating mechanism owns its own tripping coils, and they are connected in series to guarantee synchronization of the chambers, in addition to adjustable linkage for fine tuning. Series connected coils also prevent the operation of one single chamber only. Adjustable linkage design is same as commonly used for GOP (gang operated poles), when three phase breakers are operated with a single drive.
The required accuracy of mechanical setting between the two chambers for C4FN is same as for SF_6 technologies. Multiple breaks using vacuum interrupters are known to require very accurate settings to have exact same arcing time on all chambers. Otherwise, the post-arc current generates unbalanced voltage split with dramatic consequences on voltage distribution [12] and corresponding performances. Unbalanced voltage split resulting from arcing time offset is not affecting C4FN. As explained in contribution at Paris 2022 session [13] [14], “Despite larger post arc currents, it is possible to reach the highest ratings with C4FN / O_2 / CO_2 as it was the case in SF_6.”

“Negligible differences can be observed across the arcing window at a given fault current between the 3 arcing times post arcs. Negligible differences are observable for both L75 and L90. As a result, a small offset in the opening times of both interrupting units will not impact the post arc current. Therefore, the voltage distribution benefit offered using grading capacitors will be preserved in C4FN / O_2 / CO_2 even in interrupting conditions.

The double-break and double-drive design offers multiple advantages including short time-to-market and compactness.

3 420kV Bay

420kV Bay elements were developed to achieve dual gas performance:

- 5% C4FN/ 13% O_2/ 82% CO_2 at 7 bar relative rated minimum temperature -25°C.
  and
- SF_6 at 4.5 bar relative rated minimum temperature -30°C.

Type tests of disconnector and earthing switch were performed simultaneously on two poles with the same design each pole with the corresponding mixture, the poles showed similar performances regarding switching capability.

3.1 Disconnector

3.1.1 Bus transfer current switching test (BTCS)

Bus transfer current switching tests at 3000 A -25 V were performed on the disconnector according with IEC 62271-102 standard [15]. The disconnector successfully interrupted during all sequencies. Arcing and pre arcing lengths for these tests are shown in Figure 9 for both C4FN mixture and SF_6, the arc lengths are short, and they remain stable during the full sequence.

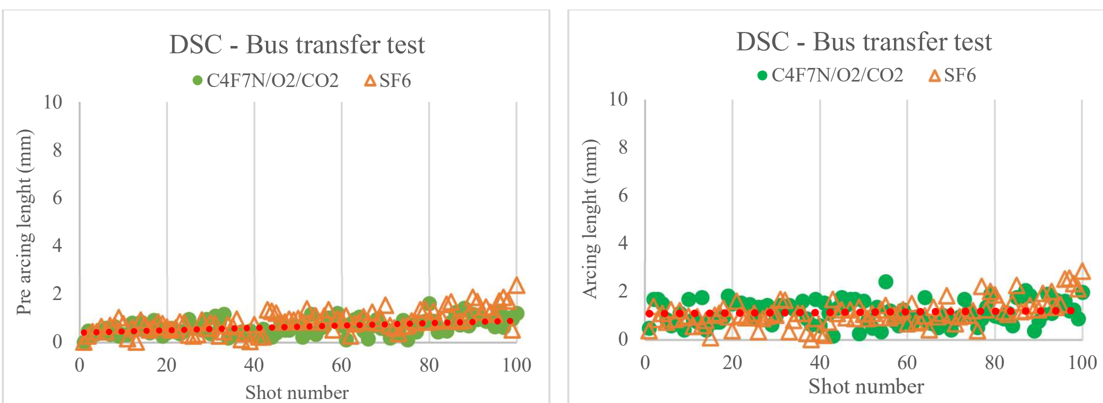

Figure 9: Arcing & pre-arcing length while bus-transfer test

The wear on arcing contacts is similar for both poles gases as visible on Figure 10.

Figure 10. Wear while BTCS test - C4FN/ O_2 / CO_2 (to the left) & SF_6 (to the right)

The increase of contact resistance after tests is less than 3% for C4FN pole and less than 4% for SF_6 pole, both values are below the maximum 20% allowed by the standard. Dielectric check tests at 80% and 100% of rated short time power frequency withstand voltage were also validated on both poles.

3.1.2 Bus charging current switching test (BCCS)

BCCS TD1 test duty was performed on one pole of the same 420 kV disconnector with the previous mixtures. This test represents the switching capability of very short portions of busbar ducts. It demonstrates the dielectric performance of the disconnector during capacitive current switching while experiencing Very Fast Transient Overvoltages.

Figure 11 shows the capacitive withstand voltage of the disconnector ΔU with the two gases as a function of arcing time for opening operations and pre-arcing time for closing operations, these curves are useful to predict the trapped charge left by the disconnectors and control the maximum arcing times [16].

The tested gases behave identically in the same disconnector design. No flashover to the tank was observed during these tests.

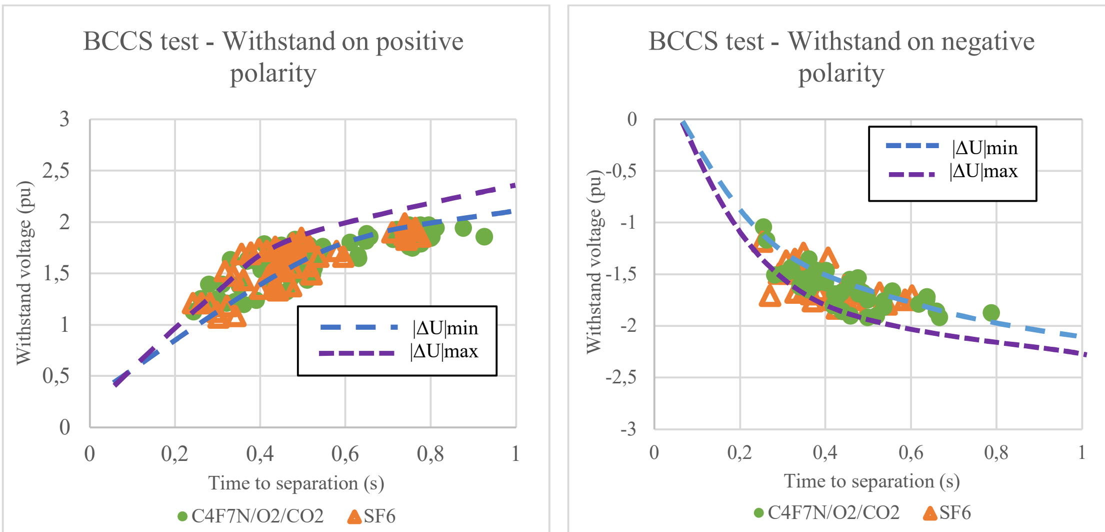

Figure 11: Breaking voltage during TD1 test

After opening operation, the last arc extinction traps a DC voltage into the short portion of floating busbar, Figure 12 shows the trapped voltage distribution left by the disconnector during the tests, it is similar between both gases.

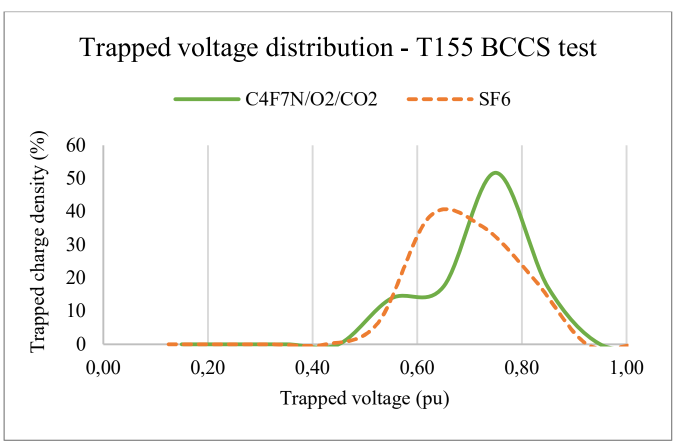

Figure 12: Trapped voltage distribution after TD1 opening operation

Long exposure pictures were taken during opening and closing operations to check the placement of arc foots. The arcs are effectively contained between the arcing contacts.

3.2 Fast earthing switch (FES)

Induced current switching performance was demonstrated with industrial version of 420 kV earthing switch in both C4FN / O_2 / CO_2 mixture and SF_6. The earthing switching integrates a device to improve gas flow around the arcing contacts [17].

Test have been performed with current and voltage values higher than IEC standard [15] to cover specific country specifications are listed in Table 1.

Table 1: ICS rating for 420kV FES

ICS ratings for 420kV FES	IEC 62271-102 specification	Tested values
Electromagnetic coupling (EM) [A_{rms}/kV_{rms}]	160/10	500/10
Electrostatic coupling (ES) [A_{rms}/kV_{rms}]	18/20	18/27.5

Figure 13 shows the arcing times of electrostatic and electromagnetic induced current switching, the electrostatic induced current performance is the same on both gases. The arcing times for electromagnetic induced currents in C4FN mixture are slightly higher than in SF_6 but remain very short < 25 ms.

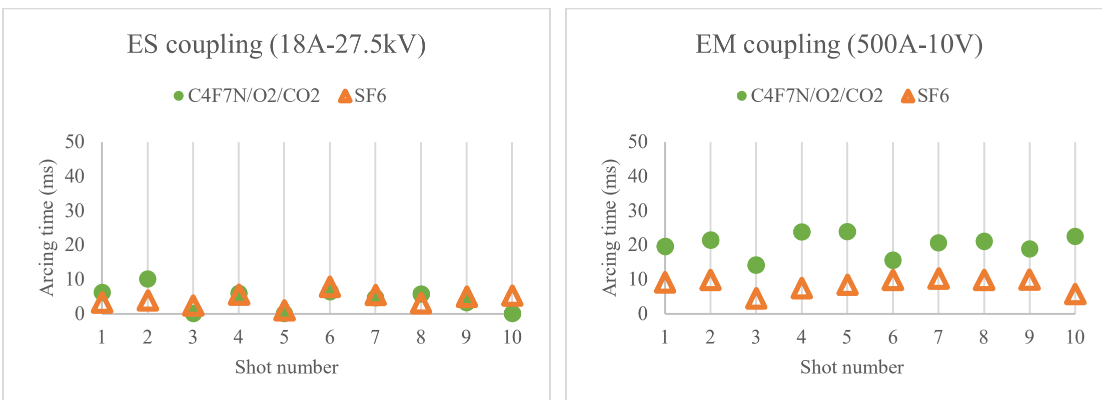

Figure 13: Arcing time during ICS tests

4 First installation

SSEN Transmission are responsible for the electricity transmission network in the north of Scotland and own and maintain AC (mainly 132 kV (145 kV), 275 kV (300 kV) and 400 kV (420 kV)) and DC transmission network in the license area. Delivery of net zero brings challenges to the electricity industry beyond generation: transmission asset owners must also look at their own CO_2e emission, and SF_6, with its extremely high global warming potential (GWP), is key part of this. Expectations for performances and technical requirements and achievements have been detailed in previous CIGRE publication [18].

After installing 420 kV GIL application without SF_6, the adoption of 420 kV GIS entirely without SF_6 represents a significant step in the development of the technology. One of the challenges of early adopter is to make sure the development is completed on time for project execution.

Close collaboration between the user and manufacturer assisted with this – a large amount of information on the existing "research" testing was shared. And overall, there was sufficient information to demonstrate that development and testing would be completed within the project program.

Thanks to the compactness design of the SF_6-free solution, the overall footprint of the solution adopted for Kintore substation is equivalent to the one if done with classic SF_6 GIS, as shown on Figure 14. This new architecture has been chosen to keep GIS footprint and at the same time a high level of accessibility and ergonomics for operation, maintenance, and repair. Access to drives, gas filling valve, gas monitoring, disconnector/earthing switch viewing windows have been checked using 3D CAD modelling. Coworking with the user teams validated this.
The project is progressing, and site work activity will start in 2023.

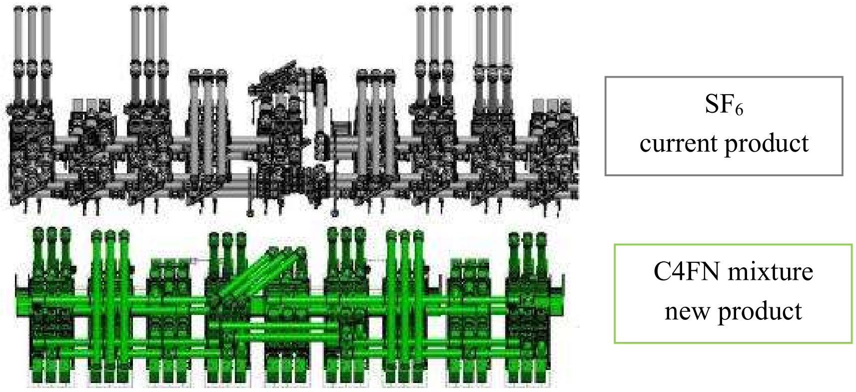

Figure 14: Kintore substation simulation with SF6 and C4FN mixture products to the same scale

5 Conclusion

A complete GIS 420 kV SF_6-free bay including circuit-breaker was developed and tested. Circuit-breaker, GIL, disconnector, and earthing switch have now demonstrated the complete set of performance with type-tests compliant with IEC standards.

Fully eliminating SF_6 in GIS substations at the highest European ratings has now become reality allowing a true drastic SF_6 emission cut.

245kV rated GIS products will shortly be available thanks to the already existing 245kV circuit-breaker and rapid adaptation of other bay elements with a new EU LIFE funding [19]

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