For power system expertise

Paper ID – 10848 **Session 2022**
Study Committee A3
PS2 - Decarbonisation of T&D Equipment

Switchgear scalability demonstration using environment friendly C4-FN / O_2 / CO_2 gas mixture in 420 kV GIS Substations

Cyril GREGOIRE*, Quentin ROGNARD, Thomas BERTELOOT, Diana LEGUIZAMON, Joël OZIL,
Samuel SOUCHAL, Félix BERNARD, Yannick KIEFFEL
GE Grid Solutions
France
cyril.gregoire@ge.com

SUMMARY

Sulphur hexafluoride (SF_6) has remained the preferred insulating and arc interruption medium for many years, particularly for high voltage equipment. Although SF_6 continues to provide the performance required for electric power applications, the industry has begun to install alternative technologies to overcome the environmental concerns associated with the long atmospheric lifetime of 3200 years and the highest known global warming potential of SF_6 of 23500 CO_2 eq. The fluoronitrile, said heptafluoro-isobutyronitrile ($(CF_3)_2$CF-CN, abbreviated as C4-FN and also called 3M™ Novec™ 4710 Insulating Gas, has been specifically developed in the purpose of SF_6 replacement for HV electrical transmission equipment. It is also identified in some publications as C_4F_7N or C4FN.

To be used in the High Voltage equipment, C4-FN has to be mixed with carbon dioxide and oxygen to achieve a performance comparable to SF_6.

As a new technology, the fluoronitrile and its admixtures also known as "g^3" have undergone extensive evaluation for both performance and safety in high voltage applications. The performance aspects of the technology have been reported in a number of publications and are well demonstrated by the installations currently operating on the grid. Consequently, this paper focuses first on the development of the C4-FN/O_2/CO_2 insulated 420 kV 63 kA GIS Circuit-breaker supported and co-funded by the European Commission under LIFE program and the Climate Change Mitigation sub-program, under LIFEGRID (LIFE18 CCM/FR/001096) project. The work specifically aimed at developing a half-pole of a 420 kV circuit breaker combining the most severe ratings of both 245 and 420 kV voltage levels introduced the major progress of the breaking unit development with all the major duties demonstrated. LIFEGRID project integrates then two 245 kV 63kA chambers in series in a double break architecture to reach the 420 kV rating offering a reduced footprint compared to its equivalent in SF_6. Secondly the paper presents the latest achievement with the fast-earthing switch and disconnector.

KEYWORDS

GIS, C4-FN, Fluoronitrile, Switchgear, Circuit-breaker, SF_6 alternative, Earthing switch, Disconnector, Scalability, 420 kV, LIFE program

1. Introduction

In recent years, extensive work has been done on SF_6-free gaseous environmentally friendly solutions presenting the advantage of a high dielectric strength and switching current capabilities close or equal to SF_6 with the benefit of a low global warming potential (GWP). Beyond SF_6, mixtures based on heptafluoro-isobutyronitrile ($(CF_3)_2CF$-CN, abbreviated as C4-FN), carbon dioxide (CO_2) and oxygen (O_2) have been recognized by regulators [14] as offering the capability to replace SF_6 while keeping the same benefits of compactness and performances and are an optimal solution for disconnector and circuit breaker applications. This specific gas mixture has been proved to meet requirements of minimum outdoor temperatures as defined in international standards (like -25°C or -30°C) features the same ratings and same dimensional footprint as the state-of-the-art SF_6 ones, with a drastic change of environmental impact: GWP (Global Warming Potential) is reduced by more than 99% compared to SF_6. The SF_6-free equipment portfolio is now enlarged, with equipment covering the HV range from 145 kV GIS to 420 kV GIL and 25 utilities have decided to move forward and to install equipment with this alternative gas that together will reduce the impact of the installed gas masses by more than 1,000,000 tons of CO_2 equivalent. These projects include more than 120 bays of 145 kV GIS, more than 5000 meters of 420 kV GIL. First applications are now commissioned and in service since 2017.
To go a step further on replacement of SF_6 in the Grid, we currently work on the capability to achieve in the 2020's the development of switchgear able to be applied on the highest voltage level of the European Grid where large amount of SF_6 is banked especially in GIS. A major milestone, paving the way of a complete SF_6 elimination, is the achievement of a 420 kV 63 kA Circuit breaker which represents the needed ratings of the European grid's backbone.

2. Circuit breaker

After several decades where multiple series breaks were needed, 420 kV SF_6 state of the art GIS circuit breakers are today realized using a single breaking unit using a self-blast-based technology.

As in SF_6, C4-FN-based gas mixtures do not show any scalability limits. This fundamental characteristic is the only path to achieve all high voltage ratings and is key to maintain dimensions and ensure a minimized footprint and cost of the switchgear. Figure 1 illustrates this behaviour for various insulating media:

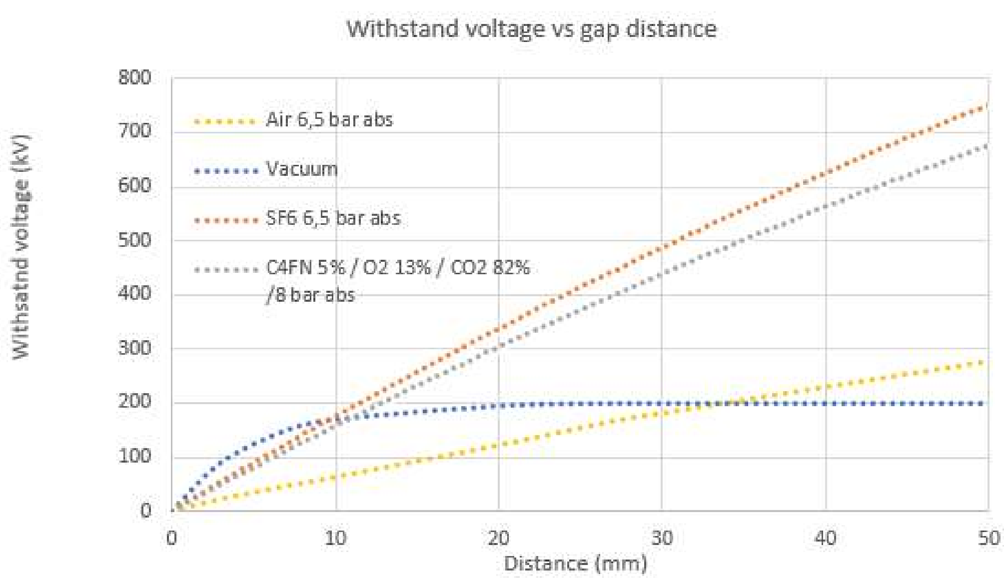


Figure 1: LI- withstand voltage vs electrodes gap distance for various insulation media: SF_6 [2], C4-FN 5 % /O_2 13%/ CO_2 82% mixture, Technical Air (79% N_2+ 21 O_2) [4], typical vacuum interrupter behaviour [3]- in slightly heterogeneous field

The gap distance increase offers a constantly and linearly rising dielectric withstand for SF_6 and C4-FN mixture. In the case of a 5% C4-FN gas mixture, chosen for the 420 kV circuit breaker development, an increase of the gas pressure at 8bar absolute allows to reach similar dielectric withstand compared to SF_6 existing switchgear. This offers the same scalability possibilities as the state-of-the-art SF_6 technology. The voltage strength of SF_6 and C4-FN mixtures linearly increases with gap length and pressure.

On the opposite, despite technological recent progress, vacuum interrupter faces physical limits towards high voltage ratings where the withstand voltage of vacuum for large gaps does not increase linearly with gap length. Figure 1 illustrates this saturated dielectric strength for typical medium voltage vacuum contacts [3] [8] [9] [10] [11]. Multiple breaks architectures are needed today to meet ratings at and above 145 kV with vacuum interrupters insulated with air resulting in large footprint, excessive costs, and limited overall climate impact improvement.

At the beginning of the project, both single and double-break architectures were studied and tested in the scope of the development of a 420 kV 63 kA breaking unit.
Single break testing confirmed that a 420 kV 63 kA is possible with design adaptations of the existing SF_6 breaking unit. Several test duties were investigated, and design optimization was done to achieve complete interrupting windows:

- Out of phase (OP2): 857 kVp achieved on single break interrupter,
- Terminal fault T100 63 kA: 630 kVp achieved on a single break interrupter,
- Short line fault with additional small capacitors achieved on a single break interrupter

This investigation phase clearly demonstrated the feasibility towards the development of a single break 420 kV circuit breaker.

However, the rising need for GIS SF_6-free solutions for both 245 and 420 kV applications and the market demand to have a complete product range pushed the strategy towards developing a breaking chamber to be used at both voltage levels (single break at 245 kV and double-break above). This allows the achievement of the highest possible 420 kV ratings and makes both products available in a short-term, avoiding large amount of SF_6 to be installed on the Grid.

The first part of the research work was focused on developing a half pole of a 420 kV circuit breaker combining the most severe ratings of both 245 and 420 kV voltage levels and the major progress of the breaking unit development with all the major duties were introduced and presented at Cigré 2021 [6].

The European Commission is currently co-funding the development of the C4-FN-based 420 kV 63 kA GIS Circuit-breaker under its LIFE Climate action program called LIFEGRID (LIFE18 CCM/FR/001096) [5] aiming at the completion of the 420 kV 63 kA GIS.

LIFEGRID project integrates two 245 kV 63 kA chambers in series in a double break architecture. Despite a double-break circuit breaker arrangement, the new complete GIS bay based on C4-FN gas mixture offers a reduced footprint compared to its equivalent in SF_6 [7].

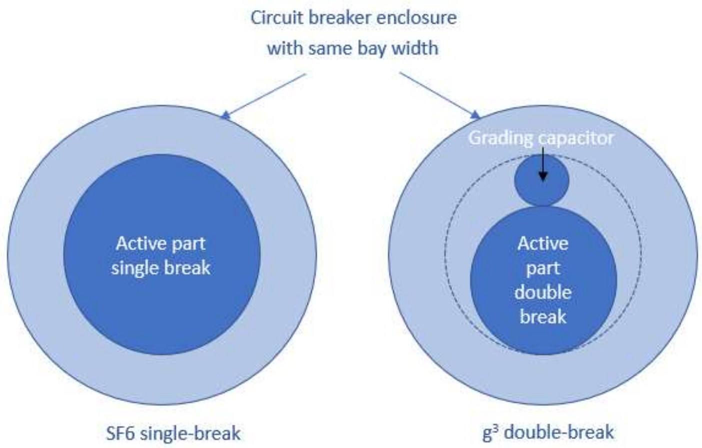


Figure 2: Cross section of the SF_6 (left) and C4-FN/O_2/CO_2 (right) circuit breaker offering the same bay width

As a result of innovative design progress in both the GIS bay and the circuit breaker, the bay width remains the same as the existing single break SF_6 architecture. Figure 2 shows a cross-section of the circuit-breaker illustrating the compactness of the active part for the double-break to maintain the same outer dimension of the enclosure.
245 kV interrupting unit offers the advantage to be more compact compared to the existing SF_6 single break version. This allows the integration of grading capacitors in the tank with no impact on the bay width. Such compact arrangement of the active parts of the circuit breaker generated constraints on the dielectric withstand design and on the breaking unit design with successful results as presented below.

a. Dielectric test results

The validation of the dielectric withstands of the new 420 kV 63kA C4FN-based circuit-breaker was done with the following gas mixture: C4-FN (5%) / O_2 (13%) / CO_2 (82%) at a pressure of 7 bar rel. Figure 3 exposes one pole of the circuit breaker which was subjected to dielectric tests and passed the following IEC 62271-203 [16] – 420 kV rating requirements:

- Power frequency 650 kV
- Combined Power Frequency 650 (+165) kV
- Switching Impulse 1050 kV
- Combined switching impulse 900 (+345) kV
- Lightning impulse 1425 kV
- Combined Lightning impulse 1425 (+240) kV

Figure 3 : 420kV GIS circuit-breaker prototype during dielectric test in High Voltage laboratory

Comfortable extra insulation margin was obtained with no flashover observed during the search for limits. Such results demonstrate the scalability of C4-FN insulation in compact switchgear architectures and the ability to reach the highest grid ratings worldwide.

b. Arc interruption behaviour comparison with SF_6

The arc quenching capability of C4-FN-gas mixture versus SF_6 was studied in order to assess if any distinctive behaviour was observed. This investigation was led on the 245 kV 63kA SF_6 original arcing chamber and its adapted version to C4-FN /O_2/ CO_2 (half-pole of a 420 kV C4-FN). As a reminder, stroke and speed are maintained identical between both interrupting units allowing a clean comparison of the arc parameters between both version of the apparatus. Necessary adaptations were brought to the arc breaking zone to adjust the breaking parameters to the alternative gas mixture properties in order to achieve favorable interruption conditions.

One important aspect of the quenching capability is the energy released by the arc. The arc energy is an intrinsic characteristic which defines the wear exposure of the breaking part and eventually establishes the electrical endurance of the switchgear. Figure 4 exposes the measured arc energy generated in both gases.

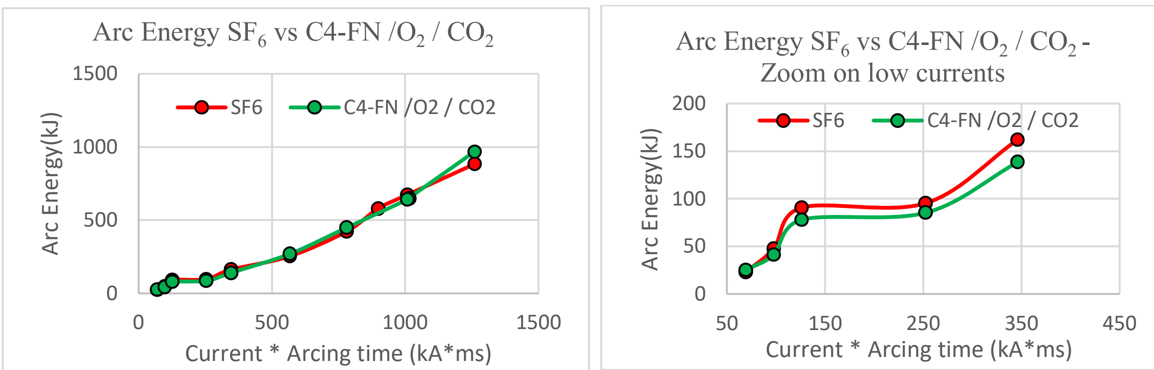
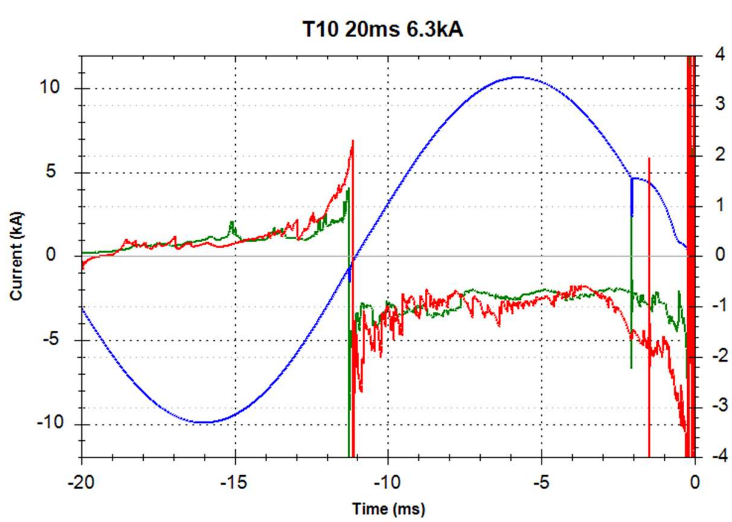


Figure 4: Arc energy as function of current amplitude and duration (left). Zoom on low arc energy (right)

The arc energy appears as very similar between the SF_6 and its C4-FN / O_2 / CO_2 mixture version. The arc energy tends to be slightly higher (+10%) for SF_6 for the lower current amplitude and slightly lower for the higher range of interrupted current. No significant difference exists in the overall released energy between both gases with the same clearing arcing windows.
Contact erosion and nozzle ablation which are limiting the lifetime of circuit breakers in both SF_6 and C4-FN/ O_2 / CO_2 are directly linked with the cumulated arc energy. Therefore, as the arc energy is the same, no change in the geometry variation along with the cumulated wear is to be expected with the change of gas.



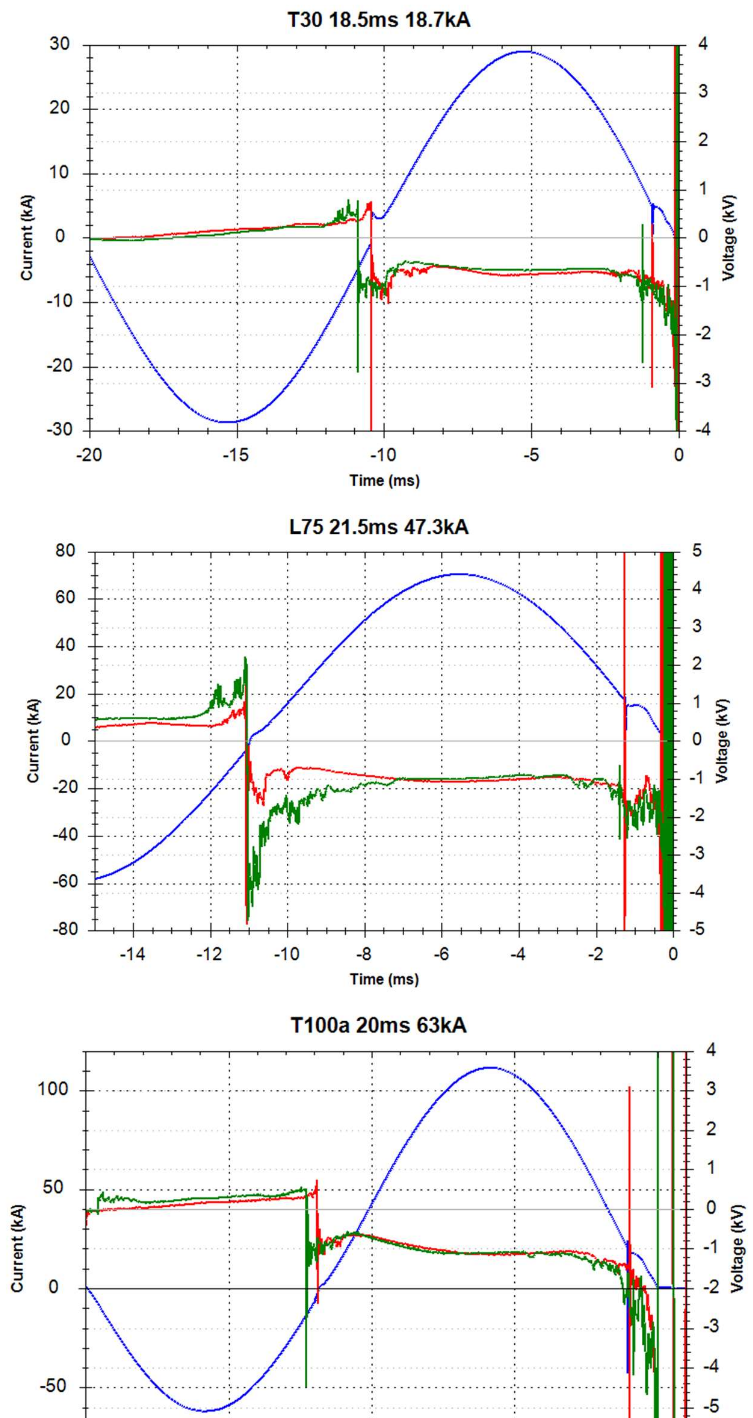


Figure 5: comparison of the arc voltage for different current level. Top:6.3kA, second 18.7kA, third 47.3kA, bottom 63kA. Interrupted current: blue curves, SF_6 5.1 bar relative arc voltage: red curves, C4-FN (5%) / O_2 (13%) / CO_2 (82%) 7bar relative: green curves

This can be explained by the fact that the established arc generally burns inside a PTFE vapor volume generated by the nozzles' ablation surrounding the arc. Therefore, the different gas flow behaviour can only be observed during the blast phase when the interrupting gas is blown on the arc. Figure 5 illustrates this aspect where it can be observed that around current zero the actual quenching gas properties impact the arc characteristics whereas during the high current phase, minor differences are detectable.

The observed difference in the arc voltage around current zero are related to the arc conductivity in the arc extinguishing phase which is related to gas flow conditions and gas characteristics.

Higher overpressure in C4-FN / O_2 / CO_2 are generally required to retrieve breaking performance similar to SF_6 [12][13]. These higher overpressures participate to the elevation of the arc voltage around arc extinction. Figure 6 illustrates this matter with overpressure comparison between SF_6 and C4-FN / O_2 / CO_2 on L75 duty at 47 kA.
The overpressure variation profile along the arcing times on several different designs shows higher overpressures on short and medium arcing times whereas long arcing times exhibit similar overpressure for both gases' versions.
The arc voltage extinction peak, which is closely related to the arc conductivity, exhibits an evolution following the overpressure profile explaining the arc voltage / arc energy profile difference between SF_6 and C4-FN / O_2 / CO_2 around current zero.

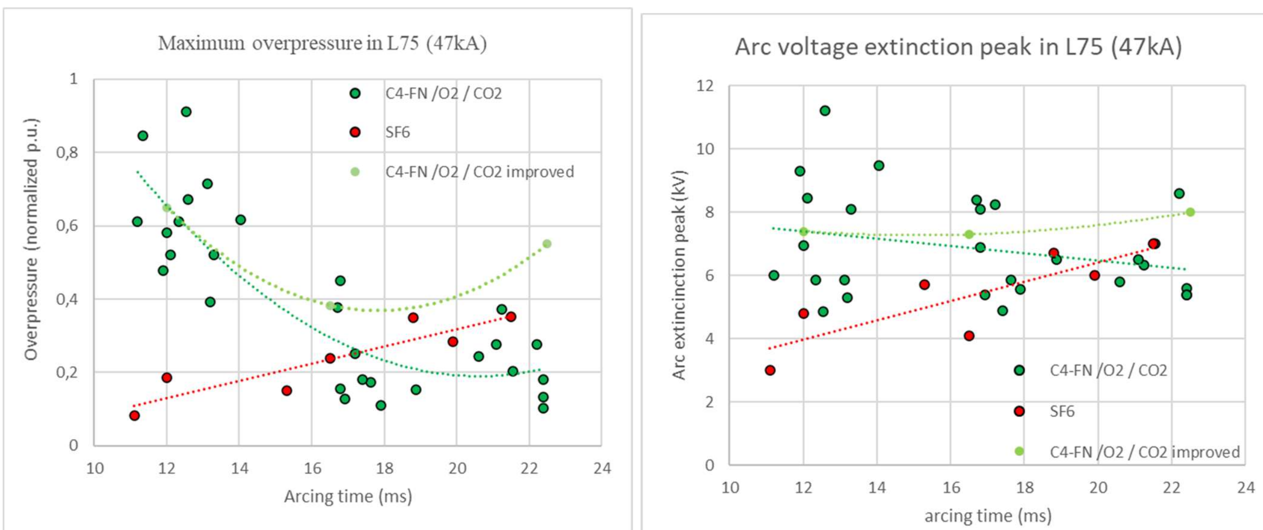


Figure 6: Overpressure and arc voltage extinction peak comparison between SF_6 (red), C4-FN/O_2/CO_2 (dark green) and improved C4-FN/O_2/CO_2 (light green)

An additional design feature was implemented in the interrupting unit. Such additional solution allows to change the overpressure profile especially on long arcing durations allowing to maintain higher overpressure on long arcing times securing low arc conductivity and enhanced breaking capability. This additional feature impact is light green-marked on figures 6.
At the end, the 245 kV 63 kA single-break and 420 kV 63 kA double-break developments demonstrate that properly designed switchgear allows the scalability for both insulation and breaking capability ensuring to keep the same bay width with no compromise on the breaking capability.

3) Fast Earthing switch

The intrinsic SF_6-free burning arc extinction capabilities are enough to ensure electromagnetically induced current switching in Fast Earthing Switches (FES). Current interruption is achieved because the free-burning arc elongates during the opening operation until a point where reignition does not occur anymore. The free-burning arc has an intrinsic arc voltage that depends on the arc length, temperature, as well as on electrodes and FES geometry. When it reaches values comparable to the circuit voltage, the current through the circuit drops and the arc temperature reduces. This allows the gas to recover its insulating properties and withstand the transient recovery voltage.

The current Is through the initial circuit when the FES is closed is defined as per the equation in Figure 7 where UL is the voltage test and ZL is an appropriate inductor to obtain the required current. During the opening operation, the electric arc creates a voltage drop between the FES terminals and the current drops too as shown in Figure 8.

$$I_s = \frac{U_L}{Z_L}$$

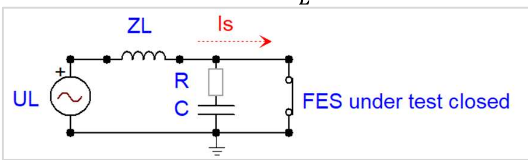


Figure 7 - Current and circuit for FES in close position

$$I_{s\ open} = \frac{U_L - U_{arc}}{Z_L}$$

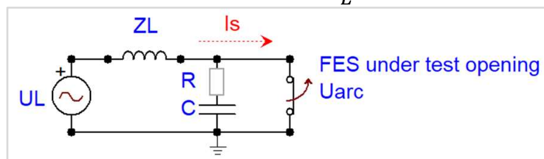


Figure 8 - Current and circuit for FES during opening

If U_L and U_{arc} have close values, the current flowing through the arc drops and it can be extinguished by the insulating gas. An example of current drop due to the increase of arc voltage is shown in the following figure 9. The circuit provides 100 Arms and the source voltage is 2.5 kVrms. The arc voltage at contact separation is only a few hundred Volts and it increases up to about 2 kVp when the final extinction happens. The last loop of current only represents 54% of the initial value.

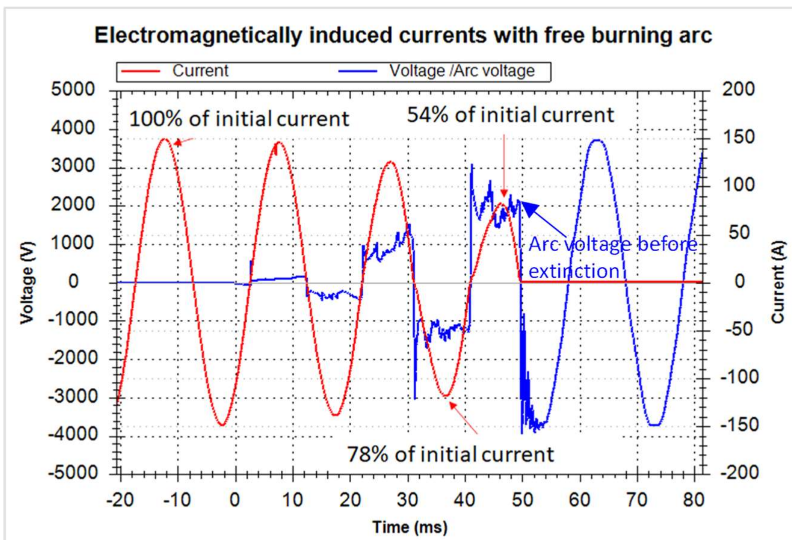


Figure 9 - Example of current drop during opening process with C4-FN (5%)/O_2 (13%)/CO_2 mixture

Experiments were carried out in typical design of FES with C4-FN (5%)/O_2 (13%)/CO_2 (82%) mixture at 0.8MPa and SF_6 at 0.65MPa following IEC62271-102 standard procedure [15], the test parameters for C4-FN (5%)/ O_2(13%)/CO_2 (82%) are the standard values for 245 kV equipment (80A-2 kVrms). The parameters for SF_6 were more severe to illustrate the difference between both gas (160A-15 kVrms).

The arcing times are shown in Figure 10, C4-FN / O_2 / CO_2 mixture successfully interrupts the current but with longer arcing times. These results are consistent with the literature for induced current switching in alternative mixtures [1].

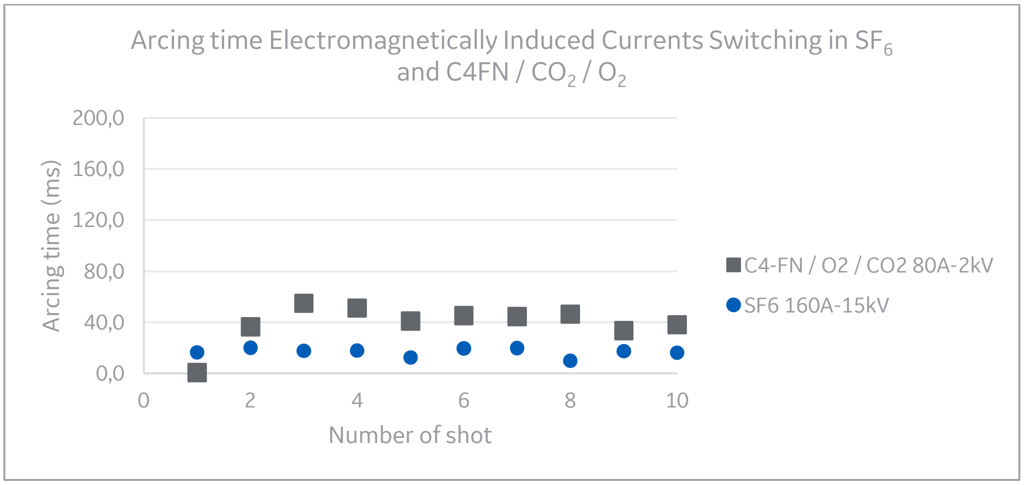


Figure 10 Comparison of arcing time in SF_6 and $C4\text{-}FN/O_2/CO_2$, SF_6 with harder conditions

For higher rated voltages than 245 kV, the breaking capability can be improved with a forced gas flow around the arc. This modification can be made on a typical design of FES keeping the same footprint as reported in [1]. The design improvements allow to keep the same drive energy.

Induced current switching experiments in 420 kV equipment were made with the modified FES and three forced gas flow profiles at the same opening speed. The current and voltage for these experiments were 400 Arms and 10 kVrms respectively. The number of operations was between 10 and 20 open and close cycles. Figure 11 shows the arcing time of a standard SF_6 design without forced gas flow (free-burning arc) and the modified FES with one of the gas profiles. The arcing times gets shorter than the typical times obtained in SF_6 even with higher current values.

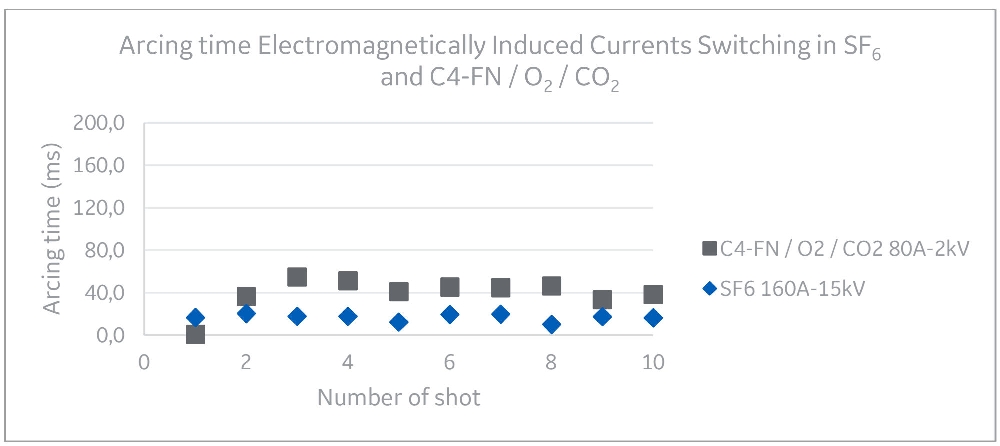


Figure 11 Comparison of arcing time in free-burning arc SF6 and forced gas flow in $C4\text{-}FN / O_2 / CO_2$

The arc voltage represents a good measurement of the insulating properties after current extinction as higher arc voltage implies lower arc conductance and thus better recovery of the insulation properties.

The following figures 12 show the arc voltage before current extinction vs time of each gas flow profile. Higher slopes of arc voltage vs time are preferable as it will reduce the breaking time and the electrical wear of the parts.

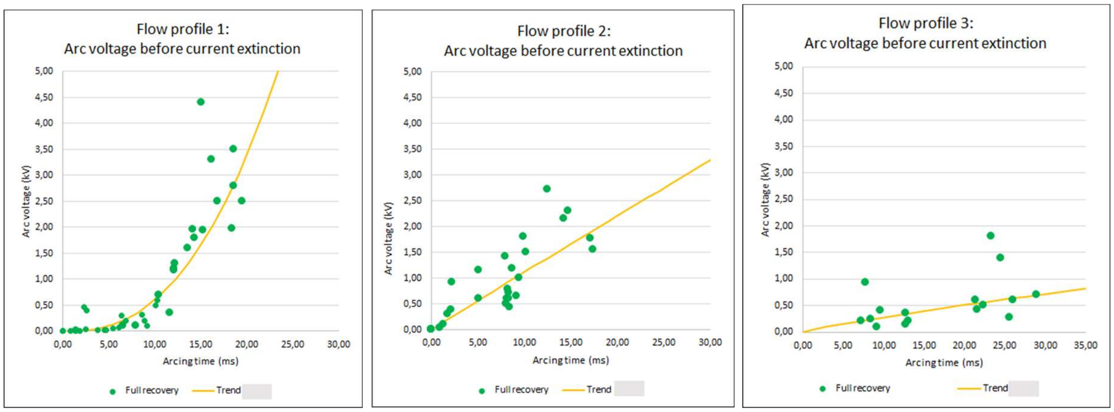


Figure 12 - Arc voltage for three gas flow profiles with C4-FN / O_2 / CO_2 mixture at 400 A-10 kV

Thanks to those experiments, the electromagnetically induced current switching using C4-FN/CO_2/O_2 mixture is achieved for the IEC 420 kV rated voltage and above with negligible impact to the equipment footprint.

4) Disconnector

Disconnector Bus transfer switching capability is well known in SF_6. For a given performance, the main parameter is the disconnector moving speed.
The capability of bus transfer switching has been demonstrated in C4-FN gas mixture (7 bar rel – gas composition: C4-FN (5%) /O_2 (13%) / CO_2 (82%). For this a complete demonstration (switching sequence + dielectric verification condition check) passed for a busbar nominal current of 5000 A in accordance with IEC standard [15]. The switching tests were performed at 3000 A (60% of nominal current).
Pre-arcing times and arcing times are stable over the complete sequence as in SF_6. The arcing contacts wear (figure 14) behavior is light and similar to SF_6 with equivalent arcing times.

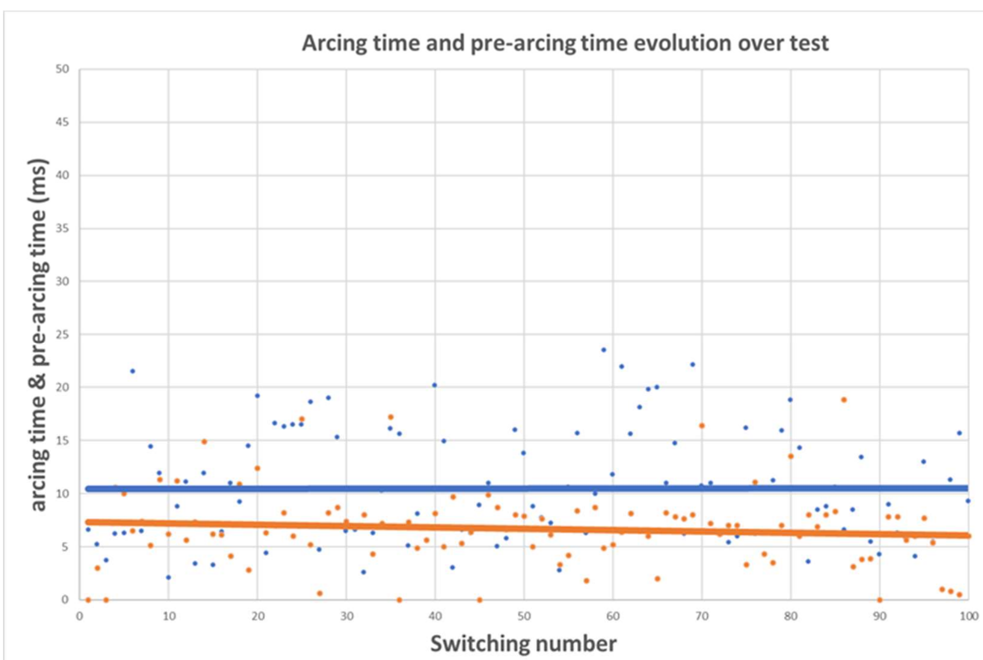


Figure 13: Arcing (blue) and pre-arcing times (orange) during bus transfer switching sequence in C4-FN / O_2 / CO_2.

Figure 14: C4-FN/O_2/CO_2 disconnector in bus transfer current switching test (left) – arcing contact after test (right)

To check the disconnector integrity after this switching sequence, a complete dielectric test has been made to find the apparatus limits. The dielectric strength has the same level as before switching test. This complete sequence allows to demonstrate the capability of C4-FN/O_2/CO_2 to reach the bus transfer current switching performance for a disconnector at 420 kV ratings.

<u>5) Conclusion</u>

SF_6 alternative technology, whatever it is, shall be scalable across the entire High Voltage range and therefore up to 800 kV with an equivalent footprint as the today optimized SF_6 technology. C4-FN/CO_2/O_2 gas mixture has already proven to be the most technically and economically alternative to SF_6 through several switchgears up to 170 kV 50 kA with the overall lower carbon footprint over the full life cycle of the product. The last research and concrete product developments described in this paper show dielectric and breaking performance for this mixture equivalent to SF_6 at 420 kV.
Single break testing after design adaptations of the existing SF_6 breaking unit confirmed that a 420 kV 63kA is possible through positive interruptions on several test duties as SLF, OP and Terminal fault with TRV up to 800kV.

In order to develop in a short-term the 420 kV GIS supported and co-funded by the European Commission under LIFE program, the strategy was to develop a 420 kV half-pole covering the most severe performances to covers both ratings 245 kV and 420 kV 63 kA.
Thanks to the knowledge of dielectric and switching capability of this new SF_6-free technology with C4-FN/O_2/CO_2 gas mixture, the complete dielectric performance of the 420 kV circuit-breaker prototype with the new gas at 7bar has been fully demonstrated.
Regarding the breaking capacity, the studies presented show that after optimization of a single 245 kV interrupting chamber, the performances are very similar to SF_6 technology while remaining in the same size. Additionally, the induced current switching with an adapted FES shows the ability to reach the highest ratings bus transfer current switching of disconnector have also been demonstrated according to the IEC62271-102 [15] standard procedures.

As a conclusion, the recent positive results according to IEC standard of a full GIS bay devices confirm the deployment of the C4-FN / O_2 / CO_2, said g^3 technology at 420 kV GIS as the best solution to replace SF_6 and keeping the same footprint as today HV products.

BIBLIOGRAPHY

[1] P.C. Stoller, M. Schwinne, J.Hengstler, F.Schober, H.Peters, T.HD.Braun and W.Albitar, "C5 fluoroketone based gas mixtures as current interrupting media in high voltage switchgear”," 2020 CIGRE SESSION 48 A3-118”,2020

[2] H. Nechmi, A. Beroual, A. Girodet and P. Vinson: “Fluoronitriles / CO2 gas mixture as promising substitute to SF6 for insulation in high voltage applications”, IEEE Transactions on Dielectrics and Electrical Insulation Vol. 23, No. 5

[3] Schneider Electric, "Cahier technique no.193 MV breaking techniques," 1999

[4] EPRI Handbook of electrical and electronic insulating materials. Table 16-14 – 1986

[5] LIFEGRID (LIFE18 CCM/FR/001096) -LIFE 3.0 - LIFE Project Public Page’. https://webgate.ec.europa.eu/life/publicWebsite/search 7340

[6] J. Ozil et al., ‘Return of experience of the SF6-free solution by the use of fluoronitrile gas’, Paris, France, 2021, pp. A3-117R.

[7] R. Luescher, ‘Einblick in die Entwicklung einer kompletten 420 kV GIS basierend auf dem 7330 klimafreundlichen Isoliergas g3’, presented at the Darmstadt conference 2021, 2021.

[8] P. Kubek, "Vacuum Circuit Breakers in High and Highest Voltage Grids," Acta Energetica, vol. 3, no. 32, pp. 124-130, Jul. 2017

[9] CIGRE Technical brochure 589 - The Impact of the Application of Vacuum Switchgear at Transmission Voltages - Working Group A3.27 -July 2014

[10] M. Liao, J. Zou, X. Duan, X. Fan, H. Sun, "Dielectric Strength and Statistical Property of Single and Triple-Break - Vacuum Interrupters in Series", IEEE Trans. on Dielectr. and Electr. Insul., Vol.14, No. 3, pp. 600-605, 2007

[11] A. Müller, "Mittelspannungstechnik, Schaltgeräte und Schaltanlagen", Siemens AG, Ausgabe 19D2 2009-11

[12] J. D. Mantilla, Kriegel, and Panousis, ‘Switching Interruption Performance Comparison between SF6, CO2 and Fluoroketones-based mixtures in HVCB’, A3-019

[13] J. D. Mantilla, M. Kriegel, and Claessens, ‘Physical Aspects of Arc Interruption in CO2/O2/Fluoroketones Gas Mixtures’, Cigre Sess. 47, 2018.

[14] European Commission, "Report from the commission assessing the availability of alternatives to fluorinated greenhouse gases in switchgear and related equipment, including medium-voltage secondary switchgear," Brussels, 2020.

[15] IEC 62271-102 Ed2.0: High-voltage switchgear and controlgear – Part 102: Alternating current disconnectors and earthing switches

[16] IEC 62271-203 : High-voltage switchgear and controlgear – Part 203: Gas-insulated metal-enclosed switchgear for rated voltages above 52 kV