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# 245kV Single Break capability for Air Insulated Switchgear SF6-free Circuit-Breaker

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## SUMMARY

As it becomes clearer for the regulatory authorities that SF6, as a potent greenhouse gas, is extremely harmful to the environment, the high voltage industry gets implied to develop alternatives to SF6 apparatus.

C4-FN gas mixtures, where C4-FN (C4F7N) is mixed with $O_2$ and $CO_2$ stands out as a more environmentally friendly option to SF6 and is a viable alternative in the field of high voltage electrical equipment. C4-FN gas mixtures behaviour has been extensively evaluated during the last years and was chosen as the preferred alternative to SF6 for insulating and breaking by several manufacturers of high voltage apparatus all around the World. High-voltage product developments involving these gas mixtures have been supported financially by UE instances on a regular basis since several years.

This technology was already implemented for Gas Insulated Switchgear application up to 420kV and Air Insulated Switchgear (AIS) up to 145kV. For AIS products, the 245kV single break interrupting chamber capability has yet to be validated.

This last subject is addressed in the context of the development of a new C4-FN gas mixture 245 kV 50 kA AIS Circuit-breaker supported and co-funded by the European Commission under LIFE program and the Climate Change Mitigation sub-program (LIFE2020 CCM-FR-001749 - LIFE SF6-FREE HV BREAKER project) [3]. Its minimum operating temperature is -30°C and the performance is to be reached without any risk of failure using the same footprint and dimensions as SF6 product. This project also includes the replicability of the breaking chamber for 420kV and 550kV Live Tank (AIS) application with spring mechanism.

This paper focuses on the use of C4-FN gas mixtures for insulating and breaking validation in a 245kV Live Tank Circuit-Breaker. The Short Line Fault performance, which is the most critical one for C4-FN gas mixtures, was reached after only two tests without additional capacitance and with a tdl $< 0.1$ µs as required by the standard IEC 62271-100 for AIS application. This excellent result is the

key output of internal simulation tools and analysis skills which reached a highly predictive level. Those tools and skills were trained thanks to already several available C4-FN gas mixtures circuit-breakers including a 145kV 3-phases encapsulated GIS, a 145kV Dead-Tank, a 145kV Live-Tank and a 420kV GIS.

The correlation between simulation and test results obtained will be detailed in this article.

**Keywords**
$SF_6$ alternatives, C4-FN, Fluoronitrile, HVCB, LCA, 245kV, SLF, outdoor application, AIS, single break, EU LIFE program, Decarbonisation, SF6-free

## 1. Intro

The current challenge is to limit climate change. The electrical equipment industry has been involved for several years in the replacement of SF6 gas, widely used in high voltage technology, by an alternative gas.
Mixtures based on heptafluoro-isobutyronitrile ((CF3)2CF-CN, abbreviated as C4-FN), associated with carbon dioxide (CO2) and oxygen (O2) reduces the Global Warning Potential by 98% compared to SF6 [1]. This new gas immediately identified as promising has been widely studied in recent years and has been implemented in products that have been installed on European networks for several years as for circuit breaker 145kV 40kA and GIL 420kV as described in [2].
The challenge now is to pursue scalability up to 245kV single break and 550 kV, as announced as possible in previous papers.
With the support of the EU through the LIFE program, the CCM-FR-001749 - LIFE SF6-FREE HV BREAKER project aims to demonstrate 245kV 50kA performance in outdoor application -30°C with the same size and ease of use as the SF6 generation [3].
The new SF6-free generation offers a product with a footprint very close to that of SF6. It is major in order not to transfer the environmental impact generated. A device without SF6 that would have a much larger footprint than the SF6 generation will generate more environmental impact due to the increased material required (Al, …) [9]
The objective of this paper is to confirm the feasibility of a 245kV 50kA single-break circuit breaker using C4FN gas mixture and achieving the same performance as SF6 generation in a live tank architecture
The first part presents the progress obtained in simulation with this new gas
The second part presents the results obtained for this SF6-free development for short line fault interruption without using an additional capacitor and for electrical endurance (E2).

## 2. Back-ground

Several C4-FN-based gas mixtures circuit-breakers have already been designed and type-tested in the last years. Gas Insulated Switchgear was of course a priority given the volume of gas involved per chamber/cubicle, followed by Dead tank circuit-breaker applications. In that sense, several interrupting chambers from 145kV for GIS and Dead Tank application have first been developed by several manufacturers, some of them being already available on the market and installed on site by grid operators [2].

They were followed by the development of a 420kV GIS circuit breaker, about to be installed on site [4].

*Figure 1 – 145kV 40kA C4-FN gas mixture circuit breaker installed on Planchamps Site in Switzerland*

For Live Tank (LT) circuit breaker application, performances were demonstrated mostly for 72.5kV & 145kV performances. In this range, C4-FN-based gas mixtures circuit-breakers are already being installed by several grid operators as showed in Figure 1.

The development of a complete range of AIS SF6-free products is necessary to engage a deep transformation of every transmission network, in particular on the 245kV range for which the live tank 50kA, -30°C worldwide need is around 4000 circuit-breakers per year.

An important step in this transition for AIS is to confirm the existence of a 245kV 50kA single break performance on a LT interrupting chamber able to function under -30°C and that can be produced at a cost consistent with the market needs. It is important to remark that as of now, there is no AIS interrupting chamber available for the specification described before and which would not involve SF6 gas.

The AIS application for 245 kV / 50 kA comes with its own specificities, as extensively described by the IEC 62271-100 standard [4].

One of them is the ITRV phenomenon, as approached in §7.103.5. The low inherent capacitance of and the high surge impedance of the circuit brings initial oscillations of small amplitude on the TRV, for interruption of high default currents in terminal fault and short line fault application.

Interruption for T100 and L90 faults shall be demonstrated considering this ITRV, one of the options being to demonstrate the Short Line Fault performance with a tdl < 100 ns.

The demonstration of breaking performance considering ITRV phenomenon is a main challenge for alternative gases, as long as success depends on the recombination capacity of the gas after breaking the electrical arc [5].

For this AIS 245 kV 50 kA application, and in this more particular case of a C4-FN-based gas mixtures circuit-breaker, it was decided to demonstrate the E2 performance as defined in the §4.2 of the IEC 62271-310 standard [6].

On a worn apparatus as described in Table 2 of the same standard, the E2 performance shall be demonstrated with the following tests:

- A T10 sequence
- A L60 sequence
- A LC1 test
- A Voltage dielectric check

It is a challenging performance to achieve for SF6-free circuit-breakers as it was already for SF6 circuit-breakers.

This choice comes with the ambition of developing a circuit-breaker with less environmental impact, as a long lifetime will reduce the global life cycle ecological impact of each apparatus.

As for our 145kV 40kA Live tank circuit breaker (already E2-type-tested), demonstrating the E2 performance including a voltage condition check also attests robustness and reliability of the device over 25years maintenance-free period [6].

## 3. <u>Simulation:</u>

### *First design :*

The development of a new live tank circuit breaker design is a complex and challenging process, particularly when the objective is to clear multiple faults such as SLF and Terminal Fault (TF) while maintaining excellent electrical endurance performance. It requires a significant amount of testing, which can be expensive and time-consuming. To mitigate these challenges, the development team has leveraged in-house simulation software to simulate and optimize the breaker design before moving to physical testing.

One of the most significant challenges in designing a breaker that can clear SLF is ensuring that it has sufficient arc breaking power while maintaining a manageable level of wear after multiple breaks. Additionally, the breaker must not generate an arc energy that is too high for the T100, as this would result in a significant amount of pressure and hot gas, which would require an oversized breaker solution with a larger footprint, higher costs, and a larger climate impact.
The development team has used 2D axisymmetric simulation tools to test multiple breaker designs for different faults, including SLF and TF. These simulation tools have enabled the team to test and optimize the designs quickly and efficiently, providing a high level of confidence in the results. The team has also demonstrated the efficacy of the simulation tools in previous developments, where there was good correlation between simulation and in-lab testing.
The graph below shows results obtain on the overpressure for both, the test (via sensor measurement) and for the simulation.

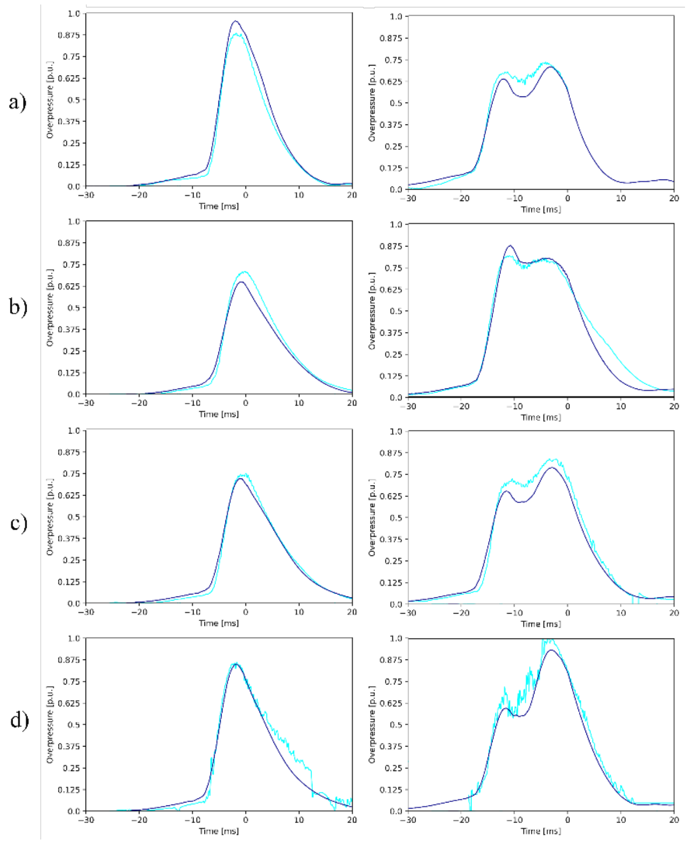


*Figure 2: Overpressure inside the thermal volume on L75 63kA faults. Cyan corresponds to in-lab test and dark blue to simulation. Minimum arcing time on the left and maximum arcing time on the right. a, b, c, d correspond do different design iterations*

This level of correlation is also observable on other faults whether it is for high or low level of current.

This previous development, helped to constitute a database with different breaker designs on different fault types. The designs were tested in the laboratory and either resulted in a break or a failure. After the tests, simulations were carried out, and using different physical quantities we establish a criterion that could predict whether a breaker had a high chance of clearing a fault or not.
Using this criterion, the team aimed to improve the interrupter design and maximize the chances of clearing SLF faults at 245kV and 50kA, without having to deal with excessive pressure and gas for T100 faults. We also ensured that the breaking capabilities were maintained even after a significant level of wear. This iterative process involved modifying various aspects of the design and finding the best configuration each time.

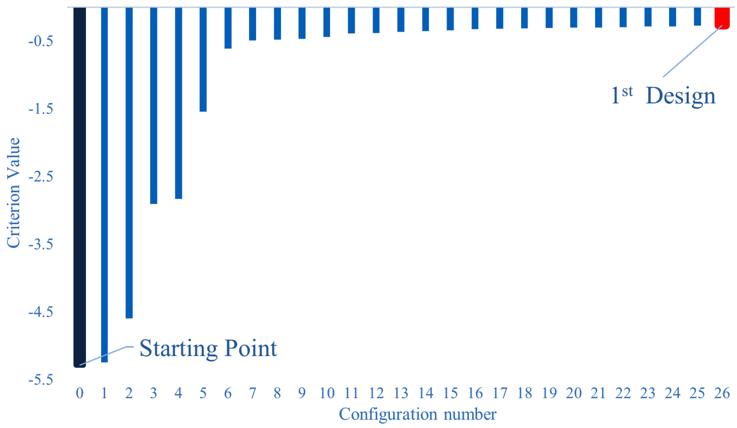


*Figure 3: Criterion value evolution through the design configurations. In red the design finally tested in the laboratory*

After approximately 25 initial iterations, the team was satisfied with the improvements made, even though the targeted criterion value was not quite reached.
This first design was then tested in the laboratory, and the results were promising for L75 faults. The performance was close to clearing on the minimum and maximum arcing times and clear for the medium arcing time.
The measurement obtained in the laboratory for this design were in agreement with the simulations predictions initially made. The following graph shows the overpressure measured inside the interrupter and the simulation prediction.

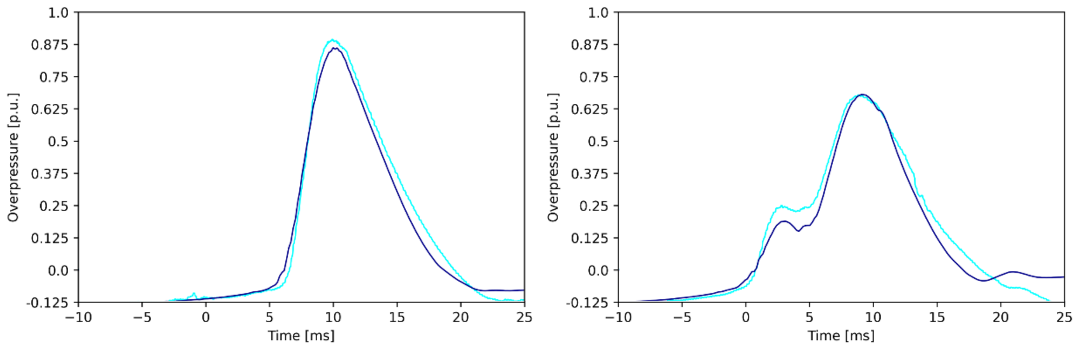


*Figure 4: Overpressure in the thermal volume for a L75 50kA faults. In cyan the test results and in dark blue the simulation prediction. On the left the minimum arcing time and the right the maximum.*

The electrical endurance was also investigated on this design and resulted in a clearing for the minimum and medium arcing time for the T10. Investigation was made using this time a 1D simulation based on an AMESIM® module. This type of fault is a perfect candidate for 1D simulation because of its low current. Indeed, this fault has a small arc energy which won't generated much hot gas, and the flow speed and recirculation will be moderate. This makes it easy to approximate the different parts of our breaker with one-dimension components.
Using this software, the impact of the arcing time was looked into using the results we had during our test.

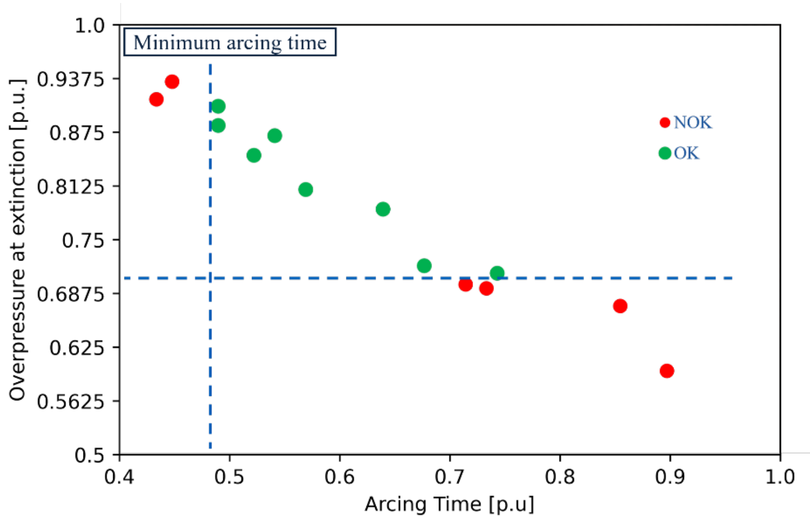


*Figure 5: Overpressure results for different arcing times obtain through 1D simulation. In green the breaking and in red the failure*

Thanks to this simulation, we can clearly see a linear decrease in the overpressure at extinction, along the arcing time. We can also see by looking into the clear shots and the no-clear shots, that below a certain arcing time the clearing capability is lost, defining our minimum arcing time. If we now look at the pressure, we can see that only above a certain value of pressure the breaker is able to clear.

### *Improvements and second design:*

To improve our initial design and obtain a clearance for all the arcing times on the SLF fault, we went through another round of iterations and after approximately 100 new iterations, we finally obtained a design which was above our breaking criterion.

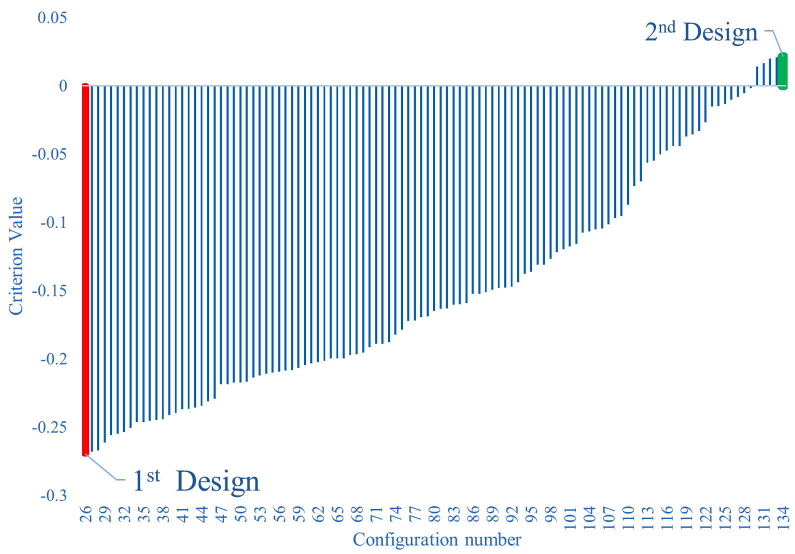


*Figure 6: Criterion value evolution through the design configurations. In red the initial design tested and in green the final improved design*

This final design gives us great confidence in its abilities to breaks all the arcing times for the SLF fault. We also tried to enhance the performance of the interrupter for the electrical endurance by improving our overpressure during small current faults, especially for extended period after the contacts separation, in order improve the clearing of long arcing times for the E2. This improvement was carried using our 1D simulation software, by, again, using an iterative process. The main complexity is to obtain a wider pressure profile, without requiring more energy, as we want to keep using a spring drive as it was the case for SF6 circuit breakers. We then solely focused on modifying the interrupter, which finally led to the results present in the following graph

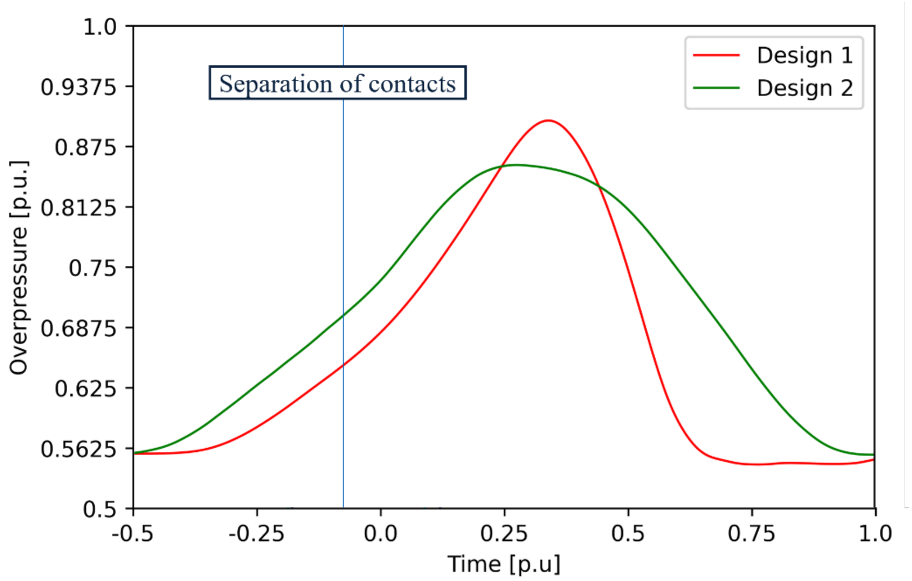


*Figure 7: Overpressure criteria inside the thermal volume (Simulation results). In red the first design and in green the new and improved design.*

We can see a clear improvement in the overpressure profile, with an overall higher pressure well after the contact separation compared to the first design. This gives us good chances for the T10's part of the electrical endurance and should obtain a pressure rise at extinction above the previously defined criteria, even for the maximum arcing time.

## 4. Validation by test

Thanks to experiments from 63kA GIS and 40/63kA AIS developments, and after these several calculation loops, the next step was the validation of the criteria and calculations by testing.
Test carried out in December 2022 at the CERDA Laboratory in Villeurbanne.

*Figure 9 : First test and investigation*

*Figure 8 : SLF Power test at CERDA*

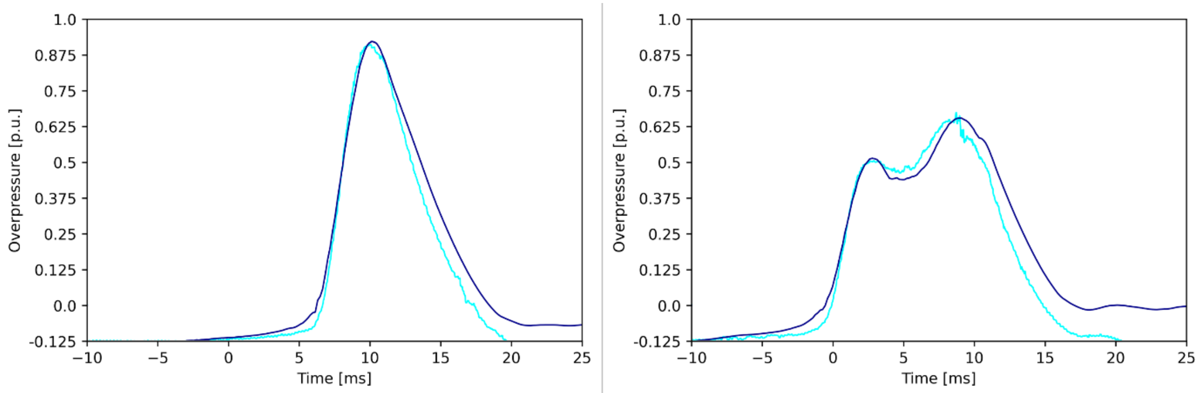


*Figure 10 : Overpressure in the thermal volume for the second design tested on a L75 50kA faults. In cyan the test results and in dark blue the simulation prediction. On the left the minimum arcing time and the right the maximum.*

Our calculations on overpressure inside thermal volume are predictive.
The maximum error between the test and the calculation is close to 5%, which is very good considering the complexity due to multi-physical domain.
L75 SLF was validated in accordance with the standard IEC62271-100 Ed3.0 on the second attempt, only after few months after the beginning of the project.

During this test campaign several test duties were investigated successfully in single break interrupting unit, and the following critical performances were validated:

- Terminal Fault T10, 459kV TRV peak validated
- T30: 400kV TRV peak achieved
- T100: most critical arcing time demonstrated

These investigations clearly demonstrated the feasibility and reliability of a LT chamber 3.5% C4-FN gas mixture without additional capacitor, with spring mechanism and the same footprint as SF6 one.

## 5. Conclusion

The development of a new C4-FN gas mixture 245 kV 50 kA AIS Circuit-breaker is being carried out with an encouraging progress, thanks to the support of the LIFE program.

In this paper we have shown that the use of simulation tools for SF6-free circuit breaker development is reliable and produces strong predictive capabilities, built upon our extensive experience in the field through previous successful developments, including a 420 kV GIS and a 145kV AIS. The development of the new 245kV chamber relied heavily on these tools which helped us to obtain rapidly and cost-effectively an adequate design.

This design was then tested and showed that 245kV 50kA -30°C performance is achievable without additional capacitance for Live Tank single break interrupter. The short line fault (SLF), which has shown to be challenging for alternative gases, has been demonstrated, and the electrical endurance (E2) validation is also well under way.
The Live Tank under development allows us to keep the same footprint and a spring mechanism, as for SF6 technology.

The C4-FN gas-mixture technology is going to replace the entirety of the SF6 Live Tank breaker up to 245 kV very soon, with a market release expected in 2024.

Thanks to the development of this 245kV chamber, higher voltage levels in AIS will be quickly implemented, with double break for 420kV and 550kV using C4-FN gas mixture.

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