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Performance investigation of SF_6 free Gas Insulated DC Systems

To reduce the CO_2 emission of electricity generation and transmission, SF_6 gas needs to be replaced by more environmentally friendly gas. A solution to replace SF_6 in high voltage equipment is the mixture of Fluoronitrile C_4F_7N with CO_2 and O_2. In this paper, a choice of insulating gas based on theoretical analysis is mentioned including intrinsic gas properties and also CO_2 footprint analysis. Experiments were then realized to verify the thermal and dielectric characteristics of gas mixture in the equipment. Finally, investigation tests were conducted with the actual SF_6 design of GIS but filled with the mixture and showed very good performance. The results confirm the feasibility of using C_4F_7N-CO_2-O_2 mixture as insulating gas in HVDC GIS.

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Introduction

France's target is to achieve 33% of renewables in the energy mix and 40% of renewables in the electricity mix by 2030 to reduce CO_2 emission [1]. Among the various renewable sources, offshore wind is an important energy source to achieve these targets. To transport offshore wind renewable energy, two technologies are possible: High Voltage Alternative Current (HVAC) and High Voltage Direct Current (HVDC). The HVDC solution is particularly suitable for the transmission of high power over long-distance. Depending on the specificity of each project, the HVDC technology is generally more interesting compared to the AC one for the power transmission higher than 1 GW and the distance above 100 km. To collect energy from different offshore windfarms, offshore platforms are a cost-effective transmission infrastructure. For these platforms where their compactness impacts directly the investment costs, DC Gas Insulated Systems (GIS) offer significant benefits in terms of space requirements.

Up to now, the available products of DC GIS are all based on SF_6 gas. SF_6 is a very performant gas for both insulating and interrupting aspects but it is a gas with very high global warming potential (GWP). To reduce the CO_2 emission of electricity generation and transmission, SF_6 gas needs to be replaced by more environmentally friendly gas. A solution to replace SF_6 in high voltage equipment is the mixture of Fluoronitrile, C_4F_7N, with CO_2 and O_2. In this paper, a choice of insulating gas based on theoretical analysis is mentioned including intrinsic gas properties and also CO_2 footprint analysis. Experiments were then realized to verify the thermal and dielectric characteristics of gas mixture in the equipment. Finally, investigation tests were conducted with the actual SF_6 design of GIS but filled with the mixture and showed very good performance. The results confirm the feasibility of using C_4F_7N-CO_2-O_2 mixture as insulating gas in HVDC GIS.

Challenges for the development of HVDC GIS

In comparison to the conventional HVAC GIS, the challenge for the design of HVDC GIS, in the insulation point of view, is the difficulty to predict the electric field under DC voltage and under different transient conditions. The electric field distribution in HVDC equipment turns progressively from a capacitive distribution which depends on material's permittivity to a resistive distribution which depends on material's conductivity. As results, various parameters which are usually neglected under AC voltage such as the operating temperature, the applied voltage, the gas humidity, the electrode roughness have to be then considered during the design of the HVDC equipment. Thus, advanced field simulations should be performed to have an accurate electric field distribution in all the possible operating and testing conditions, to have a reliable design that can then be validated by testing.

Insulating gas in high voltage equipement

In literature, different studies demonstrated the reliability of HVDC GIS using SF_6 gas as insulating medium [2][3]. The world-first 320 kV SF_6 HVDC GIS is already installed in an offshore platform in the framework of the project Dolwin6 [3]. However, SF_6 gas insulation is not an eco-friendly solution as it presents a very high Global Warming Potential (GWP). Different solutions are investigated and presented in the last decade as SF_6 alternatives. Mixtures

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based on C_4F_7N, CO_2 and O_2 have been recognized as a solution to replace SF_6 in AC high voltage equipment while keeping the same benefits of compactness and performances [4]. Another solution consists of using dry air as insulating medium in combination with vacuum interrupter to break short-circuit current [5]. While the main drawback of SF_6 gas is its very high GWP, SF_6 alternative solutions should not be chosen only based on the global warming potential of gas. To consider the global contribution of electrical equipment to the global warming, Life Cycle Assessment (LCA) is the preferred analysis as it allows to consider, not only the GWP of gas, but also a wider range of other environmental impacts including the fabrication of the equipment itself.

As mentioned in [6], a comparison is done between SF_6 and 5% C_4F_7N-13% O_2-82% CO_2 at typical rated filling pressure for electrical equipment. It is observed that any solution using SF_6 implicates a major CO_2 footprint, even with low leakage rates. On the other hand, C_4F_7N based mixtures have the lowest CO_2 impact because they keep low footprint but remove the major SF_6 impact on GWP. Solutions using vacuum interrupters and air for insulation have no direct polluting gas emissions, but the size increase has a direct impact on its footprint, making it more critical on the total CO_2 impact than C_4F_7N solutions but still better than SF_6 solution [6].

The solution based on C_4F_7N mixture is thus selected in this study as replacement for SF_6 gas in HVDC GIS. The selected gas composition is 5% C_4F_7N-13% O_2-82% CO_2 to have a mixture with liquefaction temperature of -25°C [7]. Theoretically, the ratio of dielectric strength between SF_6 and this mixture is 1.7 [8] meaning that the 320 kV DC GIS filled with minimum functional pressure of 0.55 MPa SF_6 requires a minimum functional filling pressure of 0.93 MPa of 5% C_4FN-13% O_2-82% CO_2 mixture to reach the same dielectric performance. With this such high pressure, the existing enclosures need to be modified and require increased material thickness to handle the pressure and thus increasing CO_2 footprint. On the other hand, the SF_6 filled 320 kV DC GIS has been tested with the maximum lightning voltage of 1050 kV while, in the standard IEC TS 62271-5 CD, the maximum required LI voltage is only 950 kV. This reduction of LI level can lead to the reduction of gas pressure. The minimum functional pressure is thus fixed to 0.8 MPa of 5% C_4F_7N-13% O_2-82% CO_2 and this pressure should be enough to cover the dielectric performance required by the IEC standard. The performance of DC GIS with this mixture pressure will be investigated.

Gas	SF_6	5% C_4F_7N -13% O_2 -82% CO_2
Pressure (MPa)	0.55	0.8
Equivalent thermal conductivity k_{eff} (W.m-1.K-1)	0.88	0.85

Table 1: Equivalent thermal conductivity.

Thermal performance

During the design phase of an apparatus, the thermal dimensioning of electric parts is important for the optimization of the product in order to respect the maximum temperature and temperature rise defined in the IEC 62271-1. By changing the gas, the thermal exchanges, governed mainly by convection in GIS, will be modified with a direct impact on the temperature rise.

The calculation of heat transfer via convection phenomena is quite complex as it needs to take into account the motion of fluid. To simplify the calculation process, one can consider the convection phenomenon like conduction phenomenon but with an effective thermal conductivity keff. It is much higher than the thermal conductivity as it represents the sum of heat exchanges including convection. The simplified method cannot give an exact nonhomogeneous temperature distribution inside electric apparatus, but it can give quite accurate temperature gradient. With the dimension of our 320 kV DC GIS, the effective thermal coefficient is estimated for both SF_6 and the gas mixture with their corresponding pressure (Table 1). The results show that the C_4F_7N mixture has lower k_{eff} meaning that GIS filled with this gas will have higher temperature rise than the one filled with SF_6.

Breakdown tests in gas

To investigate the dielectric performance of 5% C_4F_7N-13% O_2-82% CO_2 mixture at 0.8 MPa, dielectric tests in coaxial configuration were •••

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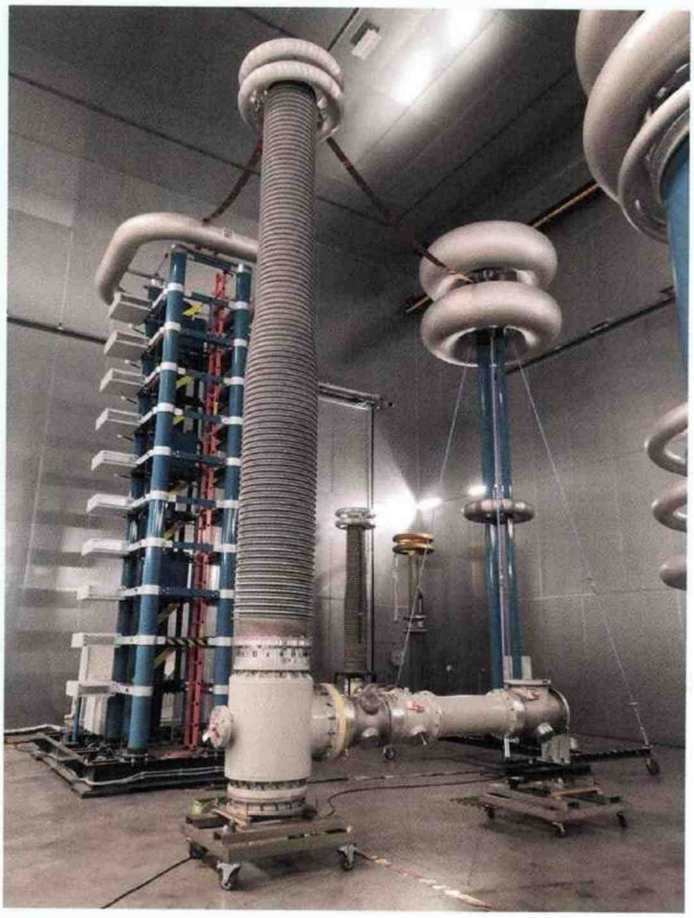
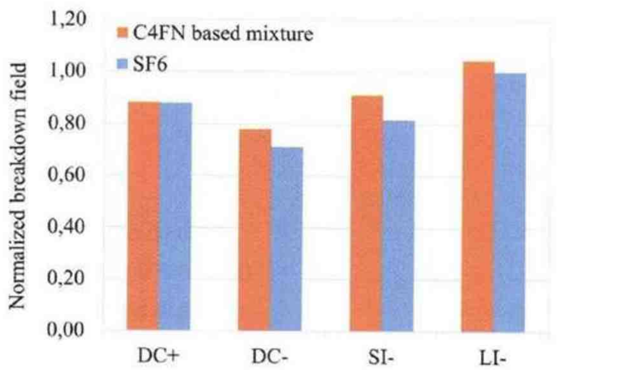


| Figure 1 : Dielectric test setup.

" To investigate the dielectric performance of 5% C_4F_7N-13% O_2-82% CO_2 mixture at 0.8 MPa, dielectric tests in coaxial configuration were performed in ISO 9001 SuperGrid Institute High Voltage Laboratory "

●●● performed in ISO 9001 SuperGrid Institute High Voltage Laboratory (Fig. 1). Different stresses including AC, DC, Lightning impulses, switching impulses were performed and the results in DC stress are then compared with the one obtained with SF_6 at 0.45 MPa. The SF_6 pressure is chosen to be close to the theoretical dielectric equivalent of the mixture based on the results presented in [8] which is about 0.47 MPa.

The results are presented in Fig. 2 for both gases in DC, SI and LI stresses. In DC stress, like SF_6, one can observe a difference in terms of dielectric strength of the mixture between positive and negative polarities. For positive polarity, both gases have the same dielectric strength while the dielectric strength of C_4F_7N based mixture is slightly higher than that of SF_6 in negative polarity. By comparing in case of SI and LI, Fig. 2 shows that the C_4F_7N based mixture has the breakdown voltage slightly higher than that of SF_6 gas but they remain very close. This difference can be directly linked to the tested SF_6 pressure that is slightly lower than the estimated theoretical dielectric equivalent



| Figure 2 : Performance comparison between SF_6 and 5% C_4F_7N-13% O_2-82% CO_2. All the values are normalized to the breakdown voltage of SF_6 in negative LI.

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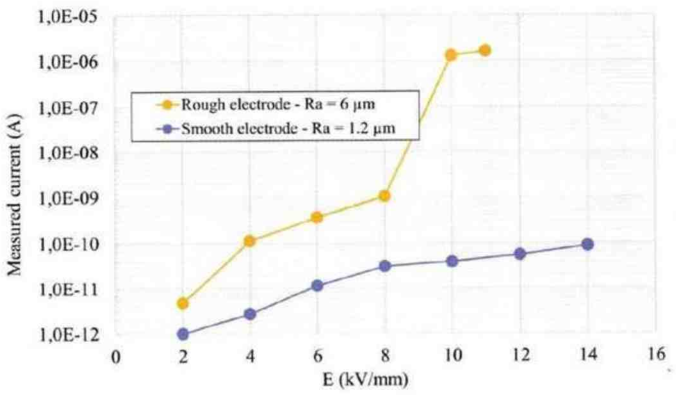

Figure 3: Leakage current measurement in 5% C_4F_7N-13% O_2-82% CO_2 mixture at 0.6 MPa.

pressure (0.45 MPa in place of 0.47 MPa). One can note that the ratio between SI and LI is more than 80% for both gases in negative polarity.

Leakage current in gas

It is demonstrated in literature that non-negligible currents are passing through gas with a high dependence on applied polarity, electrode roughness and gas humidity [9]. Experiments were thus carried out in order to characterize the 5% C_4F_7N-13% O_2-82% CO_2 mixture using the plane-plane electrode configuration.

Fig. 3 shows an example of results where the currents passing through 5% C_4F_7N-13% O_2-82% CO_2 with smooth (Ra = 1.2 µm) and rough (Ra = 6 µm) electrodes are compared. It is observed that, like SF_6, the measured current of gas mixture is much higher than that with only natural ionization (in the range of fA). Such high current is the contribution of supplementary charge carriers coming from a metallic electrode to the gas by various mechanisms such as thermionic, field emission or micro-partial discharge [9]. The high current in gas influences significantly the electric field distribution in DC stress and needs to be carefully taken into account during the design.

Gas	Value	Unit
Nominal DC voltage U_n	± 320	kV_{dc}
Rated DC voltage U_r	± 336	kV_{dc}
Rated DC withstand voltage U_{rw}	± 505	kV_{dc}
Rated LI withstand voltage U_p	±950	kV
Rated SI withstand voltage U_s	±850	kV
Rated S/IMP LI withstand voltage		
Lightning Impulse voltage	±950	kV
DC voltage	±336	kV_{dc}
Rated S/IMP SI withstand voltage		
Switching Impulse voltage	±850	kV
DC voltage	±336	kV_{dc}
Rated normal current Ir	4000	A_{dc}
Insulating medium	5% C_4F_7N – 13% O_2 – 82% CO_2	
Rated filling pressure	0.85	MPa abs @ 20 °C
Minimal functional pressure	0.8	MPa abs @ 20 °C
Minimum ambient temperature	-25	°C

Table 2: Specifications for 320 kV HVDC GIS.

HVDC GIS investigation tests

To verify the performance of DC GIS, Cigre TB842 gives the recommendation for testing [10]. It includes thermal and dielectric performances validation. Moreover, the standard IEC TS 62271-5 CD gives the rated values for insulation levels as summarized in Table 2. Tests on DC GIS filled with 5% C_4F_7N-13% O_2-82% CO_2 at 0.8 MPa have been performed according to the specifications mentioned in this table.

Test set up

A test setup was built to investigate the performance of 320 kV HVDC GIS filled with 5% C_4F_7N-13% O_2-82% CO_2 at 0.8 MPa as minimum functional pressure. The test setup consists of 9 HVDC insulators, 4 T-housings, 1 disconnector switch, 1 air/SF_6 bushing, 6 busbar compartments and 1 current transformer. The current transformer is mounted directly to the HVDC GIS to generate a load current •••

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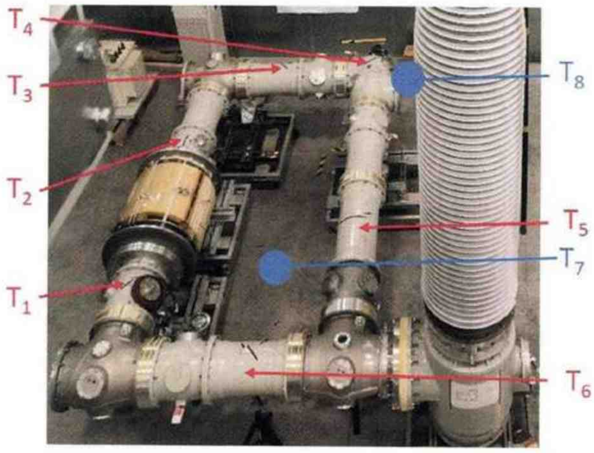

Figure 4: 320 kV DC GIS test loop. T1 to T6: positions of different temperature sensors on the enclosures. T7 – T8: ambient temperature sensors.

(max 4000 A AC) inside the loop. Humidity absorbers were also installed to limit the gas moisture content.

Temperature rise test

As the DC GIS was designed for a rated current of 4000 A, the temperature rise tests (AC current of 4000 A) were performed with different measuring temperature probes installed on the enclosure and two probes for ambient temperatures as illustrated in Fig. 4. The recorded temperatures are presented in Fig. 5. The average temperature on the enclosure is about 48°C while the average ambient temperature is 26°C meaning that the temperature rise is about 22°C.

The same test was performed for 320 kV DC GIS filled with SF_6 at 0.55 MPa [2]. The temperature rise was about 20°C and it is slightly lower than the one with gas mixture. The reason for this is that the equivalent thermal conductivity of gas mixture is slightly lower than that of SF_6 gas as illustrated in Table 1. It should be however noted that all values of temperature rise are within the required temperature rise limits of IEC 62271-1.

Dielectric performance

To verify the dielectric performance of 320 kV DC GIS filled with 5% C_4F_7N-13% O_2-82% CO_2 mixture at 0.8 MPa, tests were performed with AC voltage for partial discharge measurement, DC voltage, lightning (LI) and switching (SI) impulses as well as superimposed lightning and switching voltages. The dielectric tests follow the test procedure as mentioned in IEC standard 60060-1. For superimposed impulse voltage, the switching or lightning impulses were applied to the GIS after 2 hours of DC voltage applications with both DC polarity.

An example of test results is illustrated in Fig. 6 for the partial discharge measurement. The apparent charges are presented with the applied voltage. Fig. 6 shows that, for both applied

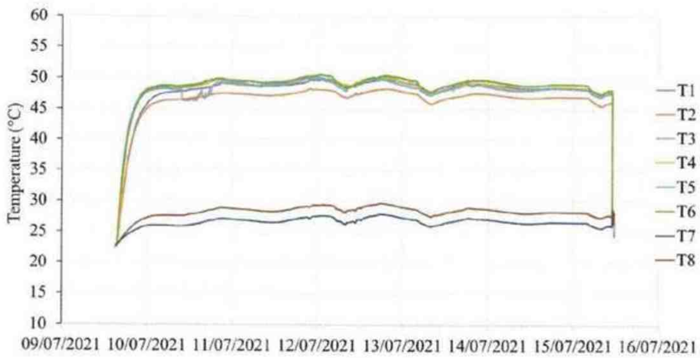

Figure 5: Recorded temperatures on difference temperature sensors.

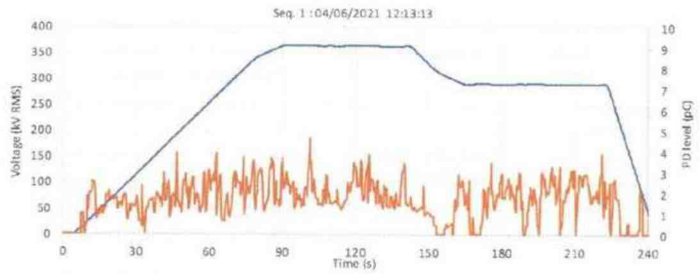

Figure 6: Partial discharge test results.

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Test	ZL/HL	Voltage (kV)	Impulse (kV)	Comment
PD AC	ZL	356/ 285 rms	/	Passed
DC withstand	ZL	+505/- 505 DC	/	Passed
LI withstand	ZL	/	+ 950/ - 950	Passed
SI withstand	ZL	/	+ 850/ - 850	Passed
S/IMP LI	ZL	+336/-336 DC	+ 950/ - 950	Passed
S/IMP SI	ZL	+336/ -336 DC	+ 950/ - 950	Passed
Polarity reversal	ZL	+/- 420 DC(2h)	/	Passed

Table 3: Performed tests.

voltage levels, the apparent charge is always lower than the limit of 5 pC fixed by IEC standard 62271-203.

Table 3 summarized the performed tests. One can underline that all the tests including the superimposed impulses passed successfully demonstrating the performance of 320 kV DC GIS filled with 5% C_4F_7N-13% O_2-82% CO_2 mixture. It confirms also that the minimum functional pressure of 0.8 MPa is enough for the rated lightning impulse voltage of 950 kV as mentioned in the recent IEC TS 62271-5 CD.

To complete the type test of 320 kV DC GIS filled with 5% C_4F_7N-13% O_2-82% CO_2 mixture, according to the Cigre recommendation [10], testing under rated current together with voltage (insulation test) needs to be done. Simulations were performed in high load conditions and showed electric fields lower than the design criteria. The experiment is planned to verify this conclusion.

Conclusions

This paper presents investigation tests of 320 kV HVDC GIS filled with 5% C_4F_7N-13% O_2-82% CO_2 gas. Typical requirements as mentioned in Cigre recommendation TB842 and IEC TS 62271-5 CD including thermal and dielectric performance were investigated. The obtained results demonstrate the feasibility of using 5% C_4F_7N-13% O_2-82% CO_2 gas as insulating gas in HVDC GIS. Further tests are planned to completely validate the performance of the SF_6 free HVDC GIS. ■

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