SF6 ALTERNATIVE – WHAT TO LEARN FROM THE HIGH VOLTAGE EXPERIENCE

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ABSTRACT

This paper presents the return of experience gained with g^3 products over the past two years through two specific examples. The first example is a 145kV g^3 GIS that has been installed in Switzerland. The second example is the 420kV g^3 GIL that has been installed in England and in Scotland. Gas handling process, on-site tests and analysis are described through these two examples. On top of that, the full environmental life cycle assessment is presented to highlight the environmental benefit of the new equipment versus the SF_6 version.

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, it has been evidenced that CO_2 is the most promising arc quenching gas. However, CO_2 shows dielectric performance which is quite low compared to SF_6 making the use of pure CO_2 not feasible in High Voltage switchgears unless changing drastically the dimension and/or the nominal pressure of CO_2 as function of SF_6 equivalent equipment. CO_2 dielectric performance must therefore be improved with an additive that has superior dielectric strength.

In this regard, GE Grid Solutions, in partnership with the 3M™ Company, has developed an environmentally gas mixture, based on heptafluoro-iso-butyronitrile $(CF_3)_2$-CF-CN (or fluoronitrile), also known as 3M™ Novec™ 4710 Dielectric Fluid [1] and mixed to carbon dioxide and oxygen. Gas mixtures of this fluoronitrile with CO_2 and O_2 were found to be an optimal solution for disconnector and circuit breaker applications. This specific gas mixture called “g^3 – green gas for grid” has been proved to be the most technically and economically promising solution with the advantage of meeting requirements of minimum outdoor temperatures as defined in international standards (like -25°C or -30°C) [2, 3].

High voltage (HV) electrical transmission equipment developed for and filled with the g^3 mixture 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 which has a GWP 23,500 times greater than CO_2 and a lifetime in the atmosphere of 3,200 years, putting it at the top of the Kyoto Protocol list [4].

The SF6-free equipment portfolio is now enlarged, with equipment covering the HV range from 145kV to 420kV. 15 utilities have decided to move forward and to install equipment with this alternative gas. GE has a number of projects on 18 sites that together will reduce the impact of the installed gas masses by more than 380,000 tons of CO_2 equivalent. These projects include more than60 bays of 145 kV GIS, more than 2000 meters of 420 kV GIL and 6 AIS 245 kV Current transformers. First applications are now commissioned and in service.

Fig. 1: 145kV g^3 GIS Substation after handover by AXPO, Switzerland early December 2017.

CHARACTERISTICS AND BEHAVIOUR OF g^3

The physicochemical characteristics of the fluoronitrile/ CO_2/O_2 mixture have been determined through a wide range of investigations. They showed by instance that the homogeneity and the composition of the gas is stable over time and the behavior of the mixture at low temperatures and liquefaction temperature of the mixture depends of the partial pressure of the different components. Regarding electrical behavior, the fluoronitrile i.e. $(CF_3)_2$-CF-CN, provides the dielectric strength to the mixture thanks to its nitrile triple function combined with fluorine. CO_2 handles the arc interruption process. O_2 plays a major role in the gas chemical decomposition especially in case of heavy arc interruption. The influence of O_2 content into g^3 has been the target of several investigations focusing on gas decomposition and the formation of powders [5]. For instance, the amount of carbon monoxide is lowered by 2 or 3 depending on O_2 ratio and the formation rate of other gaseous by-products is also significantly reduced. Furthermore, the oxygen content also positively influences the solid powders composition formed in the breaker after power arc interruption as it is shown in Fig. 2.

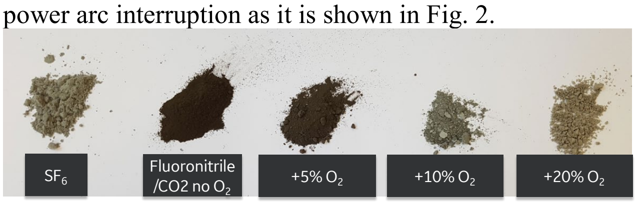

Fig. 2: Powders formed in g^3 with different oxygen content, compared to SF_6.

ONSITE GAS HANDLING MANAGEMENT

Generalities

Since SF_6 has replaced oil and air as insulating fluid in the high voltage switching equipment, site handling of insulating fluid has been significantly simplified. Tools enabling SF_6 gas handling on site are well established for decades now. Standards for handling the SF_6 gas have been established for years and revised several times.

Constraints have also developed over the last decades with the introduction of more and more severe rules and precautions for handling SF_6 in order to limit the release into the atmosphere. Manufacturers and users have adapted their procedure and international standards and guides have also been adapted accordingly.

The alternative gas to replace SF_6 that have been installed recently on several sites are made of a gas mixture and handling gas mixture on site is not new. For some specific applications, like very cold climate, gas mixture based of CF_4 and SF_6 have been installed on many applications. Gas mixture based on SF_6 and N_2 have also been installed for many years on long gas-insulated lines applications, either for cold climate conditions or to reduce the SF_6 content of the installed equipment. In these cases, the filling of the electrical equipment was performed either by partial pressure method, or thanks to a specific on-site gas mixer.

For g^3 mixture, composed of fluoronitrile, carbon dioxide and oxygen, the most industrial way to manage gas handling is to deliver on site bottles of liquefied gas mixture already prepared. Then we obtain the gaseous state by vaporization and expansion of the gas.

In the case of a single component gas, this process is relatively simple. When the gas is composed of at least two separate components, it should be ensured that vaporization occurs evenly. The homogeneity of the different components must be maintained throughout the filling process. Indeed, the liquid and gas phase compositions are different with the fluoronitrile being mostly liquid and oxygen remaining on the gas phase, CO_2 being partly liquid and gas. Moreover, the composition of the two phases, said liquid and gas, evolve with the temperature, pressure and total density making not possible the use of the gas or liquid phase independently.

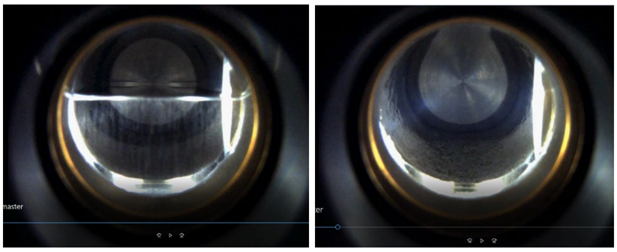

Fig 3: Liquid gas equilibrium at left. Supercritical phase at right (above the critical temperature).

Liquid to gas transition: g^3 specificities

The homogeneity of the g^3 mixture is obtained by using its supercritical state, where the mixture occupies the entire physical volume and behaves like a single gas having the density of the liquid (see Fig. 3). The transition to the supercritical state is done by heating the liquid under pressure to pass the critical point defined by its critical temperature and pressure. Its critical temperature and pressure being dependent on the molar fraction, the critical molar volume and the critical temperature of each compound in the composition of the mixture and can be estimated from the formula established by C.C. Li [6].

PROJECTS RETURN OF EXPERIENCE

Example 1: The 145kV g^3 GIS

The first example is about the world's first 123 kV GIS switchgear which runs with g^3 close to the lake of Zurich in Switzerland and owned by Axpo Power AG. The installation of the high-voltage GIS started in October 2017, see Fig. 1. The site acceptance tests were performed on the 21st of November 2017 with witnesses from utilities from France (Rte), the Netherlands (TenneT) and Switzerland (Axpo & Romand Energie) [7]. The official energisation was done in August 2018.

The switchgear F35g-145kV is designed and tested according to the relevant IEC standards. The whole switchgear including all components like circuit-breakers, disconnectors, voltage transformers etc. can operate at minimum ambient temperatures down to -25°C. The ratings and bay size of the SF_6 and the g^3 version are identical.

The main challenge to cope with the new gas was the circuit-breaker. The mass of the pressure compensated alternative gas is two times lower than for SF_6. Therefore, the speed of the gas inside the breaking chamber was influenced significantly. Due to the steeper pressure-temperature relation of CO_2 compared to SF_6, the pressure rise in the nozzle during arc extinguishing needed to be carefully evaluated and certain areas of the nozzle needed to be reinforced to cope with the new requirements.
Over all the breaker is still a single-moving single-chamber self-blast breaker element using the spring drive FK3-2 as for SF_6 even though that the changes described above were implemented.

Leak detection and gas quality check

The integral tightness test was performed in the factory using dedicated measuring equipment with the evaluation of the fluoronitrile and CO_2 losses (Fig. 4). On site, the tightness was checked using standard SF_6 leak seekers which were qualified for the CO_2 and fluoronitrile detection [8].

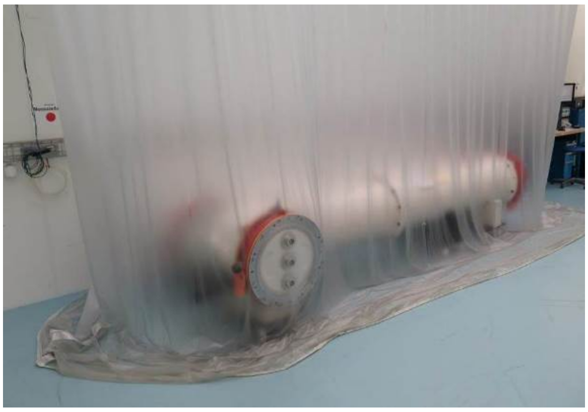

Fig. 4: Integral tightness test of a busduct in the factory.

Site acceptance tests
The standard on-site tests as described in the actual IEC standards were performed. These included the application of a one minute 50 Hz withstand voltage including partial discharge measurement according to IEC 60270 [9]. All the tests are reported in the following reference [8].

Other tests like the gas quality measurement were performed as well as the ratio measurements on the voltage transformers. No specific tests related to the alternative gas mixture were needed.

Example 2: The 420kV g^3 GIL

The second example is about the 420 kV GIL application using fluoronitrile/CO_2 gas mixture that has been installed for the first time in 2016 in south of England for National Grid at Sellindge substation [10]. Two feeders totalising 300 meters of GIL have been installed and commisisoned, as shown on the following Fig. 5.

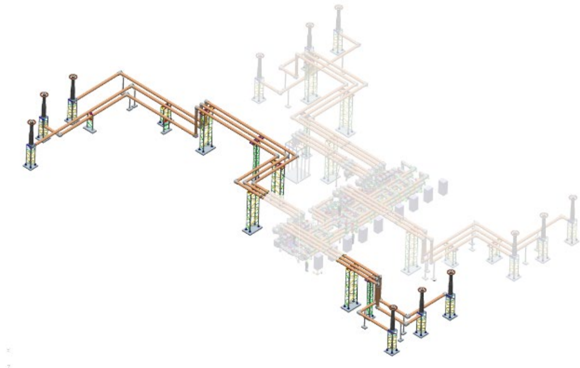

Fig. 5: Sellindge g^3 GIL pilot project

A second 420 GIL was installed in Scotland for SP Energy Networks, at Kilmarnock substation in 2018 during severe climatic conditions.

On-site g^3 handling experience

Specific gas-handling carts have been developped in order to bring the gas in the correct conditions described in previous section, before transferring to the high voltage equipment. These gas carts have been developped in coordination with companies that are familiar with handling gas mixtures, like DILO and AIR LIQUIDE companies and have been used for the first time in 2016 during installation of the first 420 kV GIL application using fluoronitrile/CO_2 gas mixture in South of England for National Grid at Sellindge substation. Two feeders totalising 300 meters of GIL have been installed and commisisoned, as shown on the following Fig. 5.
This represents a total of 750 kg of gas mixture. 40 bottles (B50 type) have been used and heated using the gas cart as shown on Fig. 6. The gas filling operation was made with the gas cart installed ourtdoor with ambiant temperature around 5°C. The accuracy of the gas filling was ensured with an accuracy of the concentration of less than 0.1%.

Fig. 6: Sellindge g^3 420 kV GIL project

The second 420 GIL project was installed in Scotland for SP Energy Networks, at Kilmarnock substation in 2018 during severe climatic conditions. Temperature down to -8°C were encountered during installation, with strong winds and some snow falls, as shown on Fig. 7. The gas hadling represented 30 bottles (B50 type), totalising more than 630 kg of gas mixture.

Fig. 7: Kilmarnock g^3 420 kV GIL pilot project.

The gas quality was measured using the GA11 analyzer manufactured by Wika specifically for g^3 measurements in GIL or circuit breakers, see Fig. 8. It combines the accurate analysis of fluoronitrile ratio using sound's speed measurement, with humidity measurement using capacitive sensors and O_2 ratio using specific optic sensor. All built-in into one portable device.

Despite the severe climatic conditions, the gas filling operation was performed successfully and gas analysis confirmed it. Percentage of gas mixture was measured with same accuracy of the newly delivered gas. Humidity was measured just after commissioning and was below -10 °C dew point on all compartments except on two of them (the dew point at filling pressure was between -10°C and -5 °C). Measurement was performed again several weeks later. Values have decreased, and gas was finally measured with a dew point lower than -10 °C at filling pressure. This confirmed the correct efficiency of the humidity absorbers installed in each compartment.

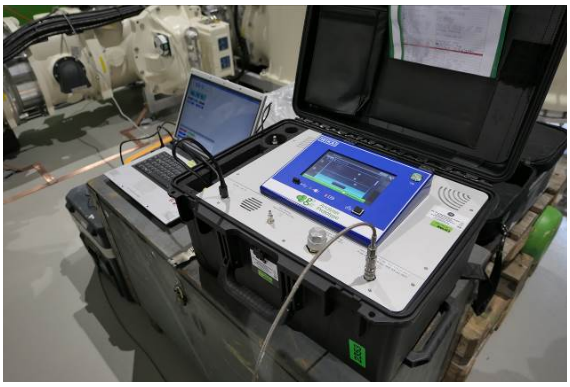

Fig. 8: Gas quality measurement on site.

Table 1 shows examples of Novec ratios and humidity levels from the cited installations (Sellindge in the UK and Kilmarnock SS in Scotland).

420 kV GIL Installations	Measured Fluoronitrile ratio %	Measured Dew Point °C Atm. P
Sellindge 2 feeders (15 compartments)	4.1	< -36
Kilmarnock 1 feeder (15 comparments)	4.2	< -32

Table 1. Novec ratios and Humidity measured on-site with GA11 g3 analyzer

On Kilmarnock project, in order to connect the overhead line to the gas/air bushings, the customer requested to reduce the pressure in the GIL compartement, as per their standard safety procedures. The gas mixture contained in the three sections of GIL including the gas bushings has been recovered using the special gas cart and pushed back into the B50 type bottles in the liquid form. Once the overhead line was connected to the gas bushing, the GIL compartement was refilled again using same procedure than initial gas filling. Gas was measured again to check that gas composition was still correct as wall as humidity level. All measurements were correct.

With this second GIL project, correct gas handling of alternative gas mixture based on fluoronitrile and CO_2 was proven whatever the outside climatic conditions. The process of gas filling, recovery and refilling was also demonstrated.

PRACTICAL CONSIDERATIONS, HEALTH AND SAFETY INSTRUCTIONS

Regarding safety aspects, the g^3 mixture is delivered on site ready to use. Except gloves and glasses as for SF_6, no specific personal protective equipment is required to handle g^3. Sniffers of Novec 4710 and CO_2 are commercially available, and as for SF_6, they allow to detect any leakage on the equipment to ensure that the gas concentration in the room is in accordance with the occupational exposure limit for worker.

In case of operation of the breaker, carbon monoxide (CO), generated from the degradation of CO_2, is by far the major degradation product observed. It is presumably one of the primary contributors to the toxicity of the arced g^3. As a result, CO is the component which is recommended to be monitored when handling arced gas.CO detectors are widely commercially available and easy to use by operators when handling the gas.

FULL ENVIRONMENTAL COMPARISON OF SF_6 AND g^3 PRODUCTS

A comparative Life Cycle Assessment (LCA) of two products, F35-145kV SF_6 and F35g-145kV g^3 complete bays was carried out in order to evaluate the environmental impact of the g^3 solution on 16 environmental indicators compare to SF_6. The results are presented on Fig. 9.

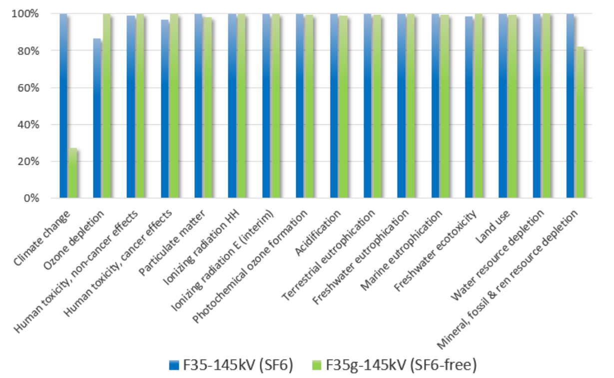

Fig. 9: LCA comparison of F35-145kV (SF_6) in blue and F35g-145kV (SF_6-free) in green.

The comparative LCA shows that F35g-145kV brings a huge reduction on the climate change impact compared to the SF_6 product. Indeed, as the Global Warming Potential (GWP) of g^3 gas is reduced by 99 % compared to SF_6 (467 versus 23'500 for SF_6), the impact of gas losses during the use phase is considerably reduced. This is of course the main advantage that is brought by the SF_6-free solution. What it is here interesting to see is that even considering the complete product over its whole life cycle, and not only the gas itself, the reduction on the climate change impact is still of -73% compared to SF_6 (considering 0.2% of leakage rate per year – the reduction will be even bigger if we considered a more important leakage rate in the study).

The ozone depletion indicator is the only indicator where the F35g-145kV (SF_6-free) is more impacting than its SF_6 pendant. As seen in the previous section, the main impact on this indicator comes from the production of PTFE material that is used in the circuit-breakers. Yet, the SF_6-free product has 1kg more PTFE than the SF_6 product. That's why the F35g-145kV is 15 % more impacting than the F35-145kV on ozone depletion on the global life cycle of the product. This may seem high at first glance, however when considering the absolute result, the increase is only 2.8 g of CFC-11 equivalent over the whole life cycle of the product of 40 years. Over all it can be concluded that the increase of this indicator is not significant because the SF_6 switchgear was already using very low quantities of PTFE.

On the 13 other indicators, the difference of the impact of the two products is less than 5 %, below the range of the uncertainty of the LCA analyses.

This study allows to demonstrate that there is no pollution transfer due to the shift on g^3 technology: the impact on climate change indicator has been reduced by 73% compared to SF_6 product, without increasing impact on other indicators like resource depletion. This has been achieved thanks to the fact that there is no oversizing of the g^3 product compared to SF_6 one (it uses the same enclosures, resulting in the same overall footprint of the switchgear), while maintaining the same performances.

CONCLUSION

Characteristics and behaviour of g^3 mixture are fully known and controlled. Adding O_2 to Fluoronitrile/CO_2 also showed numerous benefits on the gas behaviour especially in circuit breakers. Several SF_6-free products are now available, from air insulated current transformers, 420kv gas-insulated lines, to complete 145kV GIS bays, including circuit-breaker. The portfolio of available SF_6-free products will continue to expand in the near future.

The handling specificities of the gas mixture is managed using specifically designed gas carts, considering the supercritical properties of the carbon dioxide buffer gas. The on-site experience on several projects has proven the efficiency of the process, even in severe climatic conditions.

Finally, the comparative life cycle assessment with SF_6 products demonstrates that g^3 technology allows reducing considerably the impact on climate change, without pollution transfer on other environmental indicator like resource depletions. This result has been achieved as we keep the same performances with the same size of enclosures, resulting in the same overall footprint as SF_6 products.

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