ALTERNATIVE GAS TO SF_6 FOR USE IN HIGH VOLTAGE SWITCHGEARS: g^3

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ABSTRACT

The modern transmission and distribution network relies on SF_6 technology because of its remarkable arc quenching properties and dielectric insulation (approximately 3 times greater than air). However, even if SF_6 Switchgears are safe for the environment, the SF_6 insulating gas has potential significant environmental impacts if it leaks into the atmosphere. Indeed SF_6 is one of the six gases listed in the Kyoto Protocol, with a global warming potential that is 23500 times greater than CO_2.
Alternative solutions to SF_6 have been researched for a long time. Up to now, no significant success has been achieved in solutions for the transmission network. This paper presents the research conducted with fluorinated compounds to qualify a new gas to be used into high voltage equipment as SF_6 alternatives with properties significantly improved with respect to typical SF_6/N_2 mixtures or others already in use.
Potential applications of SF_6-free gas mixture, called g^3 and based on 3M™ Novec™ 4710 Dielectric Fluid for dielectric insulation and arc switching into high voltage apparatuses are reported with the aim to be low in toxicity and to reduce the global warming potential of the new mixture by more than 98% by respect to SF_6 with no or minor design modification by respect to typical SF_6 design. Research in progress on arc interrupting capability of this new gas mixture has shown promising results. We expect this new gas mixture to allow a major move towards a new generation of environmentally friendly switchgears

INTRODUCTION

The gas used most often in High Voltage Switchgear is sulfur hexafluoride (SF_6). This gas has relatively high dielectric strength, good thermal conductivity, is non-flammable and is chemically inert and nontoxic for humans and animals. After being dissociated by an electric arc, it recombines quickly and almost completely.

Nevertheless, SF_6 has the major drawback of presenting a global warming potential (GWP) of 23500 (relative to CO_2 over 100 years), and it has a lifetime in the atmosphere of 3200 years, thus placing it amongst the gases presenting the most potent greenhouse effect [1]. Therefore, 1kg of SF_6 released into the atmosphere has therefore the equivalent global warming impact as 23.5 tons of CO_2.

SF_6 was thus included by the Kyoto Protocol (1997) in the list of gases for which emissions need to be limited and the best way of limiting emissions of SF_6 consists in limiting the use of said gas, which has led industry to seek alternatives for SF_6.

EXISTING ALTERNATIVE

Research was done in past decades on substitutes to SF_6, covering different candidates including common gases (Nitrogen, air, CO_2), perfluorocarbons, and vacuum. All these technologies present advantages and drawbacks.

Available or recently developed technologies:

Traditional gases such as dry air, Nitrogen, CO_2 or their mixtures have the advantage of low global warming potential but very limited dielectric strength up to approximately 40% or less compared to SF_6. Use of such a gas as insulating or current interrupting medium would lead to drastic changes in term of high voltage product design – i.e. either filling pressure or apparatus dimension would be increased by a factor of at least 2.5. Increasing the pressure too much would impact vessels and enclosure design and safety. Increasing the size would directly impact the dimensional footprint and cost of the product making it unsuitable as a replacement product in existing substation. In circuit breaker applications, CO_2 has a higher thermal interruption capability relative to N_2 or Air.

CF_3I – trifluoroiodomethane - presents the advantage to combine high dielectric strength and current interruption capability with a low global warming potential (below 10 relative to CO_2) but is classified CMR category 3 [2, 3]. This means it is suspected to be mutagenic and therefore not suitable for large application in industrial equipment in contact with the public [4].

Vacuum is widely used in the medium voltage domain as current interruption medium. The technology is now well established and has proven to be reliable. Application in high voltage domain at 72,5 kV is now state of the art with pilot application at 145 kV. But due to the intrinsic insulating characteristics of vacuum, its insulation capability being not directly proportional to the insulating gap as it can be for pressurized gas, there is a saturation of the insulation capability for large gaps in vacuum making unlikely to use vacuum interrupters for higher voltage [5]. As a result, the application of vacuum at UHV does not appear to be economically competitive.

Therefore, none of these technologies is economically

and technically viable as an alternative to SF_6 across all the voltage ranges from 72,5 kV to UHV with the same reliability and safety for the network and workers.

DEVELOPMENT OF NEW ALTERNATIVE TO SF_6 WITH LOW GWP

A new gas mixture named g^3, based on 3M™ Novec™ 4710 fluid and CO_2, has been specifically developed to drastically reduce global warming potential relative to SF_6 and to comply with the stringent specifications of switchgears. The main specifications for the new gas can be listed as follows : high dielectric strength, high thermal dissipation, low boiling point, low toxicity, arc switching capability, compatibility with materials used in the switchgear, high stability versus temperature and time and to be easily handled on site for gas filling or topping up.

g3 mixtures:

g^3 mixtures are based on 3M™ Novec™ 4710. 3M™ Novec™ 4710 fluid cannot be used alone due to liquefaction at low temperature and has to be consequently diluted into a buffer gas. CO_2 has been selected over Nitrogen and air for its superior arc quenching capability to make the mixture suitable for disconnector and circuit breaker applications, and Novec™ 4710 ratio is g^3 mixtures are typically from $4\%_{vol}$ to $10\%_{vol}$, the remaining component being CO_2 from $90\%_{vol}$ to $96\%_{vol}$.

Physical characteristics:

As both Novec™ 4710 fluid and CO_2 follow the Van der Waals equation and the CO_2 parameters are well tabulated, the temperature dependence of the total pressure of the gas can be derived from the sum of both partial pressures. In addition to that, the gas homogeneity was carefully studied showing that no special procedures are required to obtain a homogeneous mixture comparable to SF_6/N_2 mixtures [6]. The gas remains homogeneous over long periods of time even if the temperature cools down to minimum temperature.

Experiments were performed as well by mixing several fluorinated gases with low vapor pressure but high dielectric strength to get optimal insulation performance but the liquefaction temperature was drastically modified (increased) in accordance with Raoult's law. Then it was clearly concluded that a single fluorinated gas with high dielectric performance and low boiling point in addition to CO_2 is preferable to a fluorinated gas mixture.

GWP of the mixtures:

The Global Warming Potential of the gas mixture has been calculated according to the F-gas regulation [7] where the total Global Warming Potential of a mixture that contains fluorinated greenhouse gas is calculated as a weight average, derived from the sum of the weight fractions of the individual substances multiplied by their GWP: (i) Considering a typical GIS with a 6.3 bar relative filling pressure with Novec™ 4710 fluid/CO_2 mixture for -25°C, then the total GWP for the mixture is less than 500 instead of 23500 for SF_6, reducing the GWP by 98%. (ii) Considering then a Live Tank Circuit Breaker with a Novec™ 4710 fluid/CO_2 mixture for -30°C, then the total GWP is 360 instead of 23500, reducing the GWP by 98.4%.

Class of toxicity of the mixtures:

As there is no cross reaction between the two molecules (Novec™ 4710 fluid and CO_2), the two substances can be considered separately and the toxicity of the gas mixture (LC_{50}) is calculated by taking into account the toxicity (LC_{50i}) and the mole fraction (f_i) of each substance (or volume fraction). According to the CLP regulation 1272/2008 [8], the LC_{50} (mixture) = $1/\sum f_i/LC_{50i}$.

CO_2 has an LC_{50} above 300000 ppm_v ($30\%_{vol}$) and the Novec™ 4710 fluid has an LC_{50} of about 12000 ppm_v. Consequently, for typical mixtures used in High Voltage equipment, the LC_{50} (or Acute Toxicity Estimate) of the gas would be equal to roughly 120000 ppmv ($12\%_{vol}$) and is therefore not classified by the CLP regulation 1272/2008. In addition to that, LC_{50} of different gas mixtures (CO_2 with different Novec™ 4710) was determined on mice via inhalation route. The values measured in the gas mixtures confirm the calculation. These data will be reported in a specific paper. The gas mixture is classified as nontoxic and requires no specific label.

Additional toxicity measurements made after current interruption tests demonstrates that the gas is less toxic than SF_6 under the same conditions.

Dielectric strength under power frequency:

The dielectric strength of the gas mixture was measured under AC voltage on a 145 kV GIS with Novec™ 4710 fluid ratio from 0 to 20% by volume into CO_2. The dielectric strength of pure CO_2 ($0\%_{vol}$ Novec™ 4710 fluid) was found to be equivalent to about 40% of SF_6. Adding only 6 to $7\%_{vol}$ of Novec™ 4710 fluid to CO_2 doubles its dielectric strength. For roughly 18 to $20\%_{vol}$, the dielectric strength of the mixture is equivalent to SF_6, as shown on Fig. 1. Taking as example a typical GIS, its dielectric strength with Novec™ 4710 fluid/CO_2 mixture for -25°C as minimum operating temperature is about 90% of the SF_6 value. Then the 10% dielectric strength remaining can be achieved with a moderate CO_2 overpressure according to the maximum design pressure for the enclosure and/or a design adjustment. If the minimum temperature can be maintained at -5°C in case of indoor applications, the dielectric strength of the mixture is close to that of SF_6.

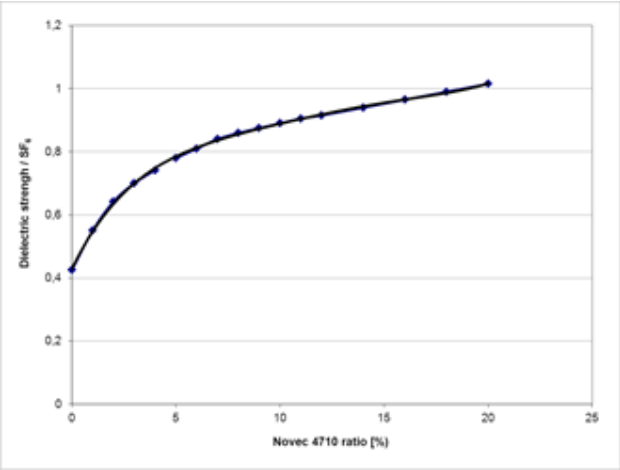

Figure1. Dielectric strength master curve for Novec™ 4710 fluid in mixture with CO_2.

The dielectric properties of g^3 were measured under inhomogeneous field as well using circuit breaker's arcing contacts with SF_6, g^3 and pure CO_2. Test results on arcing contact are presented on Figure 2 and associated values are reported in Table 1 as illustration.

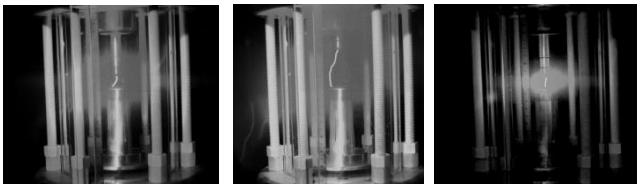

Figure 2. Breakdown tests under (a) SF_6, (b) CO_2 and (c) g^3 on circuit breaker's arcing contacts at same voltage and pressure.

	SF_6	CO_2		g^3 -25°C design	g^3 -15°C design
Voltage [kV]	72	72	72	72	72
Pressure [Mpa]	0,15	0,15	0,4	0,15	0,19
Gap [mm]	22	60	22	25	22
Diel. Strength / SF_6	1	0,37	1	0,88	1

Table 1: Contact gap and pressure to get the dielectric breakdown at same voltage under SF_6, CO_2 or g3 mixtures.

Temperature rise tests:

Temperature rise tests were performed on a fully equipped three-phase encapsulated 145kV GIS bay of the latest generation containing a circuit breaker, a current transformer, two bus bar disconnectors/earthing switches, a line disconnector/earthing switch and a cable end box. The conductors were equipped with about 200 temperature sensors to monitor temperature rise and results are plotted on Fig. 3 with respect to SF_6 for different gas formulations. A temperature rise difference of approximately 5 to 6 K is noticed which can be compensated by typical measures such as adding cooling fins to the enclosure and/or machining slots and holes to conductors to improve convection around live parts of the GIS.

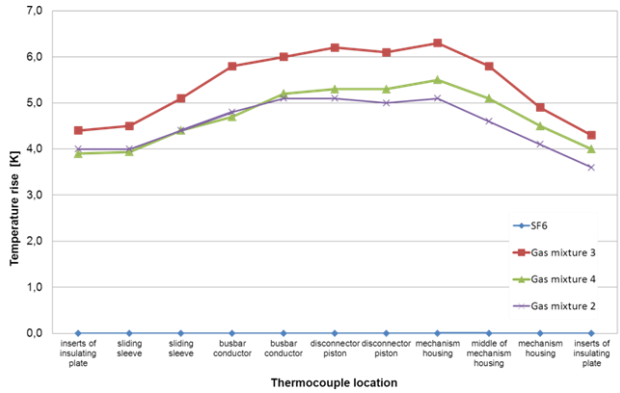

Figure 3. Temperature rise results @ 3150 A of a busbar disconnector/earthing switch filled with SF_6 and compared with three different g^3 gas mixtures (different Novec 4710 fluid ratio).

Switching performances:

The switching bus-transfer current capability under 1600A and 20V was tested over 100 C/O operations on a 420 kV disconnector designed for 5.5 bar of SF_6. The disconnector was filled with a mixture Novec™ 4710 fluid/CO_2 for -25°C at a total pressure of 5.5 bar. Fig. 4 shows that arcing time is stable over the 100 operations and the average arcing time is about 12 ms compared to a typical value of 15 ms for SF_6. This means that the gas mixture tested has a good capability of switching bus-transfer current and can be used as a substitute to SF_6 for this application. Arcing contacts present a similar electrical wear to SF_6.

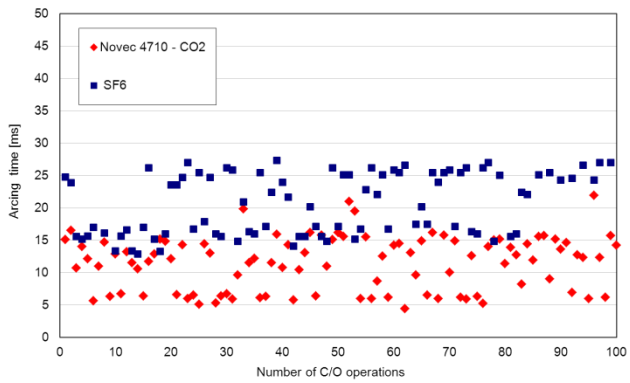

Figure 4. Arcing time versus C/O operation number on a 420 kV disconnector for Novec 4710 fluid/CO_2 mixture and SF_6.

Summary:

The new gas was validated according to the stringent specifications of High Voltage products to ensure g^3 is applicable as insulating and current interruption medium, safe to handle and has an extremely low global warming potential. The characteristics tested on apparatus can be summarized as follows:

- Dielectric performance: 85% to 100% of SF_6 performance depending on operating temperature and maximum admissible pressure (CO_2 addition),
- Operating temperature: temperatures as low as -30°C are accessible,
- Switching performance in disconnector: similar to SF_6,
- Very promising results reached on circuit breaker with the gas mixture used as current interruption medium.

Regarding the gas g^3 itself:

- Low Global Warming Potential : 98% reduction versus SF_6,
- Nontoxic : classification similar to SF_6,
- Noncorrosive: compatible with usual materials of HV equipment,
- Nonflammable: similar to SF_6.

APPLICATIONS

Perspectives:

For the first time an economically and technically viable substitute to SF_6 is available making possible the development of new ranges of GIS and AIS switchgears with similar technical, economical performances and dimensional footprint to existing SF_6 equipment with a 98% reduction of the greenhouse gas emissions.

GIS Applications:

Alstom Grid has installed more than 2500 GIS substations around the world over the last four decades. It is not easy to estimate the quantity of SF_6 gas of the installed switchgears, but one can easily figure out the benefit of replacing SF_6 gas by a gas with low global warming potential.

Once a good candidate gas is identified, one of the important development steps is to test it on real GIS equipment.

A first important parameter to consider is the design pressure of the equipment. As explained above, the new gas mixture does not use the same pressure scales than SF_6 equipment for the same dielectric performance.

Figure 5. F35 145kV GIS - Dielectric test.

The dielectric tests on a real 145kV GIS of F35 type has shown that a similar dielectric performance can be reached with a 0.1 MPa higher filling pressure of the alternative gas mixture compared to pure SF_6 gas. The thermal behavior for increased filling pressure of the alternative gas mixture g^3 is about 10% below compared to normal pressured pure SF_6 gas.

GIL Applications:

Gas insulated lines is another field of high voltage equipment that could benefit from an alternative gas solution. Over the years, Alstom Grid has installed more than 200 km of GIL. This represents a tremendous quantity of SF_6 in the existing assets. During the 2000's decade, manufacturers designed GIL projects with SF_6/N_2 gas mixtures to limit the total quantity of SF_6.

One important aspect of GIL design is its capability to carry the continuous current. Therefore, temperature rise tests have been performed on 420 kV GIL at 3150, 4000 and 5000 Amps with 5.5 bar of g^3 for a -25°C application, as shown on Fig. 6. Typically, temperature rises are in the range of 10-15% higher with the new gas mixture than with SF_6 content. This reduction factor is significant but does not prevent the implementation of this type of solution. Most GIL applications installed worldwide are given with ratings below the natural design performance of the equipment.

Figure 6. 420kV GIL temperature rise test.

Global Warming Potential savings:

Regarding global warming potential savings, a typical 145 kV 3 phases GIS bay, as presented on Fig. 7, comprises 60 kg of SF_6 which is equivalent to 1400 t of CO_2. Using g^3, the CO_2 equivalent is only 27 tons of CO_2.

Figure 7. F35 145kV GIS – Full bay.

If we consider now one of the latest 420kV GIL project with more than 14 km of single phase bus ducts, the total quantity of SF_6 installed is around 70 tons (Fig. 8). This represents 1,600,000 tons of equivalent CO_2. If it was installed with the new gas mixture, the equivalent CO_2 emission is reduced to 33,000 tons

Figure 8. 420 kV Gas Insulated Lines.

CONCLUSION

This paper presents g^3, a new potential alternative gas mixture to replace SF_6 for high voltage switchgears. g^3 is based on 3M™ Novec™ 4710 fluid used as an additive to CO_2 and presents the advantage of a significant reduction of its Global Warming Potential of more than 98% compared to SF_6. Moreover, with a dielectric strength higher than SF_6, the addition of a few volume percent of Novec™ 4710 fluid to CO_2 significantly increases the dielectric strength of the mixture to be almost equivalent to SF_6 even for operating temperature down to -25°C. This is a clear advantage when compared to other alternative solutions such as N_2, CO_2, or air, allowing designers to keep the volume and/or the filling pressure of switchgears close to the current values to remain compact and safe for workers and surroundings.

At this time, insulation, thermal dissipation and switching performances have already been validated and current interruption capability is under investigation with encouraging results already reached on a 145 kV circuit breaker. Toxicity of pure additive and gas mixtures have been determined showing that the gas mixture when new is considered as nontoxic and when polluted has to be handled as polluted SF_6. Novec™ 4710 fluid is now being registered at ECHA (REACH registration).

Therefore, the application of this alternative gas looks promising to be used as a possible substitution for SF_6 in high voltage switchgears with global warming potential of the insulating medium less than 2% of the GWP of SF_6, resulting in a reduction of 98% and higher of the greenhouse gas emissions compared to existing SF_6 switchgears.

Acknowledgments

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