doi:10.14311/ppt.2017.2.157
Plasma Physics and Technology **4**(2):157–160, 2017

ANALYSIS OF LAST DEVELOPMENT RESULTS FOR HIGH VOLTAGE CIRCUIT-BREAKERS USING NEW G^3 GAS

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Abstract. Among many alternative gases proposed to replace SF_6 as insulating gas, g^3 (green gas for grid), fluoronitril based component officially introduced at CIGRE 2014, can be now used for insulation projects and new environmental friendly circuit breakers. This gas mixture g^3, presents a reduction of the global warming potential by 98% compared to SF_6 gas and shows quite good dielectric withstand capability. Many new investigations about thermal and chemical behavior have been done and are precised in this paper. Last switching test campaigns will be presented for 145 kV applications. Simulation tools should be updated to be applicable to these projects. Developments and comparisons with last test results will be analyzed.

Keywords: SF_6 alternative gases, CO_2, Circuit Breaker, g^3.

1. Introduction

SF_6 is today extensively used in high voltage gas-insulated switchgear (GIS) and live tank circuit breakers. The positive properties of SF_6 are well known for dielectric withstand and quenching but even if manufacturers were able to reduce the SF_6 mass and the leakage rate of the different switchgears in the past years, a replacement of this gas has become into focus because of its enormous greenhouse potential. Using g^3, we target not only for a significant reduction of the global warming potential (98%), but at the same time we maintain the full ambient temperature range as reached with SF_6, same dimensions and footprint are preserved for a given voltage class as with SF_6; operating pressure values are limited to values already known in GIS and LT activities. The paper focuses on investigations on 145 kV circuit breakers GIS and LT using simulation tools and test results.

2. Reminder about g^3 characteristics

2.1. Flueronitriles as alternative solution

GE Grid Solutions, in partnership with the 3M™ Company, investigated many new compounds and mixtures including fluoroketones, fluoronitriles, hydrofluoroolefins and fluorocarbons. Fluoroketones have shown utility as dielectric fluids. However, compounds such as C5 or C6 fluoroketone have relatively high boiling points resulting in insufficient vapor pressure at low temperatures. This makes them unsuitable for many high-voltage applications. Hydrofluoroolefins (HFOs) have been seen as potential substitutes for SF_6. These molecules have unsaturated carbons and are partially fluorinated and hydrogenated. As such, their dielectric strengths stand at about 0.8 times SF_6. However, they have been found to be flammable in certain situations, causing carbon dust and deposits on the insulator in the event of gas decomposition due to arcing or sparking that prevents this gas from being used in high voltage equipment. Perfluorocarbons offer dielectric strengths that are of interest, but their GWPs are typically in the range 5000 to 12000, eliminating them from consideration. An indepth study was made of the promising chemical family of fluoronitriles. Upon conclusion of this study, a specific compound, namely heptafluoro-iso-butyronitrile $(CF_3)_2$-CF-CN, was selected and commercialized as $3M^{TM}$ $Novec^{TM}$ 4710 Dielectric Fluid [1]. Gas mixtures of this fluoronitrile with CO_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) was discovered in the frame of this partnership and is based on 4 %mol or 6 %mol $Novec^{TM}$ 4710 fluid concentration depending upon the minimum operating temperature and rated pressure required for the equipment [2, 3]. g^3 has a low toxicity level and is not classified as CMR (carcinogenic, mutagenic, reproductive toxicant) and requires no specific or additional labels compared to SF_6. The qualification of the new gas mixture was given according to International Standards and the Technical Guide to validate alternative gas for SF_6 in electrical equipment from T&D Europe [4].

2.2. g^3 characteristics

The GWPs of the gas mixtures have been calculated in accordance with the EU 517/2014 F-gas regulation, Annex IV [2]. The GWP for g^3 at 4 %mol and 6 %mol is 327 and 462, respectively. When compared to SF_6 at 23,500, these represent a 98% or greater reduction. The characteristics and performance of g^3 were examined through an extensive battery of laboratory tests.

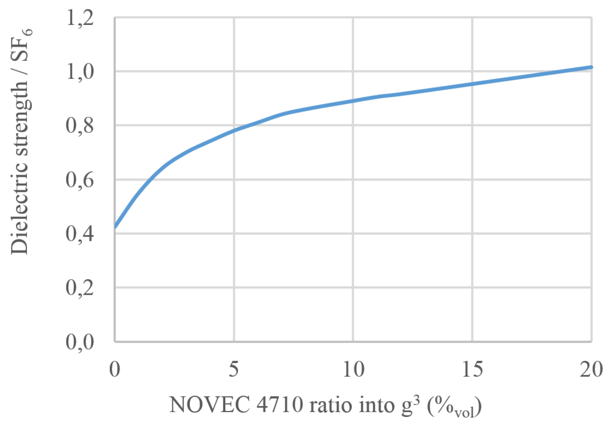

Figure 1. Dielectric strength master curve for Novec^{TM} 4710 into g^3.

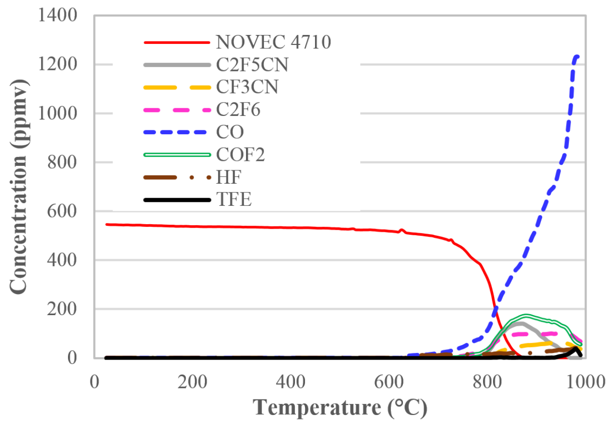

Figure 2. Decomposition products from thermal degradation of Novec^{TM} 4710.

For instance, the power frequency dielectric strength of g^3 was measured on a 145 kV GIS using Novec^{TM} 4710 fluid concentrations ranging from 0 to 20% by volume (Figure 1). At 4 %mol, the dielectric strength of g^3 is roughly 25% less than SF_6 under the same condition and pressure. This means that the overall pressure of g^3 needs to be adapted to compensate for the reduced dielectric strength of the gas mixture [3]. In addition, the thermal stability of the Novec^{TM} 4710 fluid component of the g^3 mixture was evaluated by exposing dilute gas mixtures to elevated temperatures. A mixture of approximately 500 ppmv of Novec^{TM} 4710 fluid in CO_2 was passed through a tube furnace at 1 liter/minute with temperatures increasing to 1000 °C. The fluoronitrile did not display measurable thermal decomposition until temperatures approached 800 °C (Figure 2). SF_6 decomposes at approximately 950 °C under similar conditions. The effluent of the furnace was monitored using Fourier Transform Infrared Spectroscopy and gas chromatography-mass spectrometry. Carbon monoxide was the principal degradation product detected. Above 800 °C, fluorinated species (COF_2, C_2F_5CN, CF_3CN and C_2F_6) were detected. However, all of these compounds decreased in concentration as the temperature neared 1000 °C. The following compounds were monitored but not observed: CF_4, C_3F_8, C_4F_{10}, HFP, HFC-227ea [5, 6].

3. 1D Simulation tools

The development of chambers with g^3 implies to have numerical tools to optimize the design of the chamber with reduced costs. At the early stages of the projects, we mostly use macroscopic tools to predict pressures, mass flows and arc voltage. Our macroscopic tool, called AMASIS based on an AMESIM technology (Siemens PLM Software), performs a calculation in less than 5 minutes and gives relevant information like pressure or mass flow values. The advantage is to give possibility to compute a lot of chamber designs and to take decisions based on it. It is also compatible with our mechanical models to have a full coupling between the mechanical behavior and the breaking. AMASIS has an energetic approach of the arc. Details are given in [7]. The arc volume variation as main result is based on the thermodynamical balance:

$$\frac{\mathrm{d}V_{\mathrm{arc}}}{\mathrm{d}t} = \frac{1}{\rho h}\Big[k \cdot P_{\mathrm{Joule}} - P_{\mathrm{Radiation}} - P_{\mathrm{Convection}} + \left(\frac{\mathrm{d}P_{\mathrm{arc}}}{\mathrm{d}t} + \frac{\mathrm{d}\rho h}{\mathrm{d}T_{\mathrm{arc}}}\frac{\mathrm{d}T_{\mathrm{arc}}}{\mathrm{d}t}\right) \cdot V_{\mathrm{arc}}\Big] \tag{1}$$

with:

- V_{arc}: Arc volume
- P_{arc}: Arc Pressure
- T_{arc}: Arc Temperature
- ρ: Density of the arc
- h: Enthalpy of the arc
- k: Coefficient
- P_{Joule}: Joule power
- $P_{\mathrm{Radiation}}$: Radiation power
- $P_{\mathrm{Convection}}$: Convection power

The calculated arc volume is defined between the contacts, radiates energy that cause ablation; it also interacts with the fluid and exchanges energy. Our model considers multispecies calculations, including CO_2/C_2F_4 mixtures. One typical sketch example is given Figure 3.
The calculation results are good, especially for the thermal volume overpressure and arc voltage measurements(Figure 4). AMASIS has several limitations inherent to any macroscopic tool. It does not give a precise idea of the gas temperature around the arcing contacts but permit to reduce significantly the number of 2D or 3D numerical simulations which are still required for precise investigations [8].

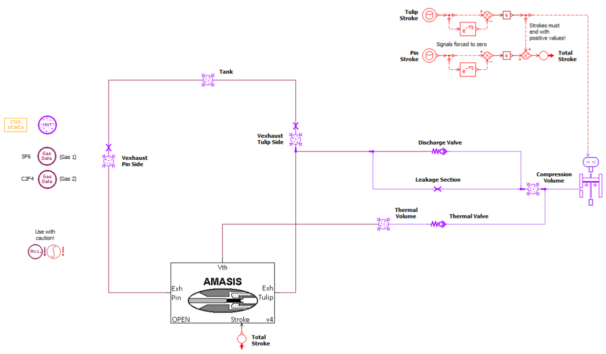

Figure 3. Simple AMASIS sketch of a chamber.

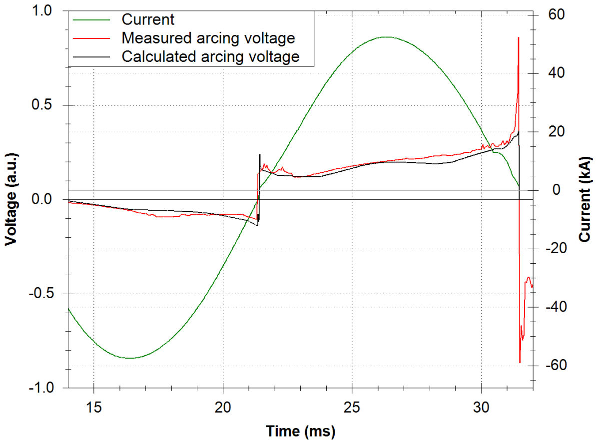

Figure 4. L90 type test result for 18.2 ms arcing time.

4. Hybrid circuit-breaker simulations

Due to the high thermal behaviour of g^3, 3D information is required to improve and optimize exhaust volumes of our breakers. Consequently, 3D simulation should be processed on a complete switchgear. This kind of simulation is not possible due to the long calculation time required even on high performance computer. In order to overcome this problem, we developed the hybrid simulation. This approach is based on a division of the interrupting unit in several areas. Each part could be simulated on the most adapted tool. The AMASIS results, issued from a full interrupting unit simulation, can be applied inside the thermal channel, as an input data in another tool (typically Ansys Fluent) to simulate the 3D flows in the heating or exhaust volumes. In the chamber, complex arc physic modeling has to be taken into account. However, in the exhaust, the principal phenomenon is the hot gas propagation. Connexion between arc modeling area and exhaust volumes is realized as a one way coupling which is acceptable in such application. In arc chambers, the parts are usually 2D axisymmetric shaped (nozzle, cap, pin…) and the exhausts are 3D shaped. So, the results of 1D or 2D simulations with arc considering equivalent sections give good data for simple 3D flow simulations in exhaust volumes. With this kind of hybrid simulation, we can implement and evaluate specific designs in order to improve the gas

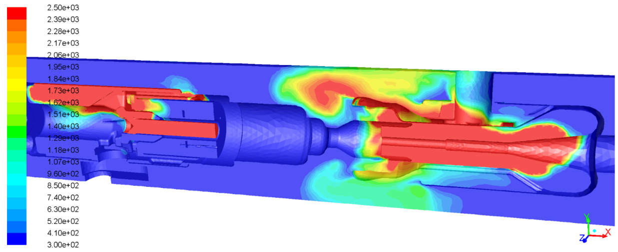

Figure 5. 3D flow simulation in exhaust volumes.

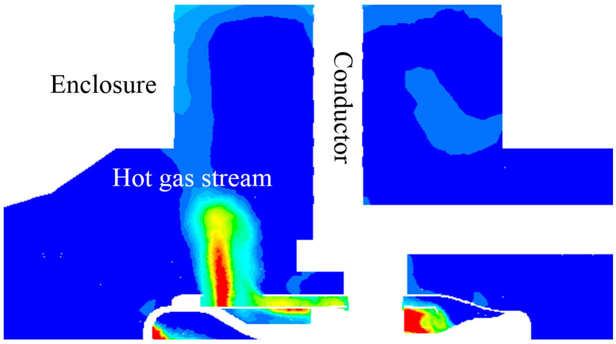

Figure 6. Evaluation of the hot gas stream to the enclosure.

mixing.

The Figure 5 shows a typical 145 kV circuit-breaker geometry with an example of input data, pressure and temperature, as a function of time on the left input side. These data are used to build the final adapted input data for real gas required by the coupling and insuring a compatibility of the data and the physics at the interface. Figure 6 represents the temperature field at one exit of the exhaust volume. This kind of result allows us to evaluate the risk to have a flashover to the enclosure or over an insulator. Thus, with sequential modifications of the chamber, all the tests required by the standards (between 10% to 100% of the default current) have been successful [9].

5. Temperature rise tests

Temperature rise tests validate the thermal behavior of the circuit breaker for the nominal current. We fixed on the interrupting unit a lot of thermocouple sensors to record the temperature all along the contacts (bolted or sliding). The test is valid when the temperature does not increase 65 °C. We performed these tests on the same test set up with g^3, pure CO_2 and SF_6 at several currents, all the sequences tested are listed in the Table 1. The results of sequences 1,2 3 and 6 were presented in [9].

Test results are very similar for the 3 gases: the maximum temperature increase has not been reached; a temperature increase of 2 °C has been measured for the CO_2 test compared to the g^3 test. An increase of 2 °C has been observed for the g^3 test compared to the SF_6 test. Under some conditions, Utilities want to be able to have higher values of current in their

Sequence	**Gas**	**Current** $[A]$
1	CO_2	3150
2	g^3	3150
3	SF_6	3150
4	SF_6 temporary over current	from 2867 A to 5985 A
5	g^3 temporary over current	from 2867 A to 5985 A
6	CO_2	3150

Table 1. Temperature rise test sequences

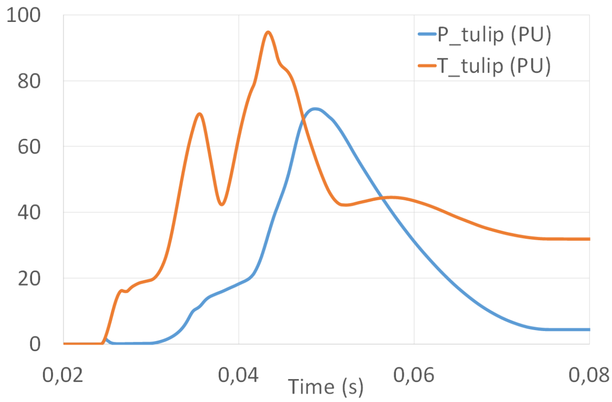

Figure 7. Temperature and pressure as an input data.

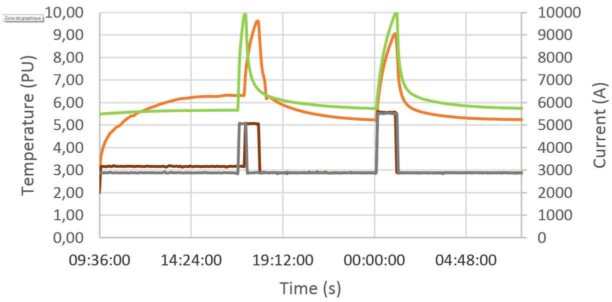

Figure 8. Temperature rise results during the over current tests.

substation for a limited duration. This special requirement has also been tested with g^3 and we compare the performance to SF_6 (sequence 4 and 5). The Figure 8 shows that results obtained on the main contacts with SF_6 and g^3 are very close.

6. Conclusion

The new alternative g^3 gas have been reminded with some new complements about gas stability and toxicity. Different simulations tools are being developed and typically an hybrid method has been presented: this approach has the advantage to run fast simulations and to optimize independently each area of the interrupting unit. Test results proved that g^3 can now be considered as a solution to replace SF_6 as insulation but also considering breaking, temperature rise and in general all performances usually required by utilities. Currently several products exist in AIS and GIS arrangement that passes all the type test. The next step for g^3 is to go for higher short circuit currents such as 50 kA and 63 kA.

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