ASSESSING POSSIBLE ALTERNATIVES TO SF6 IN MV SWITCHGEAR

JESÚS IZCARA
Ormazabal – Spain
jih@ormazabal.com

JAVIER LARRIETA
Ormazabal – Spain
jlz@ormazabal.com

JOSE MANUEL INCHAUSTI
Ormazabal – Spain
jis@ormazabal.com

SERGIO SEBASTIÁN
Ormazabal – Spain
ssm@ormazabal.com

ABSTRACT

SF6 gas is an essential part of a very well known and proven technology used in electricity transmission and distribution for insulation and current breaking purposes, allowing a reliable, safe and long life (30 to 50 years) network operation even in harsh environments.
On the other hand, the release of SF6 gas to the atmosphere has a negative environmental impact on Global Warming despite having a small influence when a life cycle assessment is done on medium voltage switchgear, where manufacturing, use and disposal of the equipment is carried out in a responsible way. That means adopting the best technologies for monitoring and leakage testing, to monitor the ageing of the electrical network, and to recover the SF6 gas at the end of life for recycling or disposal.
In parallel, ever since the GWP of SF6 was identified, R&D departments of major electrical equipment manufacturers have looked for a new technology that could replace SF6 whilst maintaining as much as possible the benefits that the SF6 Technology offers. This paper presents some tests assessing the behaviour and evolution of different gas mixtures during pilot experiences in an experimentation grid (UDEX). However, all individual efforts should be followed and/or accompanied by coordinated actions in order to standardize validation methods and subsequent appropriate revision of product standards.

NECESSITY OF STANDARDISATION

IEC standards are a worldwide-recognised framework for the development and/or specification of electrical switchgear. However, regarding alternative gases to SF6, the present possible solutions are at the "gaining experience" stage or even waiting for more manufacturers to offer new or similar solutions, and as such currently there are not enough experts (i.e. users, manufacturers, laboratories) involved nor enough knowledge/experience to develop existing or new IEC standards.
The technical committee IEC TC17 (High-voltage switchgear and controlgear) created an Ad Hoc Group (AHG-5) to elaborate a first analysis examining to what extent existing standards could be impacted by the use of alternative gases, and what aspects should be considered during the revision of existing standards. The result of that work was presented in April 2017 identifying minor necessary adaptations to be implemented in each standard, as well as further necessary research assigned to CIGRÉ, on matters where there is not enough knowledge to be standardised, such as:

- self-restoring properties of the gas after current interruption
- internal arc behaviour of alternative gases versus air and SF6
- test conversion factor (Ud/Up) for dielectric withstand compared with air and SF6
- leakage rate measurement with alternative gases (methodology, measurement at high/low temperature)
- ageing aspects of the alternative gas/gas mixture in service
- partial discharge behaviour with alternative gases

When developing standards for products, another aspect to consider is which tests could validate a design and its declared ratings. The introduction of alternative gases makes it necessary to consider if the testing parameters used in existing standards are still adequate, and if the test pass/fail criteria are appropriate.
To achieve this it is necessary to acquire knowledge and experience in the short and medium term, as well as at field and laboratory level, about the behaviour of the apparatus and technologies using those alternative gases/gas mixtures. This will in turn make it possible to develop IEC standards so facilitating the market development and structuration.

VERIFICATION OF LONG LIFE BEHAVIOUR

Moreover, all requirements identified by IEC, CIGRÉ and T&D Europe working groups, the confidence in a desired long life and moderate ageing technology, and a reliable and safe operation during the entire life of the equipment, is the most difficult topic and needs facts. There are only two ways for obtaining them:

- Laboratories prepared for long duration test: In these laboratories it is possible to design an experimentation network to reproduce different network situations, and even connect this network to a high power source to age the assets, in order to analyse the behaviour of the equipment with new gases, from the point of view of health, safety, compatibility and stability.
- Pilot experience in the field: Controlled installation in a real network with possibility to take samples for analysis, with the risk of not experiencing extreme conditions and possible consequences if failure occurs.

These enable the assessment of the ageing of the equipment along its lifetime ensuring reliable and safe operation, through the study of the following three topics.

1. Compatibility/ageing of gases and materials

New gases/gas mixtures mean, when compared to SF6 filled equipment, new sub-products may appear inside the filled enclosure which can evolve in different ways, depending on the materials in contact with such atmosphere. Due to the lower stability of low GWP gases, they could interact (react) with polymeric materials and change their properties inside the equipment. Those materials are thermosets, thermoplastics, elastomers and other materials used for manufacturing medium voltage switches, circuit breakers, insulators, bushings, gaskets, among others.
The interaction of the insulating gas with the polymeric materials leads also to the possible degradation of the insulating gas, where new molecules will appear resulting from the chemical reactions occurred. The extent to which those primary and secondary reactions can occur inside the equipment and for how long they continue, and the consequences on polymeric materials and the insulating gas itself, is a matter that needs to be known with enough precision to allow the estimation of the behaviour over the entire life of the equipment. These interactions have associated detrimental effects on the characteristics of the equipment such as voltage withstand levels, tightness or mechanical endurance.
The aforementioned matters are reasons for testing the compatibility of different gases with current and future materials used in switchgear designs for the entire life of equipment and/or define long duration tests which could be representative of the entire life of the equipment. The difficulty with this last option is that it requires accelerated chemical reactions without creating ones different to those that could happen under the conditions of pressure, temperature variations and humidity inside the gas-tight filled compartment of the switchgear. The influence of voltage stress is assessed both with the gas (or gas mixture) alone, and also with other materials present. Other possible influences should be evaluated, for example, electric arcs, corona discharges, electromagnetic fields and X-ray emission from vacuum interrupters.
Regarding some of these aspects previous studies have demonstrated the very low or null interaction of SF6 with typical polymeric materials, that could be used as a base [1] [2] [3].

2. Lifetime health and safety

The interaction between filler gases and materials, over the lifetime of switchgear at service conditions, like dielectric stress, arcs in proximity and variations of temperature inside the tight compartments, as previously explained, could create different sub-products that should be analysed from the point of view of health and safety in all possible situations of the product life-cycle, such as filling, normal operation, small leakages to the substation room, internal arc occurrence, end of life gas recovery handling for recycling or disposal, etc. For these situations CMR tests among others have been recommended by IEC, Cigré and T&D Europe working group, in order to determine consequences for human health in case of exposure to the original gas mixture and the aged/decomposed products.
Consideration should also be given to the analysis of the gas behaviour inside the equipment regarding people safety when operated, in terms of flammability, lack of oxygen in the substation room in case of total or partial release of the gas, internal arc behaviour, measures to be taken during type tests, during routing tests and for end of life process, aligned with all required REACH information for massive production.
However, standardised and widely accepted testing procedures should be defined to allow a consistent evaluation and comparable results of different gases and technologies among laboratories.

3. Performance stability

One very important aspect to have in mind, apart from fulfilling all type tests and routine tests that guarantee a determined electrical and mechanical behaviour, is to check the performance stability during the asset life to avoid future collapse of parts of the electrical network.
Today it is only possible to ensure performance stability by building pilot installations in field or in dedicated labs and letting time run. Accelerated tests may not be valid *a priori* for extrapolation of results because the complexity and mutual interaction among gases and materials, as well as the different reactions and behaviours that are created by increasing the temperature or the gases concentration, are not representative of the ageing in service conditions.

EXAMPLE OF LONG LIFE BEHAVIOUR ASSESESMENT

1. Selection of options to assess

In order to determine the gas mixtures to be used during experimentation, dielectric strength tests were carried out with mixtures of synthetic gases.

To choose these mixtures previous experiences have been taken into account [4] [5]. All potential alternatives must have a minimal GWP and the proportion of gases on each mixture must be adequate for minimum functional temperature (avoiding gas condensation).

Dielectric strength of alternative gas mixtures composed of known vector gases such as N2, CO2 or synthetic air doped with one of following new products were obtained experimentally and compared:

- heptafluoro-3-(trifluoromethyl)-2-butanone, with formula CF3COCF(CF3)2, a fluoroketone developed recently by 3M and commercialized with the name of Novec™ 5110 (C5-FK)

- tetrafluoro-2-(trifluoromethyl) propane-nitrile, with formula (CF3)2CFCN, a fluoronitrile developed also by 3M and commercialized with the name of Novec™ 4710 (C4-PFN)
- hydrofluoroolefin HFO-1234zeE, with formula CF3H=CFH

One specific equipment with a hermetic cell provided with two electrodes was implemented for comparing the dielectric strength of those mixtures and SF6.

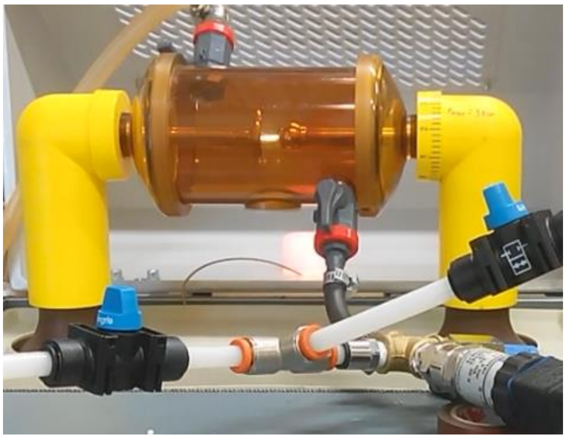

Fig 1. Used hermetic cell with the electrodes.

Although the electrical fields that exist in real MV switchgear cubicles are of very different types and complexity, the results obtained in these experiments could be used as a preliminary indication of the dielectric strength of the different gas mixtures. In any case, dielectric type tests of MV switchgear cubicles filled with the alternative gas mixture must be done.

The following figure shows a comparison of the results of breakdown voltage values for different gas mixture compositions at different pressures.

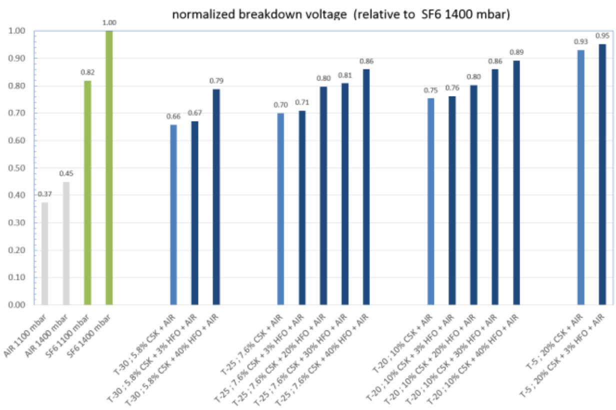

Fig 2. Comparison of breakdown voltage for different mixtures

Different pressures from 1000 to 1500 mbar (typical in MV switchgear) were tested and always compared with pure vector gases (N2, CO2, synthetic air…) and always referenced to SF6. The following significant observations were made:

- The breakdown voltage of gas mixtures increases with increasing percentage of doping product in the mixture and increasing pressure.
- The gas mixtures of C4-PFN had higher dielectric strength than gas mixtures of C5-FK for the same percentage per volume of doping product, for tested geometries.
- Doping a gas mixture of synthetic air and C5-FK with HFO-1234zeE increases the dielectric strength whilst respecting the required minimum temperature without condensation.

2. <u>Checking the stability of gas mixtures under operating AC voltage</u>

Once different gas mixtures have been selected, it is time to check their stability under operating conditions in electrical switchgear, so permanent 30 kV AC voltage has been applied to four prototype MV switchgear cubicles filled with four different gas mixtures, based on mixtures of CO2 or synthetic air with fluoroketone, C5-FK, and hydrofluoroolefin, HFO-1234zeE.

For this purpose, an experimentation network called UDEX (Demonstration and Experimentation Unit) is being used. This network is a highly configurable medium voltage network independent from the grid which allows the development and testing of new technologies, products and services in a safe and controlled environment.

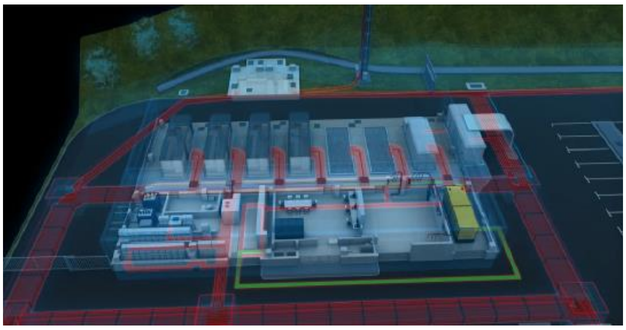

Fig. 3 UDEX Experimentation network

Alternative gas mixtures used in the four prototype MV switchgear cubicles are indicated in Table 1.

Periodically, for each cubicle, the gas pressure was measured and gas samples extracted and sent to a chemical laboratory to analyse their composition.

cubicle	gas mixture	months with 30 kV
#1	20% C5K + CO2	46.5
#2	78% HFO-1234zeE + CO2	18
#3	10% C5K + synthetic AIR	18
#4	10% C5K + 3%HFO-1234zeE + synthetic AIR	18

Table 1. Gas mixtures used in the cubicles for the long term tests under permanent voltage

A gas-chromatography/mass-spectrometry (GC-MS) analytical technique was used for the detection and identification of decomposition products in the gas samples, with the exception of CO that was detected with a gas-chromatography/thermal conductivity detector (GC-TCD) analytical technique.

A GC/MS chromatogram of one gas sample extracted from one of the prototype cubicles after 18 months under permanent 30kV AC, is shown in Figure 4.

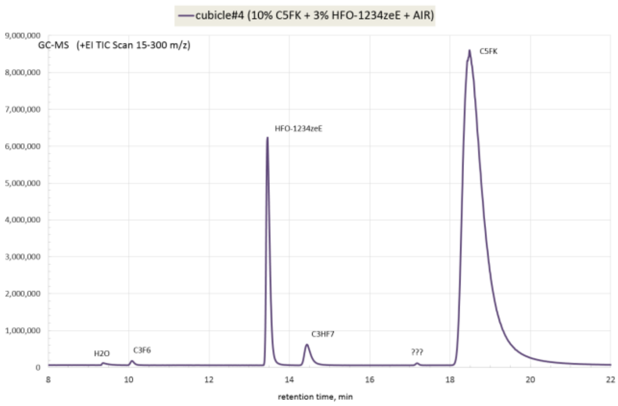

Fig. 4 GC-MS chromatogram of gas sample extracted.

Gas reference patterns of C3F6, C3HF7, CO and H2O were used for a better quantification of these products in the test samples.

A good separation of the components present in the gas samples before entering in the mass spectrometer was obtained with a 25 m length capillary column (Poraplot Q).

The results of the chemical analysis indicate that some degree of decomposition of gas mixtures occurred (Table 2). Possible causes could be: i. the influence of electrical field present in the cubicles, ii. some incompatibility of gas mixtures with materials present in the cubicles, or iii. residual content of water (ppm) in the materials.

To evaluate if these decomposition products are acceptable for the adequate performance of the cubicles in an installation under real operating conditions over the entire life duration (30 years) is a more complex issue and requires more long life assessments to check the behaviour over time.

cubicle	gas mixture composition	months at30kV	Detected decomposition products (ppmv)			
			CO	**H2O**	**C3F6**	**C3HF7**
#1	20.00% C5K + CO2	46.5	1016	61	201	1911
#2	78.71 % HFO + CO2	18	-	81	-	-
#3	10% C5K + synthetic AIR	18	-	64	432	4491
#4	10% C5K + 3% HFO + synthetic AIR	18	-	63	408	2688

Table 2. Decomposition products detected in gas samples extracted from cubicles

New samples are expected to be extracted after an additional long period of time to follow the evolution of gas mixture compositions, as well as dielectric and mechanical type tests.

CONCLUSIONS

Ever since the GWP of SF6 was identified, R&D departments of major electrical equipment manufacturers have looked for a new technology that could replace SF6 whilst maintaining as much as possible the benefits that SF6 technology has to offer, including: reduced size & footprint; very low or no maintenance required in high-voltage parts; behaviour in normal and aggressive environmental conditions; low environmental impact of the whole equipment; health and safety conditions for operator and third parties along the entire life of the equipment; long life reliable operation, and of course, cost effectiveness. This is not an easy task as there is still no clear regulatory framework, not enough field experience and no accepted standards to validate different alternatives which must ensure the maturity and reliability of the technology assessed through well monitored pilots at selected locations. Long service experiences are needed to validate the stability of these gas mixtures. The validation must consider by-product formation and its reaction with materials. Health and safety conditions during operation must also be analysed. A greater number of pilot experiences are required involving both manufacturers and Distribution System Operators.

REFERENCES

[1] Westinghouse Research and Development Center – Project 847-1: "Gases Superior to SF6 for Insulation and Interruption" Final Report (September-1982)

[2] Sangkasaad, S., Doctor of Technical Sciences Dissertation submitted to the Swiss Federal Institute of Technology, Diss. ETH No. 5738, Zurich, (1976)

[3] Ryan H.M., Watson W.L., Dale S.J. and Chantry P.J., J. Appl. Physics 50 p. 6789 (1979)

[4] Hyrenbach, M., Hintzen, T., Müller, P., and Owens, J., Alternative gas insulation in medium voltage switchgear, CIRED Conference paper 0587 (2015)

[5] Saxegaard, M., Kristoffersen, M., Stoller, P., Seeger, M., Hyrenbach, M., and Landsverk, H., Dielectric properties of gases suitable for secondary medium voltage switchgear, CIRED Conference paper 0926 (2015)