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Design Considerations for implementing SF_6 alternatives for distribution switchgear applications with focus on toxicity and load break performance

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SUMMARY

Environmentally sustainable solutions are gaining traction across the power industry. New legislations, utilities' demands, and an increasing social awareness are the main drivers for this change. All of this has put the focus on SF_6 since it's one of the more common gases used by the industry and the one with the highest global warming potential. In the last decade, several gas alternatives to SF_6 have been proposed, including the gas mixture of fluoronitriles (chemical formula: 2,3,3,3-tetrafluoro-2-(trifluoromethyl) propanenitrile) with CO_2 and O_2 that is discussed in this paper.

The interruption performance of SF_6 alternatives for transmission switchgear (HV) has been researched and documented well, but there have been very few publications related to medium voltage (MV) distribution switchgear. As there are some significant differences between MV and HV switchgear, most notably the smaller (and fixed) size, lower pressure (often not exceeding 1bar relative), and lower load break / interrupting currents; it is important to consider how the design and rating differences of MV switchgear impacts the selection of an SF_6 alternative. In this paper, the switching performance of two different load break switches, a linear puffer (LP) and a rotary switch (RS) is discussed. A variety of ratings were tested from 17.5kV/200A to 38kV/630A. For both designs, two gas alternative mixtures are used: mixture A is 85 $\%_{mol}$ CO_2 and 15 $\%_{mol}$ C4-FN; and mixture B is 85 $\%_{mol}$ CO_2, 5 $\%_{mol}$ O_2 and 10 $\%_{mol}$ C4-FN.

The results are presented with a focus on two aspects.

1. Current interruption performance compared to SF_6, and
2. Decomposition of C4-FN following interruption.

For the first one, load current and cable charging breaking performance tests were analysed to compare different arc interruption technologies and gas mixtures. The results show that although there is a reduction of arc quenching and RRDS (Rate of Rise of Dielectric Strength) when compared to SF_6, it is possible to match, or even surpass the switching performance of SF_6 by implementing improvements in the design. Cable charging presents more complications than load break due to a steeper TRV.

For the second one, gas chromatography - mass spectrometry (GC-MS) and Fourier-transform infrared spectroscopy (FT-IR), were used for the C4-FN decomposition, consumption and toxicity analysis. The results show that the decomposition of C4-FN caused by arcing during switching of MV load is low, with an insignificant increase in toxicity. Low concentrations of solid deposits were observed from switching. O_2 had little to no effect on toxicity but impacts on the effects of arc by-products.

KEYWORDS

C4F7N, C4-FN, SF6-free, Fluoronitrile, Fluoroketon, Technical air, Alternative gas, Distribution, Switching, Decomposition, Lifetime

1. INTRODUCTION

For decades, climate change and global warming have been the subject of extended discussions, but the institutional regulations have been rather loose, with little involvement from the administrations to set greenhouse gas emissions. However, since the Kyoto protocol in 1997 [1] there has been a growing awareness; within the last decade the effects of global warming had become more notable and Earth's climate models are helping to understand future impacts. Recently, the Sixth Assessment Report (AR6) from IPCC [2], provided a comprehensive analysis of the impact of carbon emissions and other pollutants in the climate. Following the trends of multiple industries, T&D is subject to new regulations and policies to reduce the carbon footprint for new installations. For the past several years, the focus has been turned towards SF_6 emission reduction and the use of substitutes for new switchgear due to SF_6's high GWP (Global Warming Potential) of 22,800, identified as the most powerful greenhouse gas [1]. Although the annual estimated SF_6 release and contribution to the global warming is dwarfed when compared to CO_2 emissions in USA (it only represents 0.1% of the total greenhouse gas emissions [3]), it's important to understand that just part of the gas stored in new GIS (Gas Insulated Switchgear) is included in the EPA estimations (10%). Hence, efficient recovery of SF_6 in existing switchgear will be important in the years to come.

1.1 MV switchgear background

As part of the efforts, GIS manufacturers are providing viable SF_6-free solutions. The transmission sector has led the technology by using the alternative gases for insulation, and as interrupting media.

The scenario in the distribution sector is completely different. Frequently the gas media in distribution GIS is used for insulation and for load current interruption. The switching of fault current is most frequently handled by vacuum interrupters insulated by SF_6. To replace SF_6 GIS, solutions such as solid insulation are well known. However, the use of solid dielectric is in general more costly, larger, and leads to lower flexibility and customization.

Technologies using air or oil has been advocated long ago due to the risk of fire, unreliability, and size.

As a replacement for SF_6 that provide the benefits of small size and flexibility, gas alternatives such as compressed air (using synthetic air), fluoroketons and fluoronitriles (referred in advance as C4-FN) have been developed in the past decade to provide SF_6-free GIS. There are benefits and disadvantages to each of the potential substitutes. It is important to understand the factors and limitations of each option to choose the gas that best suits the application.

For the North American market, it's common practice to locate the GIS outdoors, without any external source of heat, where it is exposed to weather changes and cold environments. Because of this, the device is required to be fully functional at low temperatures that can vary from -25C to -40C (-50C for Canada) depending of the location and utility requirements. MV GIS is often provided already filled by the manufacturer, meaning that the transportation is performed with the GIS already pressurized. Both requirements have a direct impact on the selection of the insulating gas. From the alternatives listed above, C4-FN is the leading candidate to substitute SF_6 for the North American market due to the lower dew point compared to fluoroketons. Synthetic air/technical air requires higher pressures to reach dielectric strength comparable to SF_6 and cannot be used as interruption media (synthetic air requires the use of vacuum interrupters), complicating the transportation and/or making the commissioning costly.

C4-FN mixtures analysed in this paper have a GWP 98% lower than SF_6. The pressure used in the GIS is similar to SF_6 switchgear, providing also similar switching and insulation performance. The pressure limit is 15psig (2 bar, abs), which is the threshold above which the GIS will be considered a pressure vessel per ASME [15].

1.2 Gas analysis tools background

For the analysis of the gas mixtures, two analytical methods were used in the laboratory. **G**as **C**hromatography (GC) coupled with various detectors like **M**ass **S**pectrometer (MS) and **T**hermal **C**onductivity **D**etectors (TCD) as well as **F**ourier **T**ransform-**I**nfra**r**ed Spectroscopy (FT-IR).

Gas chromatography itself is a common type of chromatography used in analytical chemistry to analyse mixed gaseous or liquid samples by separating the single components. Further details on the special measurement methods for alternative gases are described in Cigre brochure D1.67 [11].

After the GC column, the gas flow was split and further analysed by TCD and MS.

The quantification was carried out by thermal conductivity detectors. A TCD has the capability of detecting nearly all compounds except the carrier gas used for the chromatography. TCD produces a signal based upon the measured difference in the thermal conductivity between the sample gas and the pure carrier gas. It's a non-specific detector with detection limits down to the ppm level.

Mass spectrometry is a technique for measuring the mass-to-charge ratio of ions. Typically, it is used more for identification than for the quantification of substances. In the first step, the molecules separated after the GC column are ionised through the interaction with energetic electrons and accelerated by an electric field. After that, they are separated according to their mass-to-charge (m/z) ratio and detected.

The following identification of the detected fragments by means of the mass spectra was done with the help of the NIST library [12] or using externally acquired reference materials. Through the different measuring modes of an MS, it's possible to analyse impurities of single compounds lower than the ppm-range. One measuring mode is called **T**otal **I**on **C**hromatogram (TIC), which is the sum of the intensities generated by the ions of all m/z values of the measured range in the spectrum. In the **S**elected **I**on **M**onitoring (SIM) mode only limited mass-to-charge ratio or ranges are detected by the instrument. Due to the special selection, an increased detection level down to the ppb range can be obtained (

Figure 1).

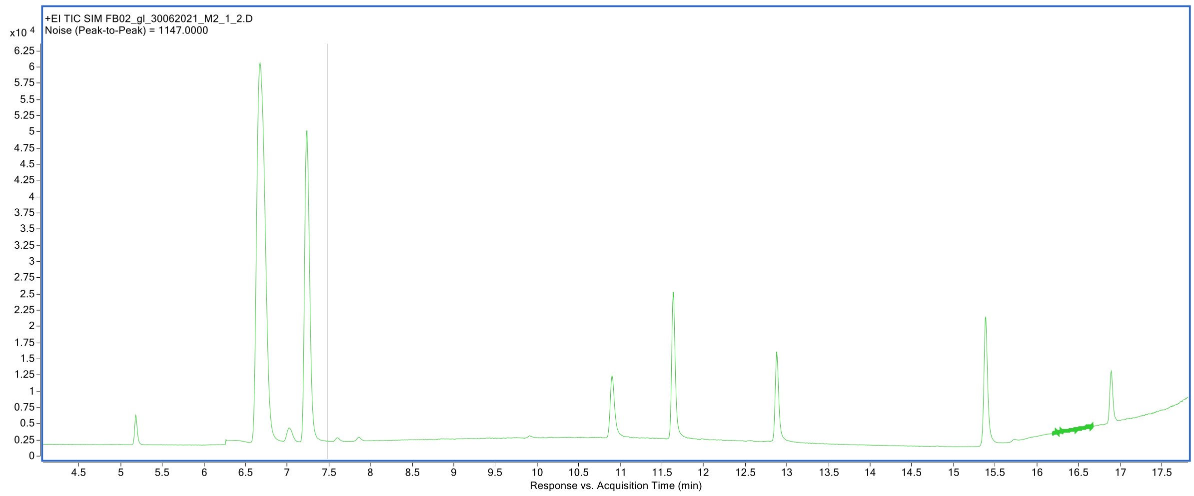

Figure 1: Enlarged chromatogram of a measurement of a C4-FN mixture after the experiments. Each peak represents one decomposition or by-product. For better visualisation, the main peak of C4-FN at retention time from 18 min is cut off.

FT-IR is a technique used to obtain an infrared spectrum of absorption or emission of a solid, liquid or gas. An FT-IR spectrometer simultaneously collects high-resolution spectral data over a wide spectral range. The absorption and transmission spectra are specific to the corresponding molecules. Those different spectral behaviour of matter regarding absorption or transmission of electromagnetic radiation may be utilized for gas-mixture analysis.

2. SWITCHING PERFORMANCE

IEEE C37.74 load break standard for up to 38kV [4] was used as the reference standard for the switching performance. As a first step to develop SF_6-free GIS, two of the most popular load breaker technologies for MV were tested using the original SF_6 design as a baseline. From the results it's possible to draw the differences between C4-FN mixtures and SF_6. During testing, numerous monitoring technologies to analyse the switching performance in the MV field were used: linear laser sensors, optic and piezo pressure sensors, and a high-speed camera with visual access to the interruption event. All of them synchronized with the power lab DAQ [5].

Along with the contact motion, pressure and visual extinction of the arc, parameters as arcing voltage were also recorded. Arcing voltage is indispensable in estimating the amount of C4-FN consumed during the interruption process and assess the interruption performance. With access to all these tools, the process of reengineering of the switches for alternative gases becomes more efficient and the need of iterative testing is simplified.

For the feasibility analysis of the current SF_6 breakers, two gas mixtures were selected as candidates to replace SF_6. Table I explains the composition, pressure and liquification temperature for each of them.

Table I : SF_6-free gas mixtures compared to SF_6 [6]

Gas mixture	Composition	Pressure [kPa]	Liq. Temp. [°C]	Density [kg/m^3]	E_b* [kV]
Mix A	15%$_{mol}$ C4-FN / 85%$_{mol}$ CO_2	160-170	-32	4.5	80
Mix B	10%$_{mol}$ C4-FN / 5%$_{mol}$ O_2 / 85%$_{mol}$ CO_2	160-170	-37	3.7	76
SF_6	SF6	160-170	< -50	10.1	84

*Breakdown voltage for rod to plane configuration and 20mm insulating gap according to [6].

The breakers under analysis are a linear puffer (LP) and a rotary switch (RS). The principle of interruption and evaluation of performance using alternative gas mixtures are explained ahead.

2.1 Linear Puffer

Load break

MV load break LP technology is based in the injection of gas axially from the compression chamber into the extinction chamber, quenching the arc and restoring the dielectric properties at current zero (CZ). The arcing energy is at least one order of magnitude lower than for HV circuit breakers, hence, the energy required for interruption and the complexity of the design is accordingly reduced. However, to optimize the design and cost, the parameters of design should be carefully analysed.

The switches tested using SF_6 and gas alternative mixtures were identical and used up to 2 pressure sensors located in the compression (P1) and extinction (P2) chambers. Also, the motion of the contact was measured by a laser sensor, synchronized with a high-speed camera. During the interruption process it's possible to account for four stages, naming them: precompression (A), arc stagnation (B), arc quenching (C) and dielectric recovery (D). A visual representation of the stages is shown in Figure 2.

It was observed that the switches using alternative gases were slightly faster than the ones using SF_6. This is explained by the density variation between gases (refer to Table I).

It was found that the arcing times for 27kV/630A were similar between both alternative gas mixtures and SF_6.

For 38kV/630A both mixtures had longer arcing time than SF_6. This is explained by the superior insulation properties of SF_6 versus C4-FN mixtures studied in this paper. Due to the steeper Rate of Rise of Recovery Voltage (RRRV), 38kV is more challenging than 27kV for alternative gases.

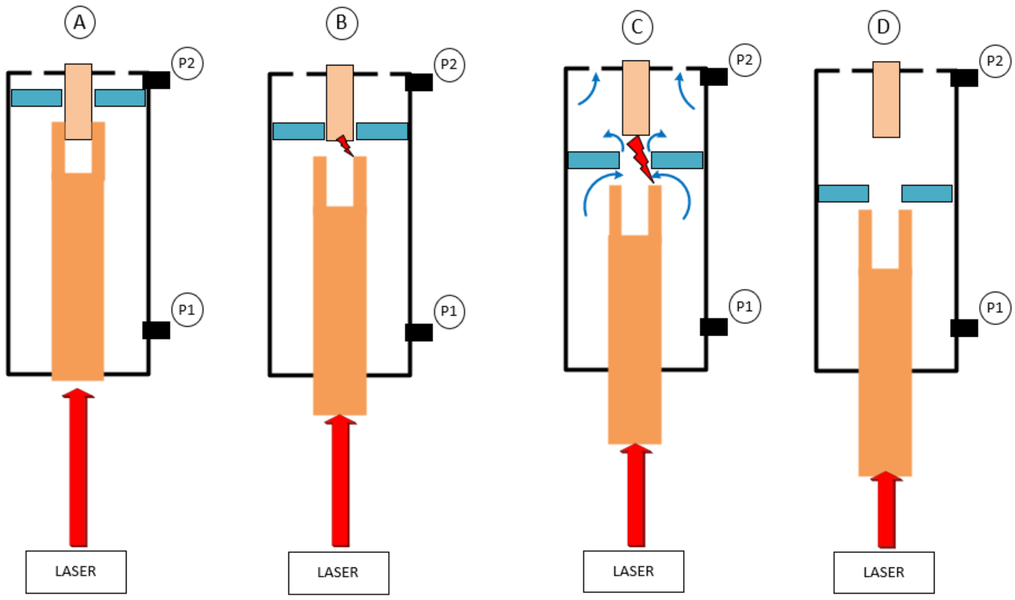

Figure 2 : Interruption stages for MV LP load breaker. A. Precompression. B. Arc stagnation. C. Arc quenching. D. Dielectric recovery.

High-speed recording was a great tool to observe the interruption phenomena and troubleshooting. In Figure 3 it can be observed 4 instances easily.

Figure 3: Stages of LP load break interruption observed with HSC, from left to right: 1- Contact separation. 2- Stagnation. 3- Current peak. 4- Instant before CZ followed by arc extinction

Cable charging

Using the same principle as for load break, switches filled with SF_6, Mix A and Mix B were tested for 27kV/20A cable charging interruption. The results of the test show that capacitive interruption is more challenging for alternative gases due to a steeper TRV (Transient Recovery Voltage) than load break. Although all gases were efficient in the interruption of 20A, both gas mixtures had reignitions and single-restrikes after current interruption. This is caused by a lower Rate of Rise of Dielectric Strength (RRDS) of the gas mixtures when compared to SF_6 for the same switch design.

Faster opening mechanism and changes in the nozzle/contact design can help to increase the initial acceleration and reduce the electrical field to improve the performance for cable charging of gas alternatives.

Figure 4: Restrike (left) and reignition (right) for gas alternative mixtures

2.2 Rotary Switch

Load break

Rotary switches are found mainly in MV applications. Their designs are very specific of the manufacturer, but they share a few peculiarities. Unlike LP, for which interruption is based on axial arc-quenching, they use the arc elongation principle. RS switches increase the arc voltage after contact separation, relying on the current zero to cool the gas media enough to recover the dielectric strength across the arcing contacts. The design consists of blade contacts attached to a rotating shaft that engages two stationary contacts with a set of barriers (Figure 5).

RS combines compact and simple design with a low energy mechanism compared to LP since they don't require gas compression. However, they are restricted to load break applications, being subject of limitations for higher currents due to the high energy of the arc (higher arcing voltage for the same current).

During testing, Mix A and Mix B shared similar arcing times. However, arcing time was notably higher than SF_6. The explanation may be the higher heat capacity of SF_6 capable to dissipate the arc more efficiently that the gas mixtures, increasing the RRDS. Also, since gas is not forced and renovated as efficiently as for LP technology in the interruption volume, decomposition of gas mixture negatively impacts the dielectric recovery of the interrupting media.

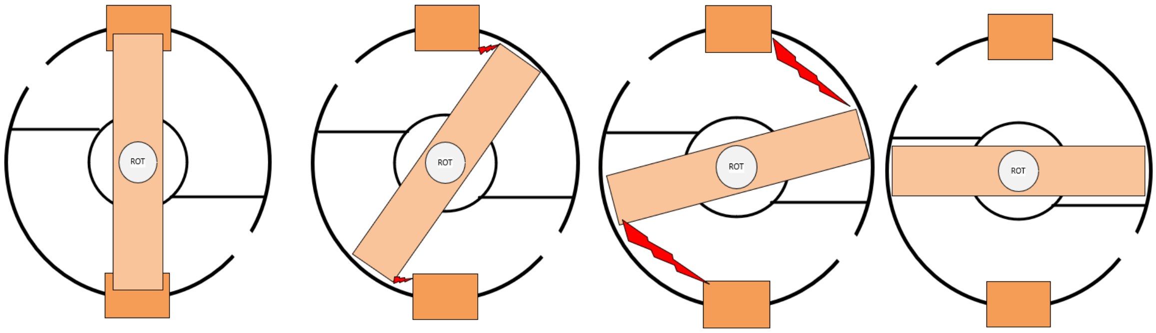

Figure 5: MV Rotary Switch interruption principle. A. Close position. B. Contact separation. C. Arc elongation. D. Dielectric recovery

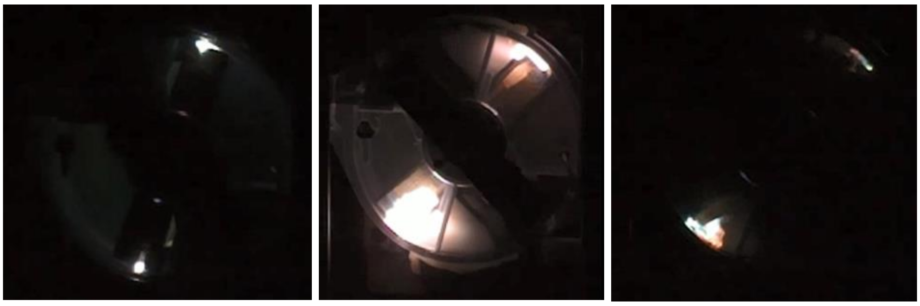

Figure 6: MV Rotary switch high speed frames for contact separation (left), arc elongation (middle) and current zero followed by dielectric recovery (right)

Cable charging

Sharing similarity with the LP design, RS using alternative gases is more susceptible to restrike and reignitions during cable charging compared to SF_6.

Replacing the arced surface material, shape and increase of opening speed improves the performance of cable charging for alternative gases notably.

3. GAS DECOMPOSITION

It's been exposed in previous works [7] that during electrical arc events the temperature reached is well above 700°C. Therefore, the C4-FN molecules are subject to decompose and break down during the ionization of plasma, not recombining after. This leads to a loss of C4-FN concentration over the lifetime of the switch. The amount is calculated based in previous publications [9] [10], using the ratio of C4-FN dissociated per MJ of arcing energy of 0.5mol/MJ.

3.1 Arcing energy determination and amount of C4-FN decomposed

The values of arcing energy per breaking operation are consistent for all gas mixtures and similar to SF_6. The parameters more relevant to calculate arcing energy are arcing voltage, current, arcing time and breaking method.

For the LP, the average arcing energy for a three-phase breaking operation for either 27kV or 38kV voltage, and 630A is 2kJ. Depending on the arcing time, the value can fluctuate from 1.5kJ to 2.5kJ. For a 50% operation (315A) the arcing energy is reduced to 0.7kJ.

In the case of the RS, the arcing energy is higher for the same rating when compared to the LP. This is caused by higher arcing voltage, result of the breaking method (arc elongation). The arcing energy fluctuates from 2.2kJ to 3.3kJ.

For both technologies, the mixtures analysed in this paper share a similar performance and arcing energy. Thereby, for estimations of gas decomposition the value of arcing energy per load break operation will be the same for both mixtures.

For some applications, MV LBS can perform the equivalent of 100 operations at full load (worst-case scenario). This translates into a gas consumption of 0.1 mol for the LP and 0.17 mol for the RS. Choosing a standard size of a MV LP switch compartment of 0.4 m^3, the loss of C4-FN due to load break switching during the lifetime of the switch would be 2.5% for Mix A, and 3.6% for Mix B. Table II shows some of the values calculated using this criteria.

Table II: Gas decomposition estimation based on arcing energy

Switch type	Mixture	Initial C4-FN [% mol]	C4-FN in 0.4m^3 [mol]	C4-FN consumption* [mol]	C4-FN decomposed [%]	End of life C4-FN [%]
LP	Mix A	15%	4.19	0.1	2.3%	14.6%
	Mix B	10%	2.79	0.1	3.6%	9.64%
RS	Mix A	15%	4.19	0.165	3.9%	14.41%
	Mix B	10%	2.79	0.165	5.9%	9.41%

**Value estimated for 100x full-load breaking operations. Energy per LP operation is 2kJ. Energy per RP operation is 3.3kJ.*

3.2 Analytical verification of the by-products

Although mixtures of most gaseous substances can be separated by using different columns in the GC, it is not possible to measure some specific substances like hydrogen fluoride (HF) or carbonyl fluorides (CF_2O, C_2F_4O) because of their reaction with the column material. Their proportion has to be determined via FT-IR measurements.

As far as possible the concentration of the by-products was determined using existing test gases.

The number of decomposition products after arcing is very diverse and many of the decomposition products are very similar in their chemical structure (fluoroalkane C_xF_{2x+2}, fluoroalkene C_xF_{2x}). Due to the low concentrations in the decomposed gas, some of the molecules can only be determined in SIM-mode with selected m/z ratios, which makes clear identification difficult. For example, for C_4F_8 there are several isomers, which means that the molecule has the same molecular formula but different chemical structures. In some cases, these can only be differentiated in the mass spectrum by distinguishing the intensities, which is made even more difficult by the low intensities in the SIM mode. The identification is also be made more precise via the retention time.

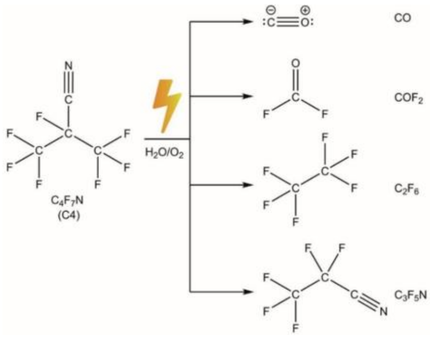

Figure 7: Schematic illustration of selected decomposition products of C4-FN in the presence of moisture and oxygen after a discharge.

4. TOXICITY

The number of theoretically possible [13] and in practice observed decomposition products [14] of mixtures with C4-FN is high. Since many of the substances are not available in pure form, a more precise estimation of the hazard potential of the entire mixture is difficult. The nitrile compounds C_3F_5N, C_2F_3N, COF_2 and HF, and as an example for toxic fluoroalkane/-alkene isomers the C_4F_8 PFIB (CAS: 382-21-8), are generally regarded as the most toxic substances that can be formed in the event of arcing of C4-FN mixtures.

Based on the gas analysis performed on gas samples from units using both technologies, values of toxicity can be estimated by the ATE (Acute Toxicity Estimation) of the mixture (ATE_{mix}). This has been performed by using the LC50 (Lethal Concentration at 50% mortality after 4 hours) for each specie in the mixture and apply the OSHA method for "Tier 3: Classification of mixtures based on ingredients of the mixture (additivity formula)" [8]. The calculation is performed using (Eq. 1).

$$ATE_{mix,n} = \frac{100(\%)}{\frac{C_1}{LD_{50\,(1)}} + \frac{C_2}{LD_{50\,(2)}} + \frac{C_3}{LD_{50\,(3)}} + \frac{C_4}{LD_{50\,(4)}} + \cdots + \frac{C_n}{LD_{50\,(n)}}} \qquad \text{(Eq. 1)}$$

The results in Table III show that the toxicity of the by-products generated during load break increase the toxicity of the mixture after completing the while type test switching sequence. However, the toxicity doesn't increase notably, staying within values of category 5 per OSHA, considered as practically non-toxic. The Table III shows the ATE_{mix} for switches that went through the standard C37.74 switching test, and in some cases, some additional load break and fault making shots. The ATE_{mix} ranges between 38,000ppm and 57,000ppm. The oxygen has little or no impact on the toxicity reduction of the arced gas samples.

Table III:Gas composition, LC50 and ATE_{mix}

Switch type	Mixture	Initial gas composition	Initial toxicity (ATE_{mix}) [ppm]	Volume of gas [m^3]	Accumulated arc energy [kJ]	After arcing (ATE_{mix}) [ppm]
LP	Mix A	15% C4-FN/ 85% CO_2	58,449.0	0.4	46.6	~49,000.0
	Mix B	10% C4-FN/5% O_2 / 85%CO_2	76,285.0	0.4	65.0	~57,000.0
RS	Mix A	15% C4-FN/ 85% CO_2	58,449.0	0.36	63.0	~38,000.0
	Mix B	10% C4-FN/5% O_2 / 85% CO_2	76,285.0	0.36	62.4	~40,000.0

5. SOLID DEPOSITS AND EFFECTS OF ARC-ERODED SURFACES

Previous publications have analysed the influence of oxygen on the gas by-products and their toxicity, but also on the generation of soot or solid powders. This has low impact in MV load breakers since the accumulated arcing energy is more than one order of magnitude when compared to HV circuit breakers (150kJ vs 3,000kJ). It has been observed that soot is also generated in SF_6 [16].

It was perceptible to the eye that mixtures with higher C4-FN concentration and without O_2 had lower visibility due to carbon particles in suspension and soot[17]. However, the amount of soot was low and almost undetectable after the load break sequence, equivalent to the one observed in SF_6.

The arc-eroded surfaces of the RS had an increased conductivity after the load break sequence, promoting the electrical breakdown by surface discharge. It was observed that 5% O_2 reduces partially the conductivity of these arc-eroded surfaces, self-restoring insulation after the breakdown. This is visible by the coloration change on the surface with and without O_2 (Figure 8).

Figure 8: Surface tracking on the arced surface without O_2 (left) and with O_2 (right)

It was proven in subsequent tests that the redesign reduces the arcing energy and arcing time, with an even more notable effect than adding O_2, surpassing the visibility of the original SF_6 switchgear. Reengineering the materials with C4-FN compatible materials has also a large impact on the effects of arcing surfaces, not requiring O_2 if arc-eroded materials are chosen correctly.

6. CONCLUSIONS

The replacement of SF_6 by other gas mixtures is not an easy task and it requires an extensive research. Gas decomposition, partial liquification of the mixture at low temperature, gas consumption and by-products from arcing add multiple challenges that are not an issue for MV SF_6 switchgear.

C4-FN gas combined with CO_2 and with/without O_2 is a viable substitute to SF_6 for MV switchgear applications. However, original SF6 design must be modified to reach equivalent values with alternative gases, specially for cable charging.

Switching of load currents for MV ratings have been proven to be feasible using gas alternatives. For load switching using LP 38kV/630A and RS 27kV/630A, changes in the design of the switch are required to match the SF_6 performance. For switching of capacitive loads, the decrease of performance when compared to SF_6 is shared for all ratings and designs. Modifications of the arcing contacts, nozzle design and opening speed can improve the performance effectively for both, load break and capacitive loads.

Life-time calculations are showing that C4-FN consumption due to current interruption, although being in fact present, have a small effect on the C4-FN concentration throughout the life of the switch. Improvement in the load break performance (mentioned in the paragraph above) will shorten arcing time, reducing the arc energy during load break and thereby decreasing the gas consumption.

Finally, toxicity value for normally arced gas samples (after standard load break sequence) shows a low level of increase in the toxicity of the gas mixture, keeping the toxicity value under category 5. Being in category 5 allows for a more permissive UN labelling and safety protocols in the case of leakage, making the reclaiming and transportation process much easier and cost effective.

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