

LOW-CURRENT INTERRUPTION IN SF₆-ALTERNATIVES

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ABSTRACT

SF₆ is used as an insulation and interruption medium in medium-voltage (MV) gas-insulated switchgear (GIS), but has a very high global warming potential. In recent years, several environmentally-friendly (eco-efficient) alternatives have been explored, focusing on dielectric and thermal properties. The interruption of low currents in MV application is emerging as an important topic for equipment manufacturers and users. The reduced arc-quenching properties of the most prominent eco-efficient alternatives may require the use of vacuum interrupters for simple load current interruptions. However, this may not be a cost-effective solution and simpler interruption principles are desirable.

In this paper, we explore low-current interruption in AirPlus™, a mixture of dry air and the C₅F₁₀O fluoroketone (C5-FK) as well as mixtures of CO₂ and C5-FK. We find that it is possible to achieve the E3 electrical endurance class (100 c/o) with a switch based on the puffer principle in AirPlus with a condensation temperature of -25°C, suitable for secondary distribution MV GIS. The chemical analysis of gas samples taken from the switchgear after 100 successful interruptions indicate only trace amounts of fluoroketone decomposition products.

INTRODUCTION

Medium-voltage (MV, 1-52 kV) gas-insulated switchgear (GIS) are key components in primary and secondary distribution networks. In MV GIS for primary and secondary distribution, the gas serves as a medium for electrical insulation and cooling, as well as the interruption of low currents (load currents, typically 1 – 1250A). SF₆ provides all these features in compact equipment and is the standard technology in modern power distribution products. Unfortunately, SF₆ has a high global warming potential (GWP).

Even though MV GIS have SF₆ emissions of less than 0.1% / year, the EU has specifically targeted SF₆ for replacement in MV GIS for secondary distribution [1].

The main technical challenges of replacing SF₆ with eco-efficient gases are the reduced dielectric strength, thermal conductivity and arc-quenching performance of non-toxic, non-flammable alternatives. Several suitable gases are under investigation and the associated thermal and dielectric challenges have been widely addressed [2-5].

In this paper, we present the results of full-scale experiments of low current interruption in MV GIS filled with AirPlus, a mixture of dry air and the C₅F₁₀O fluoroketone (C5-FK), as well as mixtures of CO₂ and C5-FK. Gas samples collected from the switchgear before and after 100 successful interruption experiments are analyzed with respect to their chemical composition.

LOW CURRENT INTERRUPTION

SF₆ is the industry's standard interruption medium for cost-effective MV load break switches. The excellent arc-quenching properties of SF₆ can be explained by high thermal conductivity and the rapid recovery of dielectric strength after arcing [6]. The most widely discussed eco-efficient alternatives, fluoronitriles (FN) and fluoroketones (FK), are mixed with background gases (CO₂ or air) to allow a sufficiently low condensation temperature (-25°C or lower for secondary MV GIS) [2]. As with thermal and dielectric properties, the arc-quenching properties of the mixtures are expected to be somewhat reduced due to the limited arc-quenching properties of the background gases. Note that CO₂ has better arc-quenching properties than air [7], but lower dielectric strength.

A further challenge with FN, FK and other SF₆-alternatives is the potential generation of dangerous by-products after arcing.

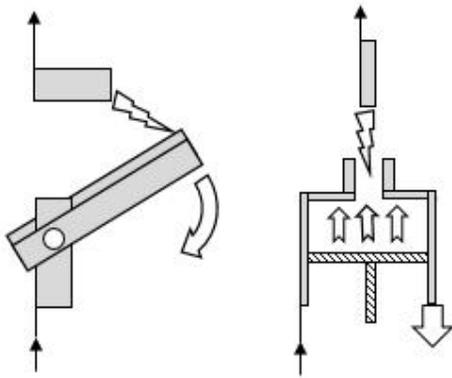


Figure 1. Basic operating principles of (left) the knife switch and (right) the puffer switch during interruption of current. The knife switch is a simple device in which two flat electrodes (knives) are rotated away from a single, static contact. The main principle for interruption is arc-quenching by the surrounding gas. The puffer switch utilizes the contact motion to compress gas and blow it in the direction of the current arc to improve cooling and arc-quenching.

SF₆ is chemically stable and recombines to a very high degree after dissociation under low current arcing, resulting in very limited quantities of by-products. FN and FK are both relatively large, carbon-chain molecules and the risk of forming toxic or dangerous by-products in typical MV networks operational conditions requires the appropriate research and understanding.

Further, by-products may also form through other chemical reactions with materials in the gas compartment. As reported by Hyrenbach et al. [3], the chemical compatibility of each material in the GIS must be carefully evaluated for chemical compatibility with the alternative gases to ensure that no decomposition takes place.

Preve et al. [8] recently reported a study of low current interruption in several SF₆ alternatives with a conventional knife-type load break switch. Failed interruptions, unwanted pressure build-up and/or the generation of toxic by-products were observed for all mixtures and it was concluded that current interruption in non-SF₆, MV network components can only be realized with vacuum technology. It was not clear from the report whether the by-products could be attributed solely to the dissociation of the gas during arcing, or if they were also formed through additional reaction paths with incompatible materials in the test object.

There are several disadvantages in using vacuum interrupters for load break switching in MV GIS. For example, vacuum interrupters are not accepted as disconnectors by the IEC standard, so a disconnector in

series is required. This leads to a more complicated operating sequence between line and ground potential, since two devices must be operated. Further, the cost of vacuum interrupters, a disconnector and two drives, increases the cost of the GIS significantly compared to the knife switch that is commonly used in SF₆.

An alternative to the knife switch and the vacuum interrupter is the commonly used puffer principle. As shown in Figure 1, rather than relying on the properties of the interruption medium (gas or vacuum) alone, the puffer switch relies on forced convection in the arcing region.

For MV load current interruption, puffer switches are more cost-effective than vacuum interrupters and have a higher level of interruption performance compared with simple knife switches. Further, puffer switches are accepted as disconnectors in the open position, simplifying the operating sequence and reducing the cost of the GIS.

EXPERIMENTS

Low current interruption

The interruption performance of a knife-type switch and two types of puffer switches were explored in eco-efficient gas mixtures with full-scale interruption experiments.

The knife switch and first puffer switch were part of commercially available compact MV GIS, (“SafeRing 24 kV” and “SafeRing 36 kV”), with gas volumes of 0.27 m³ and 0.58 m³, respectively. The second puffer switch was part of a prototype compact MV GIS with a gas volume of 0.27 m³. This prototype was constructed mainly from materials that were found to be chemically compatible with C5-FK, as outlined by Hyrenbach et al. [3]. All test objects were equipped with one bag (~500 g) of 5 Å zeolite molecular sieve (drying agent) to reduce moisture in the gas volume.

Four different mixtures of dry air, CO₂ and C5-FK were tested. The total pressure for all experiments was 1.3 bar (abs), but the partial pressures (@20°C) were varied, giving different condensation temperatures (-25°C, -17°C and 0°C) for C5-FK in the mixtures:

1. 160 mbar C5-FK (-17°C) and 1140 mbar CO₂
2. 160 mbar C5-FK (-17°C) and 1140 mbar air
3. 370 mbar C5-FK (0°C) and 930 mbar air
4. 105 mbar C5-FK (-25°C) and 1195 mbar air (AirPlus)

The interruption experiments were carried out according to the “active load” (TD_{load2}) test duty of the IEC standard for switches [9]. The rated voltages (U_r) were 12 and 24 kV and the rated current (I_r) 35 to 690 A (rms). The knife switch was tested only as single-phase. Both puffer switches were tested for full three-phase interruption. Typically, 5-10 interruptions were performed at each level of voltage or current before increasing the test duty. The experiments were stopped at the first failed interruption. A total of 34 experiments were performed with the knife switch, 215 with the first puffer switch and 100 with the second puffer switch.

Chemical analysis

The concentration of C5-FK in the fresh gas mixtures were measured with a commercially available gas density meter based on a resonant micro tube (Integrated Sensing systems Inc., model FS-GDM).

The residual concentration of C5-FK in the gas samples, taken from the prototype GIS after the interruption experiments, was measured with a newly developed gas concentration measurement system, which is based on UV-LED optical detection. This system allows for the identification of specific gases in a mixture and is not influenced by the presence of by-products [10]. The chemical composition of these samples were further measured with gas chromatography mass spectrometry (GC-MS).

RESULTS AND DISCUSSION

Low-current interruption

The limiting test series for all devices are shown in Table 1. This corresponds to the highest ratings that were tested for a specific combination of the switch and gas mixture, or the highest ratings at which the interruption failed on the first occurrence and the test series was aborted.

It is clear that the knife switch cannot operate easily with eco-efficient SF₆-alternatives. In the 34 interruption experiments conducted, the arcing time ranged from 1 to 45 ms, with an average of 14 ms. The total opening time of the switch after contact separation was ~15 ms, indicating borderline interruption performance for the tested ratings. The highest current that was interrupted without failure (5 out of 5 times) was 110 A at 12 kV. The performance does not seem to improve significantly when replacing pure air with the CO₂/C5-FK mixture, as the switch fails at ~ 220-230 A in both mixtures.

The first puffer switch performs significantly better. Especially in C5-FK-mixtures, the limiting performance is 240 A @ 24 kV with air/C5-FK (0°C) and 660 A @ 24 kV with CO₂/C5-FK (-17°C).

Table 1. Limiting test series for the interruption of each switch and gas mixture.

Switch	Gas	Ur [kV]	Ir [A]	Success [-]	Fail [-]
Knife	Air	12	223	1	1
Knife	CO ₂ /FK ¹⁾	12	227	2	1
Puffer 1	Air	12	110	10	0
Puffer 1	Air/FK ²⁾	12	470	4	1
Puffer 1	Air/FK ³⁾	12	690	5	0
Puffer 1	Air/FK ³⁾	24	240	5	1
Puffer 1	CO ₂ /FK ¹⁾	12	660	5	0
Puffer 1	CO ₂ /FK ¹⁾	24	660	2	1
Puffer 2	Air/FK ⁴⁾	24	660	100	0

^{1,2)} Mixture with C5-FK condensation temp. of -17°C

³⁾ Mixture with C5-FK condensation temp. of 0°C

⁴⁾ Mixture with C5-FK condensation temp. of -25°C (AirPlus)

It seems clear that both increasing the C5-FK concentration and replacing air with CO₂ have positive effects on interruption performance. The average arcing time of all experiments was 6.2 ms, (ranging from 0.1 to 19 ms). The opening time of the switch after contact separation was ~20 ms.

The second puffer switch was developed to further improve interruption performance. With the new design, we were able to interrupt 660 A @ 24 kV without failure 100 times consecutively, qualifying for the E3 electrical endurance class [9]. Even with the low concentration of fluoroketones in mixture no.4 (C5-FK condensation temperature of -25°C), this switch performed far better than the other switches.

The arcing time ranged from 0.5 to 13 ms, with an average value of 7 ms. The opening time of the switch after contact separation was ~ 20 ms.

The current through and voltage across the switch in one sample experiment are shown in Figure 2. The resolution is limited to 50 V, but one may still observe that the arcing voltage is of the order of ~50 - 100 V in all three phases. The accumulated arcing energy (Q) after N interruptions experienced by the gas volume can be estimated from the average arcing time (t_{arc}), current (I) and voltage drop (dU) across the arc:

$$Q = N \times t_{arc} \times I \times dU$$

$$Q = (100 \times 3) \times 0.007s \times 660A \times 100V$$

$$Q \gg 140 \text{ kJ}$$

The details of the interruption principles are outside the scope of this publication, but the experiments serve to demonstrate that low-current interruption at MV is possible in AirPlus with a device based on the puffer principle.

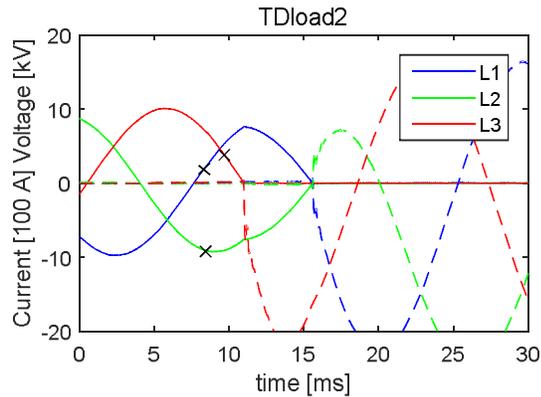


Figure 2. Sample current and voltage curves from a successful interruption experiment with the second puffer in air/C5-FK (-25°C). The black crosses marks contact separation and start of arcing.

Chemical by-products

The 100 successful interruption experiments in AirPlus with the second puffer switch further made it possible to explore the chemical decomposition of C5-FK due to low-current arcing.

In general, we expected the formation of decomposition products to be limited, as we did not observe any change in the concentration of C5-FK or gas pressure during the experiments. The results of the GC-MS of the two gas samples taken from the prototype GIS after 100 interruptions are shown in Figure 3 a) and b).

The first sample was analyzed for the content of the main decomposition product of C5-FK, heptafluoropropane (C_3HF_7). Only trace amounts (less than 0.01%) were detected, indicating that very limited decomposition had taken place.

The second sample was analyzed with a higher resolution to improve the detection of other by-products. In addition to heptafluoropropane, the following compounds were detected at trace levels:

- tetrafluoromethane (CF_4)
- carbon dioxide (CO_2)
- hexafluoroethane (C_2F_6)
- perfluoropropane (C_3F_8)
- perfluorobutane (C_4F_{10})

With the exception of CO_2 , none of these compounds are toxic according to 4-hr LC50 values.

The zeolite drying agent installed in the GIS may have absorbed some of the decomposition products during or after arcing.

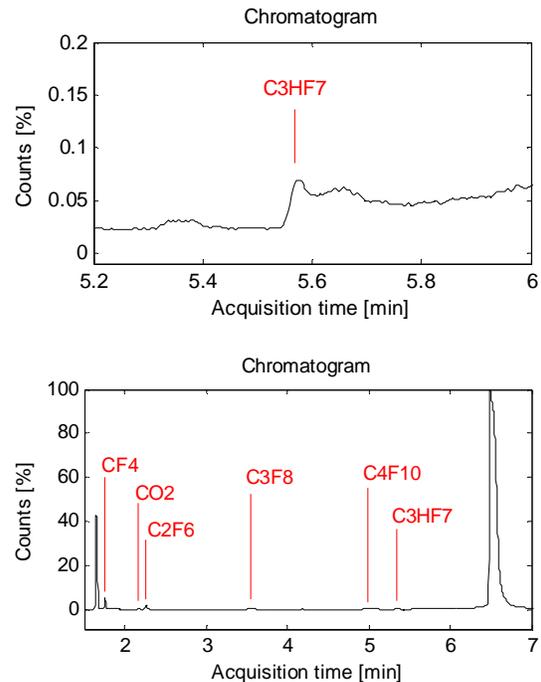


Figure 3: Chromatogram (GC-MS) of the two gas samples taken from the GIS with the second puffer switch after 100 interruptions of 660 A at 24 kV in AirPlus. (a) The first sample was analyzed only for heptafluoropropane (only a zoomed window is shown). (b) The second sample was analyzed with a higher resolution to detect additional compounds. Note that the first, unmarked peak is due to N_2 and O_2 .

Although this was not fully investigated, we may conclude that no toxic by-products will be present in the gas volume after interruption, as long as it also contains a bag of drying agent. This is, after all, the most relevant scenario for the end user.

CONCLUSION

We have demonstrated that low current interruption in a compact MV GIS with AirPlus is feasible for currents up to 660 A and voltages of 24 kV with an alternative switch design based on the puffer principle. The 100 successful interruptions were not found to cause any significant degradation of the gas and no toxic by-products were detected.

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