

Recent development of SF₆ alternative gases for switching applications

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Abstract

The available knowledge of state-of-the-art of SF₆ alternative gases in switching applications was collected and evaluated. The amount of information available is very limited and often only from single sources. The main properties and switching performance are compared to SF₆. The most promising new gases are perfluoroketones and perfluoronitriles. Due to the high boiling point of these gases, in HV applications mixtures with CO₂ are used. For MV insulation perfluoroketones are mixed with air, but also other combinations might be possible. The dielectric and switching performance of the mixtures, with mixing ratios that allow sufficiently low operating temperatures, is only slightly below SF₆. Minor design changes or de-rating of switchgear are therefore necessary. Unlike SF₆, the new gases decompose under the influence of arcing. Differences between the gas mixtures are mainly in the boiling point and the GWP.

1. Introduction

SF₆ is widely used in electric power transmission and distribution systems, as for example in gas insulated switchgear (GIS), circuit breakers (CB) and load break switches. It combines unique electrical insulation and arc interruption capability [1]. However, it is also a very strong greenhouse gas with a global warming potential (GWP) of about 23500 over a time horizon of 100 years, e.g. [2] and its use is regulated and restriction is discussed. Therefore, search for alternative gases for use in power applications has been ongoing since about two decades ago e.g. [3][4]. In the present paper we briefly review the status of the present solutions, with a focus on switching application. This review is mainly based on the most recent literature available from manufacturers. No independent confirmation is available. Since vacuum switching technology is a separate ongoing activity [5], it will be left out in the present review.

2. Search for alternative gases

The intensification of search for alternative gases started about two decades ago [3][4] after the Kyoto protocol was agreed in 1997 and further increased in the last 10 years (e.g. [6][7][8][9][10][11][12][13][14]). Important requirements for alternative gases were identified as in the following list:

- Low global warming potential (GWP) and zero ozone depletion (ODP) potential
- Low toxicity and non-flammability
- High dielectric strength, arc quenching capability and heat dissipation property
- Stability and material compatibility
- Availability on market

From various studies of gases of natural origin, CO₂ turned out to be the most promising arc quenching gas, e.g. [7][10], possibly enhanced in performance by some additives [11]. However, as was shown, the switching and dielectric performances of CO₂ are both below those of SF₆, e.g. [10][15]. Other interesting gases were identified to be fluorinated gases like CF₃I, hydrofluoroolefins (HFO1234ze and HFO1234yf), perfluoroketones (e.g. C₅F₁₀O), perfluoronitriles (C₄F₇N), fluoroethers (HFE245cb2), fluorooxiranes and hydrochlorofluoroolefins (HCFO1233zd), e.g. [6][12][13][14][16][17]. Taking all the requirements into account, the most promising candidates at present appeared to be the C5 perfluoroketone (CF₃C(O)CF(CF₃)₂ or C5-PFK) [18] and the iso-C4 perfluoronitrile ((CF₃)₂-CF-CN or C4-PFN) [19]. The dielectric performance of pure gases scales with the boiling point, i.e. gases with high dielectric strength usually also have a high boiling point, see e.g. [9]. For C5-PFK and C4-PFN, the boiling points at 0.1 MPa are 26.5 °C and -4.7°C, respectively. Thus, for application in switchgear, where a sufficiently low boiling point is needed for low temperature requirements, an admixture of a buffer gas is needed. CO₂ is selected for this role in HV due to its good arc quenching capability. In MV application air is also reported as the buffer gas in combination with C5-PFK for insulation purposes [20][21][22]. The concentration of C5-PFK and C4-PFN, and by this the performance of the mixtures, will depend on the minimum operating temperature requirement of the switchgear. An additional

alternative approach is proposed to use air for insulation and vacuum CB (VCB) for switching [23][24]. As mentioned above switching in vacuum is not within the scope of the present document.

3. Properties of alternative gases and mixtures

The properties of the selected alternative gases with reference to SF₆ are shown in table 1. The GWP for the various gases are different: the C4-PFN has a much higher GWP than CO₂ or C5-PFK that are both around 1. All the gases of interest are not flammable, have no ODP and are non-toxic according to technical and safety data sheets available from the chemical manufacturer [18][19][25][26][27]. Classification and labelling of pure substances and mixtures are according to CLP European Regulation (EC) No 1272/2008 [33][26][27]. The dielectric strength of pure C4-PFN and C5-PFK is nearly twice that of SF₆. CO₂ has a dielectric withstand comparable to air [3][15], significantly below that of SF₆.

Table 1: Properties of pure gases compared to SF₆

| | CAS number | Boiling point/°C | GWP | ODP | Flammability | Toxicity LC50 (4h) ppmv | Toxicity TWA ¹⁾ ppmv | Dielectric strength/pu at 0.1 MPa | Ref |
|-----------------|------------|---------------------|-------|-----|--------------|-------------------------|---------------------------------|-----------------------------------|-----------------|
| SF ₆ | 2551-62-4 | -64 ²⁾ | 23500 | 0 | No | - | 1000 | 1 | [6][16] |
| CO ₂ | 124-38-9 | -78.5 ²⁾ | 1 | 0 | No | >300000 | 5000 | ≈0.3 | [3][4][15] |
| C5-PFK | 756-12-7 | 26.5 | <1 | 0 | No | ≈20000 | 225 | ≈2 | [12][16][18] |
| C4-PFN | 42532-60-5 | -4.7 | 2100 | 0 | No | 12000...15000 | 65 | ≈2 | [6][16][19][25] |

¹⁾ The occupational exposure limit is given by a time-weighted-average (TWA), 8-hr

²⁾ Sublimation point

The properties of gases and mixtures when used in switchgear are shown in table 2. The concentration of admixtures of C4-PFN and C5-PFK with the buffer gas is given in the second column and is typically below 13% (mole). Note that for the use of C5-PFK in CO₂ additionally an oxygen admixture is used, since the presence of oxygen reduces the generation of harmful by-products like CO and solid by-products as soot [28]. Due to a reduced dielectric withstand of the mixtures compared to SF₆ (column 6) at the same pressure the minimum operating pressure needs to be slightly increased to about 0.7...0.8 MPa for C5-PFK and C4-PFN when using CO₂ as the buffer gas for HV application, see column 3 in table 2. For Air/C5-PFK mixtures in MV application 0.13 MPa can be kept and the dielectric withstand of SF₆ is approached. The high dielectric withstand of mixtures with relatively low admixture ratios of C4-PFN or C5-PFK can be explained by a synergy effect [6][28][29], i.e. a non-linear increase of the dielectric strength with the admixture ratio, as it is known in SF₆/N₂ mixtures [30]. The GWP of mixtures with C5-PFK is negligible, at the cost of a higher minimum operating temperature. Low temperature applications of e.g. -25°C for HV can be covered by pure CO₂ or CO₂+C4-PFN mixtures. This is at the cost of significantly reduced dielectric withstand in case of pure CO₂ or significantly higher GWP in case of C4-PFN mixtures. Due to strong dilution, the toxicity of the mixtures is below that of the pure substances, see e.g. [6][32].

Table 2: Properties/performances of gases and mixtures in MV and HV switchgear applications

| | C _{ad} ¹⁾ | p _{min} /MPa ²⁾ | T _{min} /°C ³⁾ | GWP | D.S. ⁴⁾ | Toxicity LC50 ppmv | Ref |
|---|-------------------------------|-------------------------------------|------------------------------------|-------------|---------------------|--------------------|------------------|
| SF ₆ | - | 0.43...0.6 | -41...-31 | 23500 | 0.86...1 | - | |
| CO ₂ | - | 0.6...1 | ≤ -48 ⁶⁾ | 1 | 0.4...0.7 | >3e5 | [7][10][11] |
| CO ₂ /C5-PFK/O ₂ (HV) | ≈6/12 | 0.7 | -5...+5 | 1 | ≈0.86 | >2e5 | [12][17][24][28] |
| CO ₂ /C4-PFN (HV) | ≈4...6 | 0.67...0.82 | -25...-10 | 327...690 | 0.87...0.96 | >1e5 | [6][32][14][33] |
| Air/C5-PFK (MV) | ≈7...13 | 0.13 | -25...-15 | 0.6 | ≈0.85 ⁵⁾ | 1e5 | [16][21][22] |
| N ₂ /C4-PFN (MV) | ≈20...40 | 0.13 | -25...-20 | 1300...1800 | 0.9...1.2 | >2.5e4 | [15] |

¹⁾ Concentration of admixture is in mole % referred to the gas mixture

²⁾ Typical lock out pressure range

³⁾ Minimum operating temperature for p_{min}

⁴⁾ Dielectric strength compared to SF₆ at 0.55 MPa. For the scaling of SF₆ breakdown field E_d with pressure correction in the form of E_d=84·p^{0.71} was used [30]

⁵⁾ Compared to SF₆ at 0.13 MPa, measurements were for a mixture at -15°C

⁶⁾ Calculations with Refprop: <https://www.nist.gov/srd/refprop>

4. Switching performance of alternative gases and gas mixtures

Preliminary information on the switching performance of pure CO₂ and CO₂ mixtures is collected in table 3. The performance of SF₆ is given for comparison. With an enhanced operating pressure compared to SF₆ the cold dielectric strength, which is e.g. a measure of the performance in capacitive switching, can reach that of SF₆. In the scanned literature, only qualitative statements on the switching performance of C4-PFN and C5-PFK mixtures could be found. For CO₂ a few quantitative comparisons exist. Very roughly, for pure CO₂ at an increased fill pressure of about 1 MPa, about 2/3 of the dielectric and thermal interruption performance of SF₆ might be expected. With the admixture of O₂ to CO₂ in the mixing ratio range up to 30%, an increase of the thermal interruption performance [11] and also a slight increase in dielectric strength (e.g. [34]) is expected. With the admixture of C4-PFN and C5-PFK into CO₂ the dielectric performance can be close to SF₆. The short-line fault (SLF) switching performance for the mixtures of CO₂/O₂/C5-PFK is reported to be 20% below that of SF₆ [28]. For an adapted CB with CO₂/C4-PFN a similar SLF performance to that of SF₆ is stated, e.g. [6]. There are, however, also direct comparisons of pure CO₂ with CO₂/C4-PFN and CO₂/C5-PFK mixtures using identical geometry and pressure, which show similar thermal interruption performance of CO₂ with and without admixtures [24]. IEC test duties L90 (SLF) and T100 (100% terminal fault) with the new mixtures are passed with some design modifications [36] or certain de-rating [28], suggesting that the switching performance of the new mixtures is not significantly lower than that of SF₆. This has also been shown to be valid for the bus transfer switching duty of disconnecter switches, e.g. [35][36]. It is expected that dedicated design improvements can still increase the switching performance in the future.

Table 3: Switching performance of gases and mixtures compared to SF₆ at increased operating pressures in HV applications

| | Operating pressure [MPa] | Dielectric strength/pu | SLF performance compared to SF ₆ /pu ¹⁾ | Dielectric recovery speed/pu | Ref |
|--|--------------------------|--------------------------|---|------------------------------|-----------------|
| SF ₆ | 0.6 | 1 | 1 | 1 | |
| CO ₂ | 0.8...1 | 0.5...0.7 | 0.5...0.83 | ≥ 0.5 | [7][10][11][24] |
| CO ₂ +C5-PFK/O ₂ | 0.7...0.8 | close to SF ₆ | 0.8...0.87 | close to SF ₆ | [17][24] |
| CO ₂ /C4-PFN | 0.67...0.82 | close to SF ₆ | 0.83...(1) ²⁾ | close to SF ₆ | [6][24][30] |

¹⁾ At same pressure build up

²⁾ Same performance as SF₆ is stated but it is not clear if this was under same conditions

An important point is the toxicity of the gas after arcing. C5-PFK and C4-PFN are complex molecules which start to decompose above approximately 650°C in case of C4-PFN, e.g. [30]. After arcing some C5-PFK and C4-PFN molecules do not recombine to their original structure, but form smaller molecules. A decomposition rate of 0.5 Moles/ MJ under high current switching is reported for CO₂/O₂/C5-PFK mixtures [28]. For partial discharges decomposition rates of more than one order of magnitude lower are observed for this mixture [37]. No quantitative information is given so far on the decomposition rates of C5-PFN. Note that this decomposition involving the new gases is not comparable with the decomposition of SF₆ because the latter only occurs due to chemical reactions with ablated contact and nozzle material. The decomposition involving the new gases is not seen as a problem over lifetime, but concentrations in the equipment need to be monitored or regularly checked, in a way similar to SF₆ [38]. Most toxic decomposition products for HV, i.e. mixtures with CO₂, are CO and HF, e.g. [28] [30]. The arced mixtures are regarded to have similar or lower toxicity as arced SF₆. It is recommended, therefore, to treat this in a way similar to arced SF₆. It must, however, be noted that the above statement is made only based on the limited knowledge available on the toxicity of the new gases. Formation of critical by-products under repetitive switching in a small volume is discussed in [16]. Considerable more experience seems to be needed on the post arcing toxicity of the potential SF₆ substitute gases. Additional reported issues are: material compatibility [17][30] (e.g. effects on sealings and grease), gas tightness and gas handling procedures. Therefore, it should not be expected that existing HV equipment can be filled with the new gases without design or material changes. Internal arc tests were done with all mixtures and no critical issues are reported, e.g. [6][17][21]. Heat dissipation of the mixtures is slightly inferior to SF₆ [6][17], i.e. moderate de-rating or design changes might be necessary with respect to the current carrying capability.

At present field experience is gained with CO₂ live-tank CB [39], being started some years ago. A CO₂ filled CB is also commercially available [40]. With the C5-PFK mixtures for HV (GIS with 8 bays for 170 kV, 31.5 kA, based on a 245 kV, 50 kA design) and MV (primary switchgear, 50 panels, 22 kV, nominal current: 1600 A for feeder, 2000 A for busbars) pilot installations have been in operation successfully since 2015 in Switzerland [17][38] and Germany[41]. Pilot installations with the CO₂/C4-PFN mixture are planned in several European countries [6], such as a 145 kV indoor GIS in Switzerland, 245 kV outdoor Current Transformers in Germany and outdoor 420 GIL in UK and Scotland [6][36][33].

5. Conclusions and outlook

Published information on alternative gases for SF₆ in switching applications has been reviewed. In their present state, these investigations have just started and are by far not as extensive as for SF₆. The presently available manufacturer information on properties shows that new gases (e.g. C5-PFK and C4-PFN) are available, which can compete with, but may not fully reach the performance of, SF₆ when used in mixture with CO₂ as the buffer gas. Main differences are in the insulation and interruption performances and boiling point with the latter defining the minimum operating temperature specified for the switchgear. The lowest operating temperatures (e.g. -50°C) can be reached with CO₂. However, CO₂ seems to have an overall lower interruption performance, especially in dielectric interruption and withstand, than gas mixtures containing C4-PFN or C5-PFK. The advantage of CO₂/C5-PFK mixture compared with CO₂/C4-PFN mixture is the negligible GWP of about 1 compared to 427...600 of the latter. The advantage of CO₂/C4-PFN compared to CO₂/C5-PFK is the lower minimum operating temperature of about -25°C compared to about -5°C of the latter. Since research and development of these new SF₆ alternatives has just started, design improvements can be expected in the future. Exhaustive studies on decomposition products after current switching and their level of toxicity are still required, as it was performed in the past for SF₆, in different operating conditions. Probably from all different alternatives, a convergence to a single solution can be expected on the longer term. For sure, much more investigations and experimental validations have to be carried out.

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