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RECENT TRENDS IN DEVELOPMENT OF HIGH VOLTAGE CIRCUIT BREAKERS WITH SF_6 ALTERNATIVE GASES

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Abstract: The available knowledge of state-of-the-art of SF_6 alternative gases in switching applications was collected and evaluated in an initiative of the Current Zero Club [1] together with CIGRE. The present contribution summarizes the main results of this activity and will also include the latest trends. The main properties and switching performance of new gases are compared to SF_6. The most promising new gases are at the moment perfluoroketones and perfluoronitriles. Due to the high boiling point of these gases, in HV applications mixtures with CO_2 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 reported to be only slightly below SF_6. Minor design changes or de-rating of switchgear are therefore necessary. Differences between the gas mixtures are mainly in the boiling point and the GWP.

Keywords: SF_6 alternative gases, CO_2, Circuit Breaker

1. Introduction

SF_6 is widely used in electric power transmission and distribution systems, as for example in gas insulated switchgear (GIS), circuit breakers (CB) and medium voltage (MV) load break switches. It combines unique electrical insulation and arc interruption capability [2]. 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. [3] and its use is regulated and restrictions are discussed. Therefore, search for alternative gases for use in power applications has been ongoing since about two decades ago e.g. [4][5]. The state of the art of SF_6 alternative gases for switching applications was recently addressed in an initiative of the current zero club (CZC) [1] in collaboration with CIGRE. A survey was done collecting all the available recent literature on the topic. The result was presented and discussed at a joint workshop at the CIGRE session 2016. The present paper gives the main results of this survey. Since vacuum switching technology is a separate ongoing activity [6], it will be left out in the present review.

2. Alternative gases

The intensification of search for alternative gases started about two decades ago [4][5] after the Kyoto protocol was agreed in 1997 and further increased in the last 10 years (e.g. [7][8][9][10][11][12][13][14][15]). Important requirements for alternative gases were identified as: Low global warming potential (GWP), zero ozone depletion (ODP) potential, low toxicity, non-flammability, high dielectric strength, high arc quenching and heat dissipation capability, stability and material compatibility and availability on market

From various studies of gases of natural origin, CO_2 turned out to be the most promising arc quenching gas, e.g. [8][11], possibly enhanced in performance by some additives [12], like e.g. O_2 or CF_4. However, as was shown, the switching and dielectric performances of CO_2 are both below those of SF_6, e.g. [11][16]. Other interesting gases were identified to be fluorinated gases like CF_3I, hydrofluoroolefins (HFO1234ze and HFO1234yf), perfluoroketones (e.g. $C_5F_{10}O$), perfluoronitriles (C_4F_7N), fluoroethers (HFE245cb2), fluorooxiranes and hydrochlorofluoroolefins (HCFO1233zd), e.g. [7][13][14][15][17][18]. Taking all the requirements into account, the most promising candidates at present appeared to be the C5 perfluoroketone ($CF_3C(O)CF(CF_3)_2$ or C5-PFK) [19] and the iso-C4 perfluoronitrile ($(CF_3)_2$-CF-CN or C4-PFN) [20]. 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. [10]. 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. CO_2 is selected for this role in HV due to its good arc quenching capability, e.g. [9][11][12]. In MV application air is also reported as the buffer gas in combination with C5-PFK for insulation purposes [21][22][23]. 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 [24][25].

3. Properties of pure gases and mixtures

The properties of the selected alternative gases with reference to SF_6 are shown in table 1. The GWP for the various gases are different: the C4-PFN has a much higher GWP than CO_2 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 [19][20][26][27][28]. The dielectric strength of pure C4-PFN and C5-PFK is nearly twice that of SF_6. CO_2 has a dielectric withstand comparable to air [4][16], i.e. significantly below that of SF_6. 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% (molar concentration). Note that for the use of C5-PFK in CO_2 additionally an oxygen admixture is reported, since the presence of oxygen reduces the generation of harmful by-products like CO and solid by-products such as soot [30]. Due to a reduced dielectric withstand of the mixtures compared to SF_6 (column 6) at the same pressure the minimum operating pressure needs to be increased to about 0.7…0.8 MPa for C5-PFK and C4-PFN when using CO_2 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 SF_6 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 [7][30][31], i.e. a non-linear increase of the dielectric strength with the admixture ratio, as it is known for SF_6/N_2 mixtures [32]. 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 CO_2 or CO_2+C4-PFN mixtures. This is at the cost of significantly reduced dielectric withstand in case of pure CO_2 or significantly higher GWP in case of C4-PFN mixtures. Due to strong dilution, the toxicity of the mixtures is well below that of the pure substances, see e.g. [7][33].

4. Switching performance of alternative gases

Preliminary information on the switching performance of pure CO_2 and CO_2 mixtures is collected in table 3. The performance of SF_6 is given for comparison. With an enhanced operating pressure compared to SF_6 the cold dielectric strength, which is e.g. a measure of the performance in capacitive switching, can reach that of SF_6.

In the scanned literature, only qualitative statements on the switching performance of C4-PFN and C5-PFK mixtures could be found. For CO_2 a few quantitative comparisons exist. Very roughly, for pure CO_2 at an increased fill pressure of about 1 MPa, about 2/3 of the dielectric and thermal interruption performance of SF_6 might be expected. With the admixture of O_2 to CO_2 in the mixing ratio range up to 30%, an increase of the thermal interruption performance [12] and also a slight increase in dielectric strength (e.g. [35]) is expected. With the admixture of C4-PFN and C5-PFK into CO_2 the dielectric performance can be close to SF_6. The short-line fault (SLF) switching performance for the mixtures of CO_2/O_2/C5-PFK is reported to be 20% below that of SF_6 [30]. For an adapted CB with CO_2/C4-PFN a similar SLF performance to that of SF_6 is stated, e.g. [7]. There are, however, also direct comparisons of pure CO_2 with CO_2/C4-PFN and CO_2/C5-PFK mixtures using identical geometry and pressure, which show similar thermal interruption performance of CO_2 with and without admixtures [25]. IEC test duties L90 (SLF) and T100 (100% terminal fault) with the new mixtures are passed with some design modifications [37] or certain de-rating [30], suggesting that the switching performance of the new mixtures is not significantly lower than that of SF_6. This has also been shown to be valid for the bus transfer switching duty of disconnector switches, e.g. [36][37]. It is expected that dedicated design improvements can still increase the switching performance in the future.

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. [32]. After decomposition 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 CO_2/O_2/C5-PFK mixtures [30]. For partial discharges decomposition rates of more than one order of magnitude lower are observed for this mixture [38]. 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 SF_6 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 SF_6 [39]. Most toxic decomposition products for HV, i.e. mixtures with CO_2, are CO and HF, e.g. [30] [32]. The arced mixtures are regarded to have similar or lower toxicity as arced SF_6. It is recommended, therefore, to treat this in a way similar to arced SF_6. 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 [17]. Considerable more experience seems to be needed on the post arcing toxicity of the potential SF_6 substitute gases. Additional reported issues are: material compatibility [18][32] (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. [7][18][22]. Heat dissipation of the mixtures is slightly inferior to SF_6 [7][18], 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 CO_2 live-tank CB [40], being started some years ago. A CO_2 filled CB is also commercially available [41]. With the C5-PFK mixtures for HV and MV pilot installations have been in operation successfully since 2015 in Switzerland [18][39] and Germany[42]. Pilot installations with the CO_2/C4-PFN mixture are planned in several European countries [7], such as a 145 kV indoor GIS in Switzerland, 245 kV outdoor Current Transformers in Germany and outdoor 420 GIL in UK and Scotland [7][37][34].

5. Conclusions and outlook

Published information on alternative gases for SF_6 in switching applications has been reviewed. In their present state, these investigations have just started and are by far not as extensive as for SF_6. 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, SF_6 when used in mixture with CO_2 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 CO_2. However, CO_2 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 CO_2/C5-PFK mixture compared with CO_2/C4-PFN mixture is the negligible GWP of about 1 compared to 427…600 of the latter. The advantage of CO_2/C4-PFN compared to CO_2/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 SF_6 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 SF_6, 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.

Table 1: Properties of pure gases compared to SF_6

	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	[7][17]
CO_2	124-38-9	-78.5 [2)]	1	0	No	>300000	5000	≈0.3	[4][5][16]
C5-PFK	756-12-7	26.5	<1	0	No	≈20000	225	≈2	[13][17][19]
C4-PFN	42532-60-5	-4.7	2100	0	No	12000…15000	65	≈2	[7][17][20][26] [29]

[1] The occupational exposure limit is given by a time-weighted-average (TWA), 8-hr,
[2] Sublimation point

Table 2: Properties/performances of pure 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	[8][11][12]
CO_2/C5-PFK/O_2 (HV)	≈6/12	0.7	-5...+5	1	≈0.86	>2e5	[13][18][25][30]
CO_2/C4-PFN (HV)	≈4…6	0.67…0.88	-25…-10	327…690	0.87…0.96	>1e5	[7][33][15] [34][29]
Air/C5-PFK (MV)	≈7⋯13	0.13	-25…-15	0.6	≈0.85 [5]	1e5	[17][22][23]
N2/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 SF_6 at 0.55 MPa. For the scaling of SF_6 breakdown field E_d with pressure correction in the form of $E_d=84\cdot p^{0.71}$ was used [32]
[5] Compared to SF_6 at 0.13 MPa, measurements were for a mixture at -15°C
[6] Calculations with Refprop: https://www.nist.gov/srd/refprop

Table 3: Switching performance of gases and mixtures compared to SF_6 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	[8][11][12][25]
CO_2+C5-PFK/O2	0.7…0.8	close to SF_6	0.8…0.87	close to SF_6	[18][25]
CO_2/C4-PFN	0.67…0.82	close to SF_6	0.83…(1) [2]	close to SF_6	[7][25][32]

[1] At same pressure build up,
[2] Same performance as SF_6 is stated but it is not clear if this was under same condition

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