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Recent development of alternative gases to SF_6 for switching applications

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Abstract

CIGRE Study Committee A3 held a Workshop on SF_6 alternatives jointly with Current Zero Club (CZC) on Monday, 22 August 2016 during the 2016 Paris session. Sixty experts attended. The purpose of the Workshop was to collect the available information on interrupting and switching performance with state-of-the-art of alternatives to SF_6 and then to evaluate their interrupting capabilities in comparison with SF_6 in order to decide whether any new actions are required in CIGRE, besides the recently published SF_6 paper in 2014 [1]. After opening remarks by the chairs of SC A3 and CZC, the results of the latest investigation conducted by the CZC members were presented. Five manufacturers then presented developments and on-going pilot projects with SF_6 alternatives. The amount of information presently available to make comparisons of the main properties and of the switching performance to SF_6 is very limited and is often only from a single source.. The most promising new gases are 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 only slightly below that of SF_6. Minor design changes or de-rating of switchgear are therefore necessary. The new gases decompose under the influence of arcing but do not recombine like SF_6. Physical differences between the gas mixtures are mainly in the boiling point and the GWP.

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 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 [2] and its use and release are regulated with further restriction being discussed. Consequently, the search for alternative gases for use in power applications has been ongoing since about two decades ago [3][4]. This paper briefly reviews the status of the present solutions, with a focus on switching application. This review is mainly based on the most recent literature available from some manufacturers. No independent confirmation is available. Since vacuum switching technology is a separate ongoing activity [5], it is not included in the present review.

Search for alternative gases

An intensified search for alternative gases started about two decades ago [3][4] after the Kyoto protocol was agreed in 1997 and gained increased focus in the last 10 years ([6][7][8][9][10] [11][12] [13][14]). The following important requirements for alternative gases were identified:

- 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, CO_2 is the most promising arc quenching gas [7][10], possibly enhanced in performance by some additives [11]. However the switching and dielectric performances of CO_2 are both below those of SF_6, [10] [15]. Other interesting gases were identified to be fluorinated gases like CF_3I, perfluoroketones (e.g. $C_5F_{10}O$) and perfluoronitriles (e.g. C_4F_7N [6][12][13][14][16][17]. 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) [18] and the iso-C4 perfluoronitrile ((CF_3)2-CF-CN or C4-PFN) [19]. The dielectric performance of pure gases typically scales with the boiling point, i.e. gases with high dielectric strength usually also have a high boiling point [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. CO_2 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]. 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

	CAS number 3)	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][24]

Table 1: Properties of pure gases compared to SF_6

1) The occupational exposure limit is given by a time-weighted-average (TWA), 8-hr
2) Sublimation point
3) A unique numerical identifier assigned to every chemical substance described in the open scientific literature

the switchgear. An additional alternative approach is proposed to use air for insulation [22][23].

Properties of alternative 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 either 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 [18][19][24][25][26]. Classification and labelling of pure substances and mixtures are according to CLP European Regulation (EC) No 1272/2008 [32][25][26]. 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 [3][15], 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% (mole). Note that for the use of C5-PFK in CO_2 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 [27]. Due to a reduced dielectric withstand of the mixtures compared to SF_6 at the same pressure (column 6) the minimum operating pressure needs to be slightly 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, (column 3) . For Air/C5-PFK mixtures in MV application the existing pressure of 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 [6][27][28] giving a non-linear increase of the dielectric strength with the admixture ratio; a phenomenon already known from SF_6/N2 mixtures [29]. 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 below that of the pure substances [6][31].

Switching performance of alternative gases and gas mixtures

Switching performance was discussed in the workshop mainly focusing on thermal interrupting capability corresponding to short-line fault (SLF) testing duty and on capacitive switching capability. 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 a measure of

	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][23][27]
CO_2/C4-PFN (HV)	≈4…6	0.67…0.82	-25…-10	327…690	0.87…0.96	>1e5	[6][31][14] [32]
Air/C5-PFK (MV)	≈7…13	0.13	-25…-15	0.6	≈0.85 5)	1e5	[16][21][22]
N2/C4-PFN (MV)	≈20…40	0.13	-25…-20	1300…1800	0.9…1.2	>2.5e4	[15]

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

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 [29]
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

the performance in capacitive switching, can reach that of SF_6. In the reviewed 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. In approximate terms, 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 [11] and also a slight increase in dielectric strength [33] is expected. With the admixture of C4-PFN or C5-PFK into CO_2 the dielectric performance can be close to SF_6. The short-line fault (SLF) switching performance for mixtures of CO_2/O_2/C5-PFK is reported to be 20% below that of SF_6 [27]. For an adapted CB with CO_2/C4-PFN a similar SLF performance to that of SF_6 is stated [6]. 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 [23]. IEC test duties L90 (SLF) and T100 (100% terminal fault) with the new mixtures are passed with some design modifications [35] or certain de-rating [27], 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 [34][35]. It is expected that dedicated design improvements can still increase the switching performance in the future.

An important point is the toxicity of the byproducts within 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 [29]. After arcing some C5-PFK and C4-PFN molecules do not recombine to their original structure (permanent decomposition unlike SF_6), but form smaller molecules. A decomposition rate of 0.5 Moles/ MJ under high current switching is reported for CO_2/O2/C5-PFK mixtures [27]. For partial discharges, decomposition rates of more than one order of magnitude lower are observed for this mixture [36]. 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 reversible decomposition of SF_6 where most decomposed byproducts are made from ablated contact and nozzle material.

The decomposition involving the new gases is not seen as a problem over equipment lifetime, but concentrations in the equipment need to be monitored or regularly checked, in a way similar to SF_6 [37]. Most toxic byproducts for HV circuit breaker application with C4-PEN mixtures with CO_2, include CO and HF [27] [29]. The arced mixtures are regarded to have similar or lower toxicity as arced SF_6 and it is recommended to treat them 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 [16]. 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 [17][29] (e.g. effects on sealant grease), gas tightness and gas handling procedures and 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 [6][17][21]. Heat dissipation of the mixtures is slightly inferior to SF_6 [6][17] meaning that moderate de-rating or design changes might be necessary with respect to the current carrying capability.

At present field experience of a few years is available with a CO_2 live-tank CB is commercially available. Pilot installations 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) have been in operation successfully since 2015 in Switzerland [17][37] and Germany. Pilot installations with the CO_2/C4-PFN mixture are planned in several European countries [6], including a 145 kV indoor GIS in Switzerland, 245 kV outdoor Current Transformers in Germany and outdoor 420 GIL in UK [6][35][32].

Conclusions and outlook

Published information on alternative gases to 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 SF_6 when used in mixture with CO_2 as the buffer gas. It is unclear whether they can reach the full performance of SF_6 in the future. 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

	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][23]
CO_2+C5-PFK/O2	0.7…0.8	close to SF_6	0.8…0.87	close to SF_6	[17][23]
CO_2/C4-PFN	0.67…0.82	close to SF_6	0.83…(1) [2)]	close to SF_6	[6][23][29]

Table 3: Switching performance of gases and mixtures compared to SF_6 at increased operating pressures in HV applications

1) At same pressure build up. 2) Same performance as SF_6 is stated but it is not clear if this was under same conditions

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 for 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. A convergence to a single solution may be expected on the longer term but only following further extensive investigations and experimental validations.

CIGRE actions

A previous CIGRE paper [1] reported that there were no alternative interrupting media comparable to SF_6 covering the complete high voltage and breaking current ranges as needed by today's power systems with the same reliability and compactness as modern SF_6 circuit breakers. It also emphasized that the environmental impact of any specific applications should be evaluated and compared using the Life Cycle Assessment approach from its production to disposal as regulated by ISO 14040. Recent developments begin to create a case for reviewing the earlier conclusion but the available information on long-term interrupting capability with SF_6 alternatives is still limited. On this basis SC A3 decided not to initiate a new WG to investigate the interrupting and switching capability and will continue to collect scientific data. Other aspects relating to the introduction of alternatives to SF_6 for insulation purposes continue within CIGRE such as WG B3.45: Gas handling and WG D1.67: Insulation properties. By setting a preferential subject related to SF_6 alternatives, SC A3 will discuss this subject at coming 2017 Winnipeg colloquium and 2018 Paris Session.■

References:

[1] P. Glaubitz et al., "CIGRE Position Paper on the Application of SF_6 in Transmission and Distribution Networks", Electra, Vol 34, No. 274, 2014

[2] T. Stocker et al., "Climate Change 2013: The Physical Science Basis", Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 2013, https://www.ipcc.ch/report/ar5/wg1/

[3] L. Niemeyer, "A Systematic Search for Insulation Gases and Their Environmental Evaluation", Gaseous Dielectrics Vol VIII, pp. 459-464, 1998

[4] L. Christophorou, J. K. Olthoff, and D. S. Green, "Gases for Electrical Insulation and Arc Interruption: Possible Present and Future Alternatives to Pure SF_6", US Department of Commerce, Technology Administration, National Institute of Standards and Technology, 1997

[5] CIGRE 589, "The Impact of the Application of Vacuum Switchgear at Transmission Voltages", WG A3.27, 2014

[6] Y. Kieffel et al., "Green Gas to Replace SF_6 in Electrical Grids", IEEE Power and Energy Magazine, Vol. 14, No. 2, pp. 32-39, 2016

[7] T. Uchii et al, "Fundamental Research on SF_6-Free Gas Insulated Switchgear Adopting CO_2 Gas and Its Mixtures", Proceedings of International Symposium on Eco Topia Science ISETSO7, 2007

[8] T. Ueno et al, "Evaluation of SLF Interruption Capability on Various Gases", XV International Conference on Gas Discharges and their Applications, Toulouse, 2004

[9] M. Rabie and C. M. Franck, "Predicting the Electric Strength of Proposed SF_6 Replacement Gases by Means of Density Functional Theory", 18th International Symposium on High Voltage Engineering, Seoul, Korea, 25-30 August, 2013

[10] P. Stoller et al., "CO_2 as an Arc Interruption Medium in Gas Circuit Breakers", IEEE Trans Plasma Science, Vol. 41, No. 8, pp. 2359, 2013

[11] T. Uchii et al., "Thermal Interruption Capabilities of CO_2 gas and CO_2-based Gas Mixtures", Proceedings of the XVIII International Conference on Gas Discharges and Their Applications, Greifswald, Germany, 2010

[12] J. D. Mantilla, N. Gariboldi et al., "Investigation of the Insulation Performance of A New Gas Mixture with Extremely Low GWP", Electrical Insulation Conference (EIC), Philadelphia, USA, 2014

[13] M. Taki et al., "Interruption Capability of CF_3I Gas as a Substitution Candidate for SF_6 Gas", IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 14, No. 2, pp. 341-346, 2007

[14] Y. Kieffel et al., "SF_6 Alternative Development for High Voltage Switchgears", Cigré Paper D1-305, Paris, 2014

[15] K. Juhre, E. Kynast et al., "High Pressure N_2, N_2/CO_2 and CO_2 Gas Insulation in Comparison to SF_6 in GIS Applications", 14th Int'l. Symp. High Voltage Eng.(ISH), Paper C-01, pp. 1-6, 2005

[16] C. Preve et al., "Validation Method for SF_6 Alternative Gas", CIGRE, 2016

[17] D. Tehlar et al., "Ketone Based Alternative Insulation Medium in a 170 KV Pilot Installation", CIGRE Colloquium, Nagoya, Japan, 2015

[18] 3M™ Novec™ 5110 Dielectric Fluid, Technical Data Sheet, 2015

[19] 3M™ Novec™ 4710 Dielectric Fluid, Technical Data Sheet, October 2015

[20] Saxegaard et al., "Dielectric Properties of Gases Suitable for Secondary MV Switchgear", CIRED, Paper 0926, 2015

[21] Hyrenbach et al., "Alternative Gas Insulation in Medium Voltage Switchgear", CIRED, 2015

[22] N. Presser, "Advanced Insulation and Switching Concepts for Next Generation High Voltage Substations", CIGRE B3-108, 2016

[23] S. Kosse, "Development of CB with SF_6 Alternatives", Presentation at Workshop of Current Zero Club with CIGRE SC A3 on Switching in Alternative Gases, CIGRE, 2016

[24] J.G. Owens, "Greenhouse Gas Emission Reductions through Use of a Sustainable Alternative to SF_6" EIC, 2016

[25] 3M™ Novec™ 5110 Dielectric Fluid, Safety Data Sheet, 2014, 31-6591-7 (UK), rev. date 24/09/2014

[26] 3M™ Novec™ 4710 Dielectric Fluid, Safety Data Sheet, 2016, 33-6330-6 (UK), rev. date 19/08/2016

[27] J. D. Mantilla et al., "Environmentally Friendly Perfluoroketones-based Mixture as Switching Medium in High Voltage Circuit Breakers", CIGRE A3-348, 2016

[28] P. Simka et al., "Dielectric Strength of C5 Perfluoroketone", Proc 19th Int Symp High Voltage Eng, Pilsen, Czech Republic, 2015

[29] H. Hama , S. Okabe et al., "Insulation Co-ordination Related to Internal Insulation of Gas Insulated Systems with SF_6 and N_2/SF_6 Gas Mixtures under AC Conditions", CIGRE WG C4.302, 2008

[30] European Regulation (EC) No. 1272/2008 on "Classification, Labelling and Packaging of substances and mixtures"

[31] Pohlink, et al., "Characteristics of Fluoronitrile/CO_2 Mixture-an Aternative to SF_6", CIGRE, D1-204, 2016

[32] E. Laruelle et al., "Reduction of Greenhouse Gases in GIS Pilot Project in UK", Cigré, Paper C3-304, 2016

[33] H. Zhao et al., "Prediction of the Critical Reduced Electric Field Strength for Carbon Dioxide and Its Mixtures with 50% O_2 and 50% H_2 from Boltzmann Analysis for Gas Temperatures up to 3500 K at Atmospheric Pressure", Journal of Physics D: Applied Physics, Vol.47, pp. 325203, 2014

[34] Y. Kieffel et al., "SF_6 Alternative Development for High Voltage Switchgears", EIC, Seattle, Washington, USA, 2015

[35] D. Gautschi, "Application of a Fluoronitrile Gas in GIS and GIL as an Environmental Friendly Alternative to SF_6", CIGRE, B3-106, 2016

[36] T. Hammer, "Decomposition Of Low GWP Gaseous Dielectrics Caused By Partial Discharges", 21st Int Conference on Gas Discharges and Their Applications, Nagoya, Japan, 2016

[37] P. Müller, "Praxiserfahrungen der Ersten 170-kV-GIS mit Alternativem Isolationsmedium Basierend auf Ketonen", GIS Anwenderforum, Darmstadt, Germany, 2016

[38] P. Söderström et al., „Suitability Evaluation of Improved High Voltage Circuit Breaker Design with Drastically Reduced Environmental Impact", CIGRE, 2012