

RECENT TRENDS IN DEVELOPMENT OF HIGH VOLTAGE CIRCUIT BREAKERS WITH SF₆ ALTERNATIVE GASES

M. SEEGER^{a,*}, R. SMEETS^b, J. YAN^c, H. ITO^d, M. CLAESSENS^a, E. DULLNI^e,
L. FALKINGHAM^f, C. M. FRANCK^g, F. GENTILS^h, W. HARTMANNⁱ,
Y. KIEFFEL^j, S. JIA^k, G. JONES^c, J. MANTILLA^a, S. PAWAR^l, M. RABIE^g,
P. ROBIN-JOUAN^j, H. SCHELLEKENS^h, J. SPENCER^c, T. UCHII^m, X. LI^k,
S. YANABU^k

^a ABB Switzerland Ltd, Corporate Research Center, Segelhofstrasse 1K, CH-5405 Baden-Dättwil, Switzerland

^b DNV GL, Utrechtseweg 310, 6800 ET, Arnhem, Netherlands

^c University of Liverpool, Department of Electrical Engineering and Electronics, Liverpool, L69 3GJ, UK

^d Mitsubishi Electric Corp., Tokyo Building 2-7-3, Marunouchi, Chiyoda-ku, Tokyo 100-8310, Japan

^e ABB AG, Bahnstrasse 39-4, D-40832 Ratingen, Germany

^f Vacuum Interrupters Limited, Sir Frank Whittle Business Centre, Great Central Way, Rugby CV21 3XH, UK

^g ETH Zürich, Rämistrasse 101, 8092 Zürich, Switzerland

^h Schneider Electric, 35, rue Joseph Monier, 92500 Rueil-Malmaison, France

ⁱ Siemens AG, Corp.Tech., Otto-Hahn-Ring 6, 81739 Munich, Germany

^j GE Grid Solutions, 51 Espl. du Général de Gaulle, 92900 Puteaux, France

^k Xi'an Jiaotong University, 28 Xianning West Road, Beilin, Xi'an, Shaanxi, China

^l Crompton Greaves, Dr. Annie Besant Road, Worli, Mumbai – 40001, India

^m Toshiba Corp., Power and Industrial Systems R&D Center, 8 Shinsugita-cho, Kanagawa 235-8523, Japan

* martin.seeger@ch.abb.com

Abstract. The available knowledge of state-of-the-art of SF₆ 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 SF₆. 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 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 reported to be only slightly below SF₆. 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: SF₆ alternative gases, CO₂, Circuit Breaker.

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 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 SF₆ 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. [7–15]). Important requirements for alternative gases were identified as: Low 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, CO₂

	CAS number	Boiling point °C	GWP	ODP	Flammability	Toxicity LC50 (4h) ppmv	Toxicity TWA ¹⁾ ppmv	Dielectric strength at 0.1 MPa	Ref
SF ₆	2551-62-4	-64 ²⁾	23500	0	No	-	1000	1	[7, 16]
CO ₂	124-38-9	-78.5 ²⁾	1	0	No	>300000	5000	≈0.3	[4, 5, 17]
C5-PFK	756-12-7	26.5	<1	0	No	≈20000	225	≈2	[13, 16, 18]
C4-PFN	42532-60-5	-4.7	2100	0	No	12000...15000	65	≈2	[7, 16, 19-21]

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

²⁾ Sublimation point

Table 1. Properties of pure gases compared to SF₆.

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. O₂ or CF₄. However, as was shown, the switching and dielectric performances of CO₂ are both below those of SF₆, e.g. [11, 17]. Other interesting gases were identified to be fluorinated gases like CF₃I, hydrofluoroolefins (HFO1234ze and HFO1234yf), perfluoroethanes (e.g. C5F10O), perfluoronitriles (C₄F₇N), fluoroethers (HFE245cb2), fluorooxiranes and hydrochlorofluoroolefins (HCFO1233zd), e.g. [7, 13–16, 22]. Taking all the requirements into account, the most promising candidates at present appeared to be the C5 perfluoroethane (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. [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. CO₂ 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 [23–25]. 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 [26, 27].

3. Properties of pure 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 [18–20, 28, 29]. The dielectric strength of pure C4-PFN and C5-PFK is nearly twice that of SF₆. CO₂ has a dielectric withstand comparable to air [4, 17], i.e. significantly below that of SF₆. The prop-

erties 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 CO₂ 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 SF₆ (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 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 [7, 30, 31], i.e. a non-linear increase of the dielectric strength with the admixture ratio, as it is known for SF₆/N₂ 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 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 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 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 filling pressure of about 1 MPa, about 2/3 of the dielectric and thermal interruption

	C _{ad} ¹⁾	p _{min} ²⁾	T _{min} ³⁾	GWP	D.S. ⁴⁾	Toxicity LC50 ppmv	Ref
		MPa	°C				
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, 22, 27, 30]
CO ₂ /C4-PFN (HV)	≈ 4...6	0.67...0.88	-25...-10	327...690	0.87...0.96	> 1e5	[7, 15, 21, 33, 34]
Air/C5-PFK (MV)	≈ 7...13	0.13	-25...-15	0.6	≈ 0.85 ⁵⁾	1e5	[16, 24, 25]
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 = 84p^{0.71} was used [32]

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>

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

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 [12] and also a slight increase in dielectric strength (e.g. [35]) 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 [30]. For an adapted CB with CO₂/C4-PFN a similar SLF performance to that of SF₆ is stated, e.g. [7]. 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 [27]. 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 [30], 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. [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 CO₂/O₂/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 C4-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 [39]. Most toxic decomposition products for HV, i.e. mixtures with CO₂, are CO and HF, e.g. [30, 32]. 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 [22, 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, 22, 24]. Heat dissipation of the mixtures is slightly inferior to SF₆ [7, 22], 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 [40], being started some years ago. A CO₂ 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 [22, 39] and Germany [42]. Pilot installations with the CO₂/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, 34, 36].

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 prop-

	Operating pressure MPa	Dielectric strength	SLF performance compared to SF ₆ ¹⁾	Dielectric reco- very speed	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, 27]
CO ₂ +C5-PFK/O ₂	0.7...0.8	close to SF ₆	0.8...0.87	close to SF ₆	[22, 27]
CO ₂ /C4-PFN	0.67...0.82	close to SF ₆	0.83... (1) ²⁾	close to SF ₆	[7, 27, 32]

¹⁾ At same pressure build up

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

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

erties 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.

References

- [1] Current Zero Club (CZC). <http://www.currentzeroclub.org/>.
- [2] P. Glaubitz, S. Stangherlin, JM Biasse, F. Meyer, M. Dallet, M. Pruefert, R. Kurte, T. Saida, K. Uehara, P. Prieur, H. Ito, E. Kynast, A. Janssen, R. Smeets, and Dufournet D. CIGRE position paper on the application of SF₆ in transmission and distribution networks. *Electra*, 34(274):34-39, 2014.
- [3] 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/rephort/ar5/wg1/>.
- [4] L. Niemeyer. A systematic search for insulation gases and their environmental evaluation. In *Gaseous Dielectrics VIII*, pages 459-464. Springer Science & Business Media, 1998.
- [5] L. Christophorou, J. K. Olthoff, and D. S. Green. Gases for electrical insulation and arc interruption: Possible present and future alternatives to pure SF₆. US Department of Commerce, Technology Administration, National Institute of Standards and Technology, 1997.
- [6] R. Smeets, L. Falkingham, M. Backman, T. Betz, I. Cotton, R. Doche, L. Drews, M. Eiselt, M. Glinkowski, D. Johnson, S. Hambarde, V. Hinrichsen, N. Inoue, H. Ito, K. Kagawa, S. Kulkarni, Y.-G. Kim, R.K. Smith, Z. Liu, W. Pepper, P. Meyer, S. de Moraes, F. Richter, J.-S. Ryu, N. Kubota, H. Saito, S. Shoal, L. Violleau, S. Yanabu, and Y. You. Cigre 589: The impact of the application of vacuum switchgear at transmission voltages. WG A3.27, 2014.
- [7] Y. Kieffel, T. Irwin, P. Ponchon, and J. Owens. Green gas to replace SF₆ in electrical grids. *IEEE Power and Energy Magazine*, 14(2):32-39, 2016.
- [8] T. Uchii, Y. Hoshina, T. Mori, H. Kawano, T. Nakamoto, and M. Toyoda. Fundamental research on SF₆-free gas insulated switchgear adopting CO₂ gas and its mixtures. In *Proceedings of International Symposium on EcoTopia Science ISETSO7*, 2007.
- [9] T. Ueno, K. Mochiduki, H. Mizoguchi, S. Yanabu, S. Okabe, and S. Yuasa. Evaluation of SLF interruption capability on various gases. In *XV International Conference on Gas Discharges and their Applications*, Toulouse, 2004.
- [10] M. Rabie and C. M. Franck. Predicting the electric strength of proposed SF₆ replacement gases by means of density functional theory. In *18th International Symposium on High Voltage Engineering*, Seoul, Korea, 2013.
- [11] P. C. Stoller, M. Seeger, A. A. Iordanidis, and G. V. Naidis. CO₂ as an arc interruption medium in gas circuit breakers. *IEEE Trans. Plasma Science*, 41(8):2359-2369, 2013.
- [12] T. Uchii, A. Majima, T. Koshizuka, and H. Kawano. Thermal interruption capabilities of CO₂ gas and CO₂-based gas mixtures. In *Proceedings of the XVIII International Conference on Gas Discharges and Their Applications*, Greifswald, Germany, 2010.
- [13] J. D. Mantilla, N. Gariboldi, S. Grob, and M. Claessens. Investigation of the insulation performance of a new gas mixture with extremely low GWP. In *Electrical Insulation Conference (EIC)*, Philadelphia, USA, 2014.
- [14] M. Taki, D. Maekawa, H. Odaka, Mizoguchi H., and S. Yanabu. Interruption capability of CF₃I gas as a substitution candidate for SF₆ gas. *IEEE Transactions*

- on *Dielectrics and Electrical Insulation*, 14(2):341–346, 2007.
- [15] Y. Kieffel, A. Girodet, F. Biquez, Ph. Ponchon, J. Owens, M. Costello, M. Bulinski, R. van San, and K. Werner. SF₆ alternative development for high voltage switchgears. In *Cigre*, 2014. Cigre Paper D1-305, Paris.
- [16] C. Preve, R. Maladen, D. Piccoz, and J.-M. Biasse. Validation method for SF₆ alternative gas. In *Cigre*, 2016.
- [17] K. Juhre and E. Kynast. High pressure N₂, N₂/CO₂ and CO₂ gas insulation in comparison to SF₆ in GIS applications. In *14th International Symposium on High Voltage Engineering (ISH)*, pages 1–6, 2005. Paper C-01.
- [18] 3M™ Novec™ 5110 dielectric fluid. Technical Data Sheet, 2015.
- [19] 3M™ Novec™ 4710 dielectric fluid. Technical Data Sheet, 2015.
- [20] J.G. Owens. Greenhouse gas emission reductions through use of a sustainable alternative to SF₆. In *IEEE Electrical Insulation Conference (EIC)*, 2016.
- [21] H. E. Nechmi, A. Beroual, A. Girodet, and P. Vinson. Fluoronitriles/CO₂ gas mixture as promising substitute to SF₆ for insulation in high voltage applications. *IEEE Transactions on Dielectrics and Electrical Insulation*, 23(5), 2016.
- [22] D. Tehlar, T. Diggelmann, P. Müller, R. Buehler, N. Ranjan, and C. Doiron. Ketone based alternative insulation medium in a 170 kV pilot installation. Cigre Colloquium, Nagoya, Japan, 2015.
- [23] M. Saxegaard, M. Kristoffersen, P. Stoller, M. Seeger, M. Hyrenbach, and H. Landsverk. Dielectric properties of gases suitable for secondary MV switchgear. CIGRE, 2015. Paper 0926.
- [24] M. Hyrenbach, T. Hintzen, P. Müller, and J. Owens. Alternative gas insulation in medium voltage switchgear. CIGRE, 2015.
- [25] M. Mann, F.-J. Koerber, R. Uhl, and P. Mueller. Ein Beitrag zur Evaluierung von alternativen Isoliergasen in Gasisolierten Hochspannungs-Schaltanlagen. In *Hochspannungs-Schaltanlagen: Anwendungen, Betrieb und Erfahrungen*, Darmstadt, 2015.
- [26] N. Presser. Advanced insulation and switching concepts for next generation high voltage substations. In *Cigre*, 2016. B3-108.
- [27] A. Kosse. Development of CB with SF₆ alternatives. In *Cigre*, 2016. Presentation at Workshop of Current Zero Club with CIGRE SC A3 on Switching in Alternative Gases.
- [28] 3M™ Novec™ 5110 dielectric fluid. Safety Data Sheet, 2014. 31-6591-7 (UK), rev. date 24/09/2014.
- [29] 3M™ Novec™ 4710 dielectric fluid. Safety Data Sheet, 2016. 33-6330-6 (UK), rev. date 19/08/2016.
- [30] J. D. Mantilla, M. Claessens, and M. Kriegel. Environmentally friendly perfluoroketones-based mixture as switching medium in high voltage circuit breakers. In *Cigre*, 2016. A3-348.
- [31] P. Simka and N. Ranjan. Dielectric strength of C5 perfluoroketone. In *Proceedings of 19th International Symposium on High Voltage Engineering*, Pilsen, Czech Republic, 2015.
- [32] H. Hama, S. Okabe, M. Muhr, T. Britten, K. Juhre, C. Neumann, U. Prucker, and A. Sabot. Insulation co-ordination related to internal insulation of gas insulated systems with SF₆ and N₂/SF₆ gas mixtures under AC conditions. In *Cigre*, 2008. WG C4.302.
- [33] K. Pohlink, Y. Kieffel, J. Owens, Meyer F., F. Biquez, Ph. Ponchon, and R. van San. Characteristics of fluoronitrile/CO₂ mixture—an alternative to SF₆. In *Cigre*, 2016. D1-204.
- [34] E. Laruelle, A. Ficheux, Y. Kieffel, and M. Waldron. Reduction of greenhouse gases in GIS pilot project in UK. In *Cigre*, 2016. Paper C3-304.
- [35] H. Zhao, X. Li, S. Jia, and A. B. Murphy. Prediction of the critical reduced electric field strength for carbon dioxide and its mixtures with 50 % O₂ and 50 % H₂ from boltzmann analysis for gas temperatures up to 3500 K at atmospheric pressure. *Journal of Physics D: Applied Physics*, 47(32):325203, 2014.
- [36] D. Gautschi. Application of a fluoronitrile gas in GIS and GIL as an environmental friendly alternative to SF₆. In *Cigre*, 2016. B3-106.
- [37] Y. Kieffel and F. Biquez. SF₆ alternative development for high voltage switchgears. In *IEEE Electrical Insulation Conference (EIC)*, Seattle, Washington, USA, 2015.
- [38] T. Hammer. Decomposition of low GWP gaseous dielectrics caused by partial discharges. In *21st Int Conference on Gas Discharges and Their Applications*, Nagoya, Japan, 2016.
- [39] P. Müller. Praxiserfahrungen der Ersten 170-kV-GIS mit Alternativem Isolationsmedium Basierend auf Ketonen. In *GIS Anwenderforum*, Darmstadt, Germany, 2016.
- [40] P. Söderstöm, J. Lidholm, and U. Åkesson. Suitability evaluation of improved high voltage circuit breaker design with drastically reduced environmental impact. In *Cigre*, 2012.
- [41] ABB. Live tank circuit breaker – LTA 72.5 kV. <http://new.abb.com/high-voltage/AIS/selector/lta>.
- [42] M. Engel. Einsatz von ökoefizientem Isoliergas in einer Mittelspannungsschaltanlage. In *GIS Anwenderforum*, Darmstadt, Germany, 2016.