HOLISTIC EVALUATION OF THE PERFORMANCE OF TODAY'S SF_6 ALTERNATIVES PROPOSALS

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ABSTRACT

Gases with high dielectric strength and good arc extinguishing properties are the major insulation and switching media in modern gas insulated switchgear and circuit breakers. In this context, revived by the revision of the European regulation on fluorinated gases in 2014, the investigation and evaluation of possible substitutes for the gas SF_6 (sulphur hexafluoride) is even more in the focus of sciences' and industry's current research and development activities, attended by activities at IEC, Cigré, IEEE and T&D Europe. In order to assess the technical performance of possible alternative gases a structured analysis of the gas properties and their impact e.g. on the product design and performance is necessary. This contribution gives an overview of criteria for evaluation of the performance of SF_6 gas-alternatives today proposed by manufacturers of gases and switchgear. The considered criteria are discussed from a holistic view. Based on that, the performance of proposed SF_6 gas-alternatives is evaluated adequately.

INTRODUCTION

Nowadays SF_6 (sulphur hexafluoride) is the state-of-the art insulating and arc quenching medium used in gas-insulated switchgear, guaranteeing safe current interruption and high dielectric strength. At the same time, if released to the environment, SF_6 is a strong greenhouse gas with a global warming potential of 22800 CO_2 (carbon dioxide) mass equivalents [1].

After being on the agenda of research and development activities of science and industry for many years, the revision of the European regulation on fluorinated gases in 2014 even more turned the focus on the properties of possible gas-substitutes for SF_6.

Political and societal discussion on this topic showed, that a detailed evaluation of the ecological reasonable possibilities and the technical limits of any possible alternative arc quenching and insulating gases (e.g. air, carbon dioxide or fluorinated gas mixtures) is required to carefully access their application potential (cf. also [2]).

Thus in this contribution an overview of criteria is given for this evaluation of the performance of today's SF_6 gas-alternatives proposed by manufacturers of gases and switchgear. The criteria are classified into several categories based on more than 50 years application experiences with technical gases in electrical equipment, considering as well actual governmental, environmental and regulatory aspects.

The categories considered for the assessment of possible alternative gases are:

- Technical performance
- Safety, reliability and long term stability
- Environmental and health impact

In the following sections these criteria are addressed starting with an overview of today discussed possible alternative gases.

PROPERTIES OF ALTERNATIVE GASES

In the focus of recent research activities on SF_6 alternatives, natural gases or gas mixtures (e.g. air or CO_2) as well as fluorinated gas compounds or its use in gas mixtures are considered as possible substitutes. Table 1 gives a basic overview of various natural gases focussing on their dielectric strength compared to SF_6 and their boiling point. Amongst others these parameters have to be considered when assessing the applicability of those gases for medium and high voltage equipment. In addition the global warming potential (GWP) is listed in CO_2 mass equivalents.

Table 1. Properties of possible alternative natural arc quenching and insulating gases [3,4].

Gas	Dielectric strength / p.u.	Boiling point at 0.1 MPa / °C	GWP
SF_6	1	- 63	22800
Air	~ 0.43...0.5	-194	0
N_2	~ 0.4	- 196	0
CO_2	~ 0.45	-79	1

In order to compensate the reduced dielectric strength of these alternative natural gases compared to SF_6, fluor compounds, e.g. fluoroketones or fluoronitiriles are admixed to a natural carrier gas like e.g. CO_2 [4-7]. But this comes along with a significant increase of the boiling point. Nevertheless these gas-mixtures are also considered during the following assessment.

ARC QUENCHING PERFORMANCE

The optimization of today's circuit-breaker technologies as well as the development of new current interruption concepts requires a deep understanding of the physical processes during the switching operation. This includes the interaction between the used insulation and quenching gases and the switching arc. Especially with regard to the discussion about substituting SF_6 by alternative quenching and insulation gases, a technical evaluation of the arc quenching capability, as well as the application potential of alternative switching gases, such as carbon dioxide, air or gas mixtures of CO_2 and mixtures using fluoroketone or fluoronitrile respectively, which are already applied in a few selected switchgear or circuit-breaker demonstration installations, is necessary.

Experimental approach

For this purpose a reference experimental setup, that allows the determination of the arc quenching capability of different gases and of the axial resistance distribution of the switching arc around the current zero crossing, was developed in cooperation with the Institute for High Voltage Technology (IFHT) of RWTH Aachen University. The applied measuring principle is based on capacitive field sensors measuring the potential of the arc. The use of multiple sensors allows the determination of the potential drop along the arc and therefore the determination of the arc resistance distribution (cf. figure 1). The blowing of the arc is implemented by a gas flow from an external pressure vessel through radial distributed blowing openings in the middle of the insulation nozzle system. The reference circuit-breaker model is located inside a test vessel, filled with the blow gas at ambient pressure.

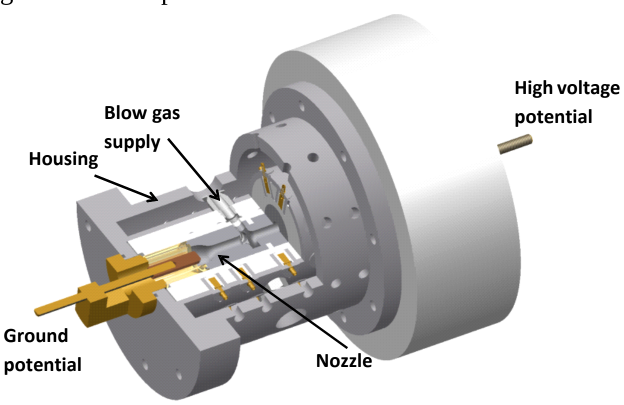

Figure 1. Cross-sectional view of the reference circuit-breaker model for the characterization of the arc quenching capability.

The arc quenching capability of the reference gas SF_6, the natural gases CO_2, N_2 (nitrogen) and air as well as fluorinated gas mixtures of carbon dioxide with a fluoroketone and a fluoronitrile, respectively, are characterized experimentally. The test current is supplied by the high voltage circuit of a synthetic test circuit. The amplitude of the current was adjusted to values of $I < 2.1$ kA at a frequency of approximately $f \approx 955$ Hz.

In figures 2 and 3 the results of the experimental investigations of the gases listed above are shown in comparison to SF_6. The arc quenching capability is characterized by the thermal interruption limit di/dt_{limit} of the reference circuit-breaker model in each gas. Figure 2 shows the results for an absolute blow gas pressure of $p_{abs} < 0.2$ MPa, which is a typical pressure range for medium voltage applications. The results show an increased thermal interruption capability of CO_2 up to 14% related to the fluorinated gas mixtures in this pressure range.

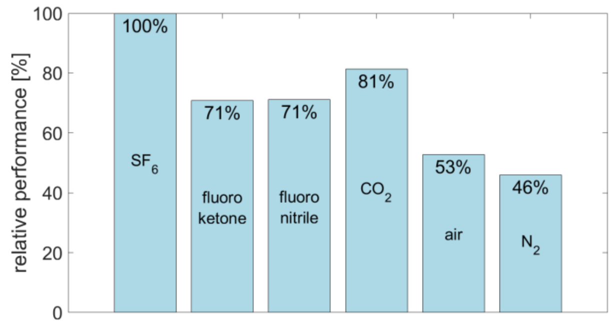

Figure 2. Comparison of the thermal arc interruption performance of different alternative gases and gas mixtures (CO_2 with fluoroketone and fluoronitrile) related to SF_6 for blow gas pressures < 0.2 MPa (typical medium voltage applications)

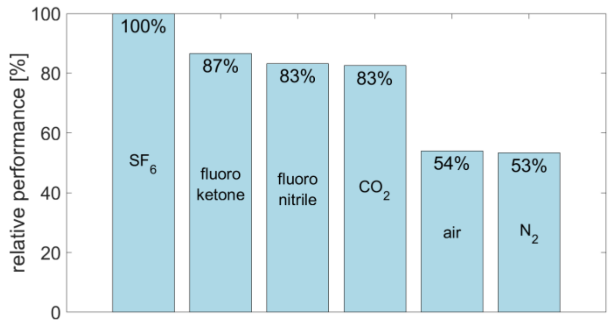

Figure 3. Comparison of the thermal arc interruption performance of different alternative gases and gas mixtures (CO_2 with fluoroketone and fluoronitrile) related to SF_6 for blow gas pressures > 0.5 MPa (typical high voltage applications)

Figure 3 exemplarily shows the experimental results for high voltage applications at an absolute blow gas pressure of $p_{abs} >$ 0.5 MPa. The thermal interruption capability of the fluorinated gas mixtures is in the range of 83%...87% compared to SF_6. CO_2 reaches a thermal interruption capability of 83% compared to SF_6. Overall, there is no significant increase in the thermal interruption capability achieved by adding the specific fluorinated components to the gas. Air and nitrogen show a substantially lower thermal interruption capability compared to SF_6, CO_2 or the fluorinated gas mixtures. The results of the investigation of the axial arc resistance distribution around the current zero crossing performed with the same reference circuit-breaker model support the assumption of the effectiveness of different cooling mechanisms depending on the applied quenching gas. The natural

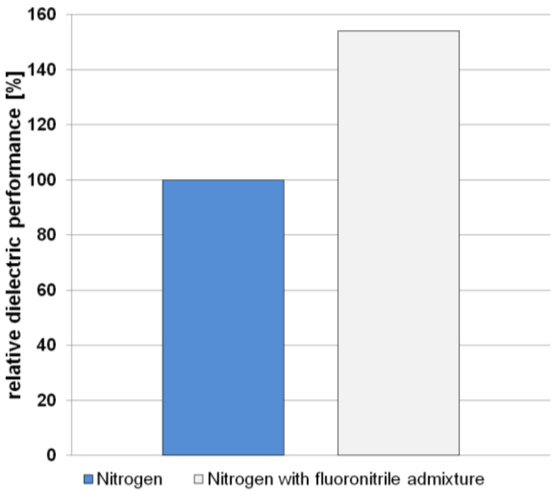

Figure 4. Comparison of the dielectric performance of nitrogen and nitrogen with fluoronitrile admixture in a sphere-sphere arrangement at gas pressures > 0.5 MPa (typical high voltage applications)

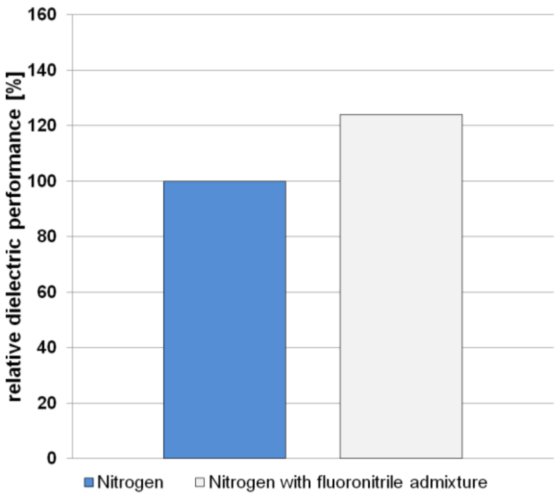

Figure 5. Comparison of the dielectric performance of nitrogen and nitrogen with fluoronitrile admixture in a sphere-plane arrangement at gas pressures > 0.5 MPa (typical high voltage applications)

gases show a high importance of convective cooling, while SF_6 as well as the fluorinated gas mixtures show an enhanced role of turbulent cooling. Moreover turbulences in the arc channel around the stagnation point in the blow gas supply layer (cf. figure 1) support the interruption of the current.

DIELECTRIC PERFORMANCE

As mentioned above, the admixture of fluorinated compounds to a natural carrier gas is one option to increase its dielectric performance. In figures 4 and 5 two exemplary measurement results of the relative dielectric performance of pure nitrogen and a fluoronitrile-nitrogen mixture under AC voltage stress are exemplarily depicted for a pressure of $p_{abs} > 0.5$ MPa (typical high voltage applications). From the results a strong dependency of the improvement of the dielectric strength on the geometry of the test object is observed. This effect becomes even more visible when changing from test arrangements (sphere-sphere or sphere-plane arrangements as shown in fig. 4 and 5) to real switchgear geometries for medium voltage as well as for high voltage applications. Thus the design of future switchgear with SF_6 gas-alternatives requires a detailed consideration of the gas and material properties. In this context it is also expected that a significant change of the design criteria, used for SF_6 switchgear for the last decades, could be necessary.

SAFETY, RELIABILITY AND LONG TERM STABILITY

In preceding investigations the decomposition of low GWP gas mixtures induced by partial discharges was investigated by applying pulsed dielectric barrier discharges [8]. For these investigations the degree of decomposition of the gases tested was below 5% emulating approx. 50 years of strong partial discharge activity. Nevertheless the analysis of the resulting decompositions products yields the occurrence of compounds with partially very high GWP (and partially high-toxic) in the gas mixture stressed by partial discharges (cf. table 2) [8]. Thus, the overall GWP of the filling gas of a gas-insulated switchgear filled with alternative fluorinated insulating gas mixtures might increase during its operational lifetime. This effect has to be considered when evaluating the environmental impact of leakage rates of equipment applying SF_6 gas-alternatives.

Table 2. Exemplary experimental results for decomposition product concentration of a nitrogen gas mixture with 3% C5-Perfluoroketone content after treatment with dielectric barrier discharges with $E_{spec} \approx 0.3$ Wh/Nl (from [8]).

Product	X (prod) [ppm]	Fraction of the decomposition product related to initial C_5-PFK concentration
CF_3-CF_3	138	0.46%
CF_3-CF_2-CF_3	167	0.56%
CF_2=CF-CF_3	37.5	0.28%

ENVIRONMENTAL AND HEALTH IMPACT

The assessment of the characteristics of possible SF_6 alternatives also includes the consideration of environmental, health and safety aspects based on experiences with SF_6 gained over the last decades [9]. Thus an evaluation of different criteria with regard to pure gases, gas mixtures as well as the separate constituents of these gas mixtures is mandatory. As specified by T&D Europe amongst others the following aspects have to be considered [9]:

- Global Warming Potential over 100 years
- Ozone depletion potential
- LC50 4h (50% lethal concentration) on animals
- TLV-TWA (threshold limit value - time weighted average) based on tests performed on animals
- CMR (carcinogenic, mutagenic and reprotoxic) classification
- Flammability
- Required protective equipment for gas handling
- Solubility in water
- Persistency and degradability (abiotic and biotic)
- Bioaccumulation (BCF)

For the multiplicity of SF_6 gas-alternatives recently discussed in research and development up to now partly only sparse information of the gases themselves as well as of possible by-products from arcing require further, much deeper assessment and intense investigations.

CONCLUSION

Figure 6 summarizes the different criteria discussed in this contribution. Considering low environmental and health impact as well as safety and reliability during operation and handling of the equipment, the natural gases air or nitrogen yield promising properties.

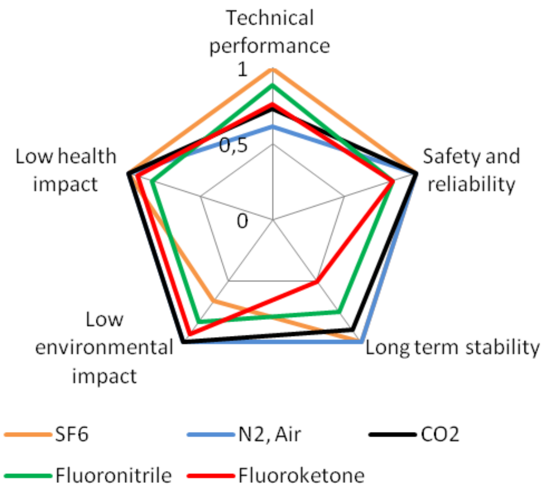

Figure 6. Holistic comparison of the evaluation criteria for SF_6 alternatives under consideration

Nevertheless the reduced technical performance, e.g. reduced dielectric strength of these possible SF_6 gas-alternatives, creates new challenges to be coped with by smart switchgear design. Comparing the recent approaches for targeted SF_6 gas-alternatives it becomes obvious, that a technically and economically optimized one-fits-all solution, as it is available by using SF_6 as arc quenching and insulating medium during the last decades up to today, cannot be achieved but that application-specific solutions (considering various and different gas compounds, gas mixtures, filling pressures, concentration of admixtures) are required.

Acknowledgments

The authors thank the Institute for High Voltage Technology of RWTH Aachen University and the High-Voltage Laboratories of the Technical University of Darmstadt for performing parts of the experimental investigations.

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