DIELECTRIC PROPERTIES OF GASES SUITABLE FOR SECONDARY MEDIUM VOLTAGE SWITCHGEAR

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ABSTRACT

SF_6 is the dominating technology for gas insulated switchgear due to its excellent dielectric, thermal and arc quenching properties. Unfortunately, SF_6 suffers from a very high global warming potential (GWP). Even though medium voltage switchgear is sealed for life with less than 0.1% emissions per year, the EU has specifically targeted SF_6 for replacement in medium voltage switchgear for secondary distribution.

The dielectric strength of alternative gases is of particular interest due to its impact on minimum electrode separation and external dimensions of the switchgear. A promising alternative with very low GWP and high dielectric strength is given by a mixture of perfluorinated ketones (PFK) and air or CO_2. In this paper, we present studies of the dielectric properties of a PFK/air mixture with a dew point below -25°C, making it suitable for secondary medium voltage switchgear. The withstand level of an optimized design is predicted for air and PFK/air using the streamer theory and compared with the results of full-scale tests of lightning impulse and power frequency withstand levels. The measured lightning impulse withstand level is found to be ~60% higher for the PFK/air mixture than for pure air. Finally, we show that switchgear designed for 12 kV rated voltage insulated with dry air can be scaled up to 24 kV rated voltage by replacing the dry air with the -25°C PFK/air mixture.

INTRODUCTION

Medium voltage (MV, 1- 72 kV) gas insulated switchgear and ring main units (RMU) are key components in the primary and secondary distribution network. In RMUs, a collection of switches is typically placed in a single, gas-filled compartment. The gas serves as a medium for electrical insulation, cooling and current interruption of load currents. SF_6 provides all these features in compact equipment and has dominated the power distribution industry for several decades. Unfortunately, SF_6 has a very high GWP of ~23,000 CO_2 equivalents.
MV switchgear is sealed for life with less than 0.1% emissions per year, but unwanted emissions can occur due to improper handling. The industry is therefore eager to find a suitable alternative. The EU has further targeted secondary MV switchgear specifically and aims to assess the situation by July 2020 [1]. If it is found that a viable alternative exist, a proposal will be made to restrict the use of SF_6 in these products.

The dielectric strength of alternative gases is of particular interest because it determines the minimum electrode separation and the external dimensions of the RMU. Backwards compatibility with existing installations is a strict requirement in RMU design and increasing the outer dimensions is therefore not an option. Dry air offers the lowest possible environmental impact at a very low cost, but has a limited dielectric strength. As recently demonstrated by Bjørtuft et.al [2,3], 12 kV ratings can be achieved with dry air alone, but higher ratings will require larger outer dimensions.

Several SF_6 alternatives with reduced GWP have been investigated over the years [4,5], including SF_6/N_2 mixtures [5], perfluorcarbons (PFC) [6], fluoroxiranes (FO) [7] and fluoronitriles [8]. Excluding SF_6/N_2 mixtures, the common drawback for these synthetic fluids is their high boiling point. In order to utilize them in switchgear with operating temperatures as low as -25°C, they would typically have to be mixed with a background gas, such as air or CO_2.

Another promising alternative that offers high dielectric strength and a very low GWP of 1 was recently presented by Mantilla et.al. [9]. The gas is a mixture of perfluorinated ketones (PFK) and technical air or CO_2. In this paper, we compare key properties of the above-mentioned SF_6 alternatives and present studies of the −25°C PFK/air mixture at 1.3 bar, suitable for secondary MV switchgear.

THEORY

Key properties of SF_6 alternatives

Estimations of key properties of air and SF_6 are presented in Table 1 together with a selection of the most promising non-toxic, non-flammable alternatives. These are the c-C_4F_8 perfluorcarbon (PFC) [6], the C_4F_8O fluoroxirane (FO) [7,8], the $(CF_3)_2CFCN$ fluoronitrile (FN) [8,10] and the $C_5F_{10}O$ perfluorketone (PFK) [9]. In addition to the pure gases, mixtures with air at a dew point of -25°C and total pressure of 1.3 bar (measured at +20°C) are considered, these being the relevant minimum operating parameters for secondary MV switchgear. A mixture with 25% SF_6 in air, having similar dielectric strength as the PFK/air mixture is included for comparison.

The maximum concentration of a gas *A* in a different background gas *B* is given by the saturation vapor pressure of gas *A* at the selected operating temperature. A vapor pressure curve is often determined experimentally over a temperature range for each gas, but estimates can also be made using the Clausius Clapeyron equation, as described by Devins [11]. For the purpose of comparison, we estimate the critical field strength (E_{cr}, a measure of dielectric strength) of a mixture (*A/B*) by a linear scaling of the critical field strengths of the pure gases *A* and *B*, i.e.

$$E_{cr}(A/B) = x \cdot E_{cr}(A) + (1 - x) \cdot E_{cr}(B) \qquad (1)$$

Here, *x* is the partial pressure fraction (molar fraction) of *A* in *A/B*. This is given by the saturation vapor pressure at the desired operating temperature (-25°C) divided by the total pressure (1.3 bar). Note that non-linear (synergy) effects are expected to increase the critical field strengths of gas mixtures [9]. These are not included in the estimated values in Table 1.

The GWP of the mixtures can be estimated with a similar approach. However, as described in the F-gas regulation [1], one should consider the mass fraction rather than molar fraction as the measure of concentration. Due to the large molar masses of many fluorinated molecules, this number can be very different from the corresponding molar fraction in a gas mixture with air.

In Table 1, one clearly sees that the critical field strengths of all the alternative gas mixtures drop well below that of pure SF_6. The FN/air mixture retains the highest critical field of all the mixtures, but at a remaining GWP of 1,723. The PFK/air mixture is reduced to ~50% of the critical field of SF_6, but with a very low GWP of less than 1. Note that synergy effects are not included and preliminary measurements indicate a higher E_{cr} for this mixture. The other mixtures have lower critical field strengths than FN/air and higher GWP.

Table 1. *Estimated critical field strength (E_{cr}), global warming potential (GWP), saturation vapor pressure at -25°C (Ps -25C) and molar mass (Mm) of air, SF_6, and alternative gases. Properties of mixtures with air with condensation points below -25°C at total pressure 1.3 bar (@20°C) are also included. The mixing ratios are defined by the total pressure and Ps-25C of the alternative gas.*

Gas	E_{cr} [kV/mm bar]	GWP [-]	Ps-25C [mbar]	Mm [g/mol]
Air [12]	2.7	0	-	29
SF_6 [12]	8.9	23 000	-	146
PFC [6]	11.6 a)	8 700	488 b)	200
FO [7,8]	14.2 a)	4 100	419	200
FN [8,10]	16.9 a)	2 300	400	195
PFK [9]	18.2 a)	1	135 c)	266
SF6/air	4.3 d)	14 522	1300	-
PFC/air	6.0	7 010	1300	-
FO/air	6.4	3 142	1300	-
FN/air	7.1	1 723	1300	-
PFK/air	4.3	< 1	1300	-

a) Linearly scaled relative to SF_6 from reported value
b) Estimated with Clausius Clapeyron equation [11]
c) Preliminary measurements for the present study
d) 25% SF_6 in Air, giving similar E_{cr} as the PFK/air mix.

Considering the PFK/air mixture as an SF_6 alternative in secondary MV switchgear has the clear advantage of reduced GWP, but a redesign will be required in order to maintain the withstand voltage levels of a design with the reduced dielectric strength of the gas mixture.

Dielectric design

Dielectric design of MV switchgear is mainly concerned with reducing the maximum electrical field stresses that occur under lightning impulse withstand (LI)- and power frequency withstand (PFW) test duties as defined in the IEC 62271-1 standard [13]. The electrical field distribution of a 3-D geometry can be found from a numerical solution of the Poisson equation using e.g., finite element-, boundary element- or other iterative methods [12, 14].

The withstand level of a switchgear typically depends on the maximum field strengths of a few hotspots in the design. These are points where the electrodes are located close together and their shape is constrained by e.g. functional requirements. The tip of a knife switch is a typical example, as the center knife has a limited thickness and the electrode separation is limited by the size of the bay and/or mechanical considerations. The field distribution of a 3-position disconnector and earthing switch (3DE) is shown in Figure 1a, clearly indicating the enhanced field strength (hotspot) at the tips of the knives.

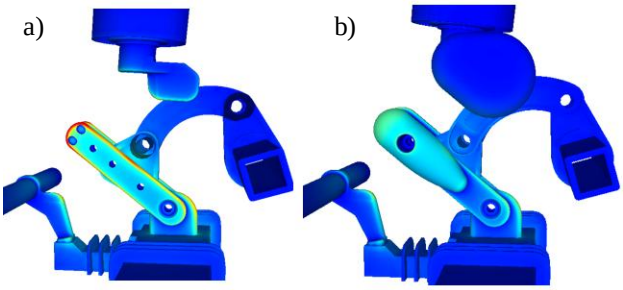

Figure 1. ***a)*** *Simulated electrical field distribution in a standard 3DE knife switch and* ***b)*** *optimized knife switch, redesigned with field controllers on the moving knives and static contact. For an applied voltage of 125 kV, the color scale ranges from 0 to 18 kV/mm, with a maximum field of 16.6 kV/mm in the original design and 10.0 kV/mm in the optimized design.*

A redesign to accommodate the reduced dielectric strength of SF_6 alternatives, such as air or PFK/air mixture must address these hotspots. A common technique is to attach field controllers or increase the radii of critical components to reduce the net field strength. The effect of adding such field controllers is shown in Figure 1b, where the maximum field strength is reduced by 40%.

Predicted withstand levels

The withstand level of a switchgear design can be predicted by combining calculations of electrical field stresses with the streamer criterion [14]. In short, one considers the critical voltage (inception voltage U_{inc}) required to induce a self-propagating avalanche of charged particles that bridges the electrode gap and induces a full discharge.

For gaseous insulation media, the net number of charged particles generated per unit length due to collisions between electrons and gas molecules is denoted the effective ionization coefficient. This varies with the gas density and strength of the electrical field and is a characteristic property of the gas.

The predicted withstand levels in this paper are based on the single lowest calculated inception voltage in the tested switchgear. The calculations are based on electrostatic field calculations using the boundary element method and the streamer criterion [14]. Published values for ionization coefficients were used for air and SF_6 [15]. The value for the streamer constant (K) was set to 9.15 for air and 10.5 for SF_6 [14]. Preliminary values for the ionization coefficient of PFK were obtained by fitting empirical data from breakdown measurements in a uniform field configuration. A streamer constant of 10.5 was also used for the PFK/air mixture.

EXPERIMENT

Two types of tests were performed to investigate the withstand levels of a MV switchgear design with different gases:

1. Lightning impulse withstand test (LI).
2. Short duration power frequency withstand test (PFW).

Rated withstand levels and definitions for both tests are given in IEC 62271-1 [13] and 60060-1 [16]. For the LI test, 1.2/50 µs impulses were applied in a sequence of 2 impulse applications at 80% peak value and 15 impulse applications at 100% peak value for each polarity. The test is defined as passed if less than 3 breakdowns occur in a series of 15. For the PFW test, an AC voltage was ramped manually to the full amplitude and maintained for 60 seconds. The test is passed if no breakdown occurs. In addition to the required LI and PFW levels given by IEC 62271-1 (LI_1 and PFW_1) for each rated voltage level (U_r), an increased test duty of 5% for LI (LI_2) and 10% for PFW (PFW_2) was included. An overview of the applied test duties for each gas is given in Table 2.

The test object was a commercially available SafeRing/SafePlus Air 12 kV CV unit from ABB. A single line diagram of the test object is shown in Figure 2. The unit was modified to include a detachable back-plate and PMMA top-plate to allow for a quick replacement of damaged components and photography of discharges during testing. Electrical field simulations were performed to ensure that these modifications did not affect the field distribution in the high-stress regions. The test duties described above were applied to all possible combinations of closed and open switches for each phase.

For example, for a single configuration and phase, all but one switch (disconnector, load break switch or circuit breaker) were kept closed and the high voltage was applied from one side, while the other was kept on grounded potential. This procedure ensures a systematic verification of the withstand level of the complete test object.

Table 2. *Test duties for the gases. The LI_1 peak value and PFW_1 rms value were chosen according to IEC 62271-1 to correspond to different rated voltages (Ur) for each gas. In addition, LI_2 and PFW_2 were applied to all configurations and LI_{max} to the single weakest configuration.*

	Ur kV	**LI_1** kV	**LI_2** kV	**LI_{max}** kV	**PFW_1** kV	**PFW_2** kV
Air	12	75	79	89	28	31
PFK/air	24	125	131	146	50	55

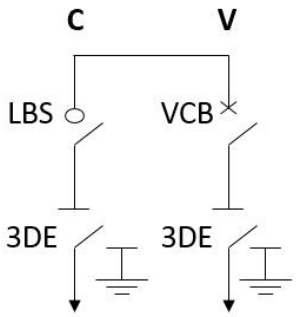

Figure 2. *Single line diagram of the test object (SafeRing Air 12 kV, CV). Panel C comprises a load break switch (LBS) based on vacuum technology and a 3-position disconnector and earthing switch (3DE). The V panel contains a vacuum circuit breaker and a 3DE switch. All switches are enclosed in a sealed tank, pressurized to 1.3 bar with the gas under investigation.*

Finally, the strength of the gases was investigated by further increasing the LI peak value in steps of 5 kV from the standard value (LI_2) until the test failed (LI_{max}). This was restricted to a single configuration corresponding to the weakest point in the design, which was predicted by simulations to be across the disconnector gap of the 3DE switch (see Figure 1). Potential breakdowns were predicted to occur from the tip of the switch to the fixed contacts or back wall (not shown). Technical air and a mixture of 10.4% (molar fraction) PFK in air (PFK/air) at total pressures of 1.3 bar (@20°C) were tested.

RESULTS AND DISCUSSION

The predicted streamer inception voltage levels (U_{inc}) for the test object with air and PFK/air at a total pressure of 1.3 bar are presented together with the experimentally determined withstand levels under LI and PFW test duties in Table 3. The predicted inception voltage in SF_6 is also presented, but was not explored with experiments. The general withstand levels that were systematically tested and passed for all configurations are denoted LI_{full} and PFW_{full}. The test duty with increased test voltages that was passed for the single weakest configuration is denoted LI_{single} .

The general withstand levels LI_{full} and PFW_{full} agree with the required test duties for three different rated voltages (see Table 2). As per design, the air insulated test object is seen to pass the duties for 12 kV rated voltage with a 5% margin for LI and a 10% margin for PFW. Replacing air with the PFK/air mixture is found to raise the general insulation level to a minimum of 131 kV for LI and 55 kV for PFW. This corresponds to the required test duties for 24 kV rated voltage, with 5 and 10% margins for LI and PFW respectively.

Table 3. *Predicted streamer inception levels (U_{inc}) and experimentally determined withstand levels for LI and PFW test duties in air, PFK/air -25°C mixture and SF_6 at 1.3 bar. The LI_{full} and PFW_{full} were passed for all configurations, while LI_{single} was the maximum withstand level passed for the single weakest configuration (but not tested for the other configurations).*

	U_{inc} kV peak	LI_{full} kV peak	LI_{single} kV peak	PFW_{full} kV rms
Air	75.5	79	84	31
PFK/air	122.0	131	136	55
SF_6	184.3	-	-	-

The experimentally determined maximum LI withstand levels (LI_{single}) for air is consistent with the predicted streamer inception level (U_{inc}) within the expected uncertainties. Note that breakdown is expected only above the inception level. The difference between inception prediction and maximum withstand level in the experiments is 11.3% for air. For the PFK/air mixture the experimentally determined withstand level is greater than 136 kV, which is 11.5% higher than the predicted streamer inception value. These discrepancies are probably due to the uncertainties of the streamer inception estimates. From the perspective of dielectric design, a more precise description is desirable. This will be addressed in a separate study. Finally, note that the experimentally determined LI withstand of 136 kV (LI_{single}) for the PFK/air mixture is ~62% higher than that of pure air (84 kV).

The experimental results obtained in this study underline the dominating influence of SF_6 on switchgear design over the past decades. Due to the very high dielectric strength, SF_6 based designs can actually allow an electric field distribution that is not optimized. This gives the benefit of increased flexibility with regard to e.g., reduced costs and standardization of parts. On the other hand, this also demonstrates that there is a lot to be gained from critically re-investigating existing designs.

In the case of the simple 3DE knife switch explored in this study, a net reduction of 40% in maximum field strength is achieved by introducing two pairs of relatively inexpensive field controllers. This further opens the way for utilizing a low-GWP insulating medium with a reduced dielectric strength compared to SF_6. For the design explored in this study, this makes it possible to provide a completely SF_6 free RMU for 24 kV rated voltage. Even at a minimum operating temperature of -25°C and pressure of 1.3 bar (@20°C) there is no need to increase the outer dimensions of the RMU.

CONCLUSION

Dielectric properties of a mixture of $C_5F_{10}O$ perfluoroketone (PFK) and air suitable for the minimum operating conditions in secondary medium voltage switchgear (-25°C and 1.3 bar @20°C) have been compared with air in a typical switchgear design with standardized tests of lightning impulse withstand and power frequency withstand levels. The reduced dielectric strength of this gas mixture can be balanced by optimization of the electrical field distribution of critical components in the switchgear. Replacing dry air with a PFK/air mixture in a commercially available switchgear rated for 12 kV is shown to increase the withstand level to that required for 24 kV rated voltage.

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