A Comparative Study on the Breakdown Characteristics of SF6 and 20% C3F7CN / 80% CO2 Gas Mixture in a Coaxial Configuration

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A Comparative Study on the Breakdown Characteristics of SF_6 and 20% C_3F_7CN / 80% CO_2 Gas Mixture in a Coaxial Configuration

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***Abstract*- Gas Insulated Lines (GIL) are considered an attractive alternative technology to overhead lines for transmission of high power over long distances. However, a key drawback is the use of sulphur hexafluoride (SF_6) as the main dielectric medium. SF_6 is listed as a greenhouse gas with a Global Warming Potential (GWP) of 23,500 times higher than CO_2. As SF_6 is widely used in the power industry, there are increasing research activities to find a cost-effective and technically viable alternative candidate with significantly lower environmental impact. This paper investigates the feasibility of replacing SF_6 in high voltage equipment with a more environmentally friendly gas named C_3F_7CN. A reduced-scale coaxial prototype was developed which replicates the quasi-uniform electric fields as found in a full-scale GIL. The test samples were subjected to standard lightning impulse (1.2/50 µs) of both polarities. The results have shown that the mixture of 20% C_3F_7CN / 80% CO_2 can reach a dielectric strength equivalent to 100% SF_6 gas. In coaxial configurations, the positive lightning impulse breakdown voltage is in general higher than the negative polarity, especially at higher pressures. In conclusion, C_3F_7CN mixtures can be a potential candidate of replacing SF_6 for insulation applications such as gas insulated lines and busbars which is an encouraging step towards a more environmentally friendly future transmission network.**

I. INTRODUCTION

Sulphur hexafluoride (SF_6) is widely used in gas insulated switchgear (GIS), lines (GIL) and busbars (GIB). Although SF_6 is an ideal gas for insulation and arc-quenching purposes, its high environmental impact is a huge concern when it leaks into the atmosphere. The urgency in finding a suitable replacement is reflected by the recent EU F-gas regulation 2014 [1], since the use of SF_6 has been restricted in some applications. However, SF_6 is still widely used in the power industry as there is no readily available one-for-one replacement candidate. The initiative to replace SF_6 in high voltage equipment applications within the power industry has been growing over the past few years and C_3F_7CN gas is considered as one of the potential candidates.

C_3F_7CN, commercially known as Novec^{TM} 4710, is an odorless, colorless and non-flammable gas which belongs to the family of fluoronitrile gases [2]. It shares similar physical and chemical properties to SF_6 such as being highly electronegative, chemically inert and non-ozone depleting. In its pure form, it has double the dielectric strength of SF_6 with more desirable environmental properties [2]. In addition, the short atmospheric lifetime of C_3F_7CN gas allows it to decompose within 30 years [3]. The main drawback of this gas is its high boiling point (-4.7°C) which makes it necessary to mix it with a carrier gas such as CO_2. Previous studies [3][4] have shown that a mixture of CO_2 with 20% C_3F_7CN content has an equivalent dielectric strength to pure SF_6 under disk and sphere-sphere electrode configurations. Therefore, this specific mixture was chosen to be investigated in this paper.

The research aim is to examine the differences in the breakdown characteristics of 100% SF_6 and the 20% C_3F_7CN / 80% CO_2 gas mixture using a coaxial test configuration. A reduced-scale coaxial prototype replicating the electric field distribution in gas insulated lines/busbars was developed to test both gases in quasi-uniform electric fields. Breakdown tests were conducted using the standard lightning impulse (1.2/50 µs) of both polarities. The pressure and polarity effects on the breakdown voltage are compared between SF_6 and the 20% C_3F_7CN / 80% CO_2 mixture.

II. ENVIRONMENTAL IMPACT AND TOXICITY PROFILE

C_3F_7CN has a GWP of 2,100 [2] in its pure form but this reduces when the gas is used in low concentrations as part of a mixture. Fig. 1 shows the calculated GWP values based on the reduced density of the gas mixture. As anticipated, it shows that the GWP of a mixture decreases with lower C_3F_7CN concentrations. The mixture investigated in this paper has a 20% C_3F_7CN content with a GWP of ≈1,100, which represents a 95% reduction of SF_6 [5].

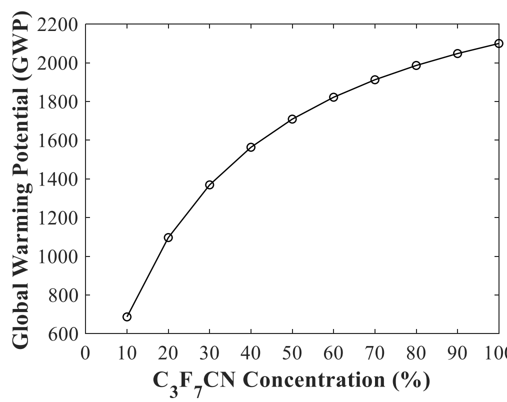

Fig. 1. Calculated GWP in relation to C_3F_7CN concentration in a mixture.

The toxicity profile of C_3F_7CN has been addressed by previous studies where they report that its 4-hour LC_{50} (lethal concentration at 50% mortality) is between 10,000 ppmv and 15,000 ppmv [3]. This value, just like the GWP, varies when using C_3F_7CN as part of a mixture and according to CLP regulation 1272/2008 it is categorized as a practically non-toxic gas [6].

III. Experimental Setup and Procedure

A. Experimental Setup

The experimental circuit diagram and setup are shown in Fig. 2 and 3(a) respectively. A stainless-steel pressure vessel that can go up to 10 bar (abs) was fabricated for the experimental investigation, as shown in Fig. 3(b). The pressure vessel has a SF_6 bushing which can withstand 325 kV AC and 750 kV lightning impulse voltages. A 2 MV Haefely Marx impulse generator was used for generating the standard lightning impulse (1.2/50 μs). Prior to any gas filling, the pressure vessel was filled with CO_2 for an extended period to purge the impurity and absorb any residual moisture. The pressure chamber was then vacuumed down to 1 mbar and filled with the desired gas up to the chosen test pressure. For the C_3F_7CN/CO_2 gas mixture, the gas was left in the pressure vessel for an extended period for the mixture to become homogeneous before any testing.

B. Experimental Procedure

The up-and-down procedure was used in accordance to BS EN 60060-1 [7] and the statistical analysis for determining the 50% breakdown voltage, U_{50}, was carried out with the same method as described in [8]. A set of 30 impulses was used for the up-and-down procedure with a time interval of 2 minutes between each impulse.

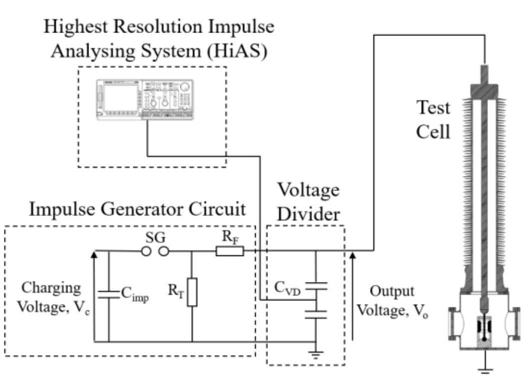

Fig. 2. Experimental test circuit.

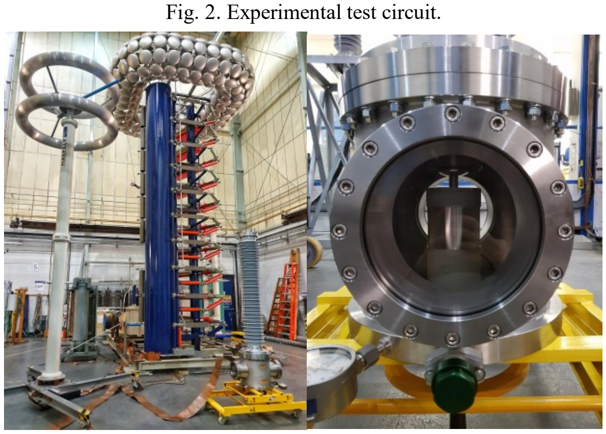

Fig. 3. (a) Experimental setup and (b) pressure vessel.

IV. Reduced-Scale Prototype

A. Methodology and Simulation

In coaxial configurations, there is a trade-off between the field uniformity and the gap spacing, 'g', from the high voltage conductor to the grounded enclosure. It is well established that there is an optimal ratio between the design parameters shown in Fig. 4, which results in the lowest electric field intensity applied on the insulation [9]. The optimal ratio is $R_b/R_a = e$ or $\ln(R_b/R_a) = 1$.

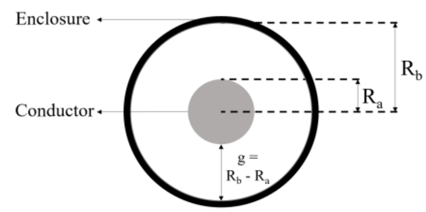

Fig. 4. Coaxial electrode design parameters.

Electric field computations were carried out using COMSOL 5.3 software to validate this theory and develop the optimized design for the coaxial electrode used in this paper. Fig. 5 shows how the conductor radius affects E_{max} and the field utilization factor of a coaxial arrangement with a 30 mm inner enclosure diameter. As shown in Fig. 5, using a conductor radius (R_a) that exceeds the optimal ratio, the field becomes more uniform. However, as g becomes smaller the electric field intensity increases. Vice versa, with a conductor radius smaller than the optimal ratio, g increases but the electric field becomes more divergent, which results in an increased electric field stress on the conductor surface. As anticipated from the theory [9], the coaxial design that has the lowest point on the E_{max} curve shown in Fig. 5 and therefore most likely to have the maximum breakdown voltage is when the ratio of inner enclosure (R_b) to outer conductor radius (R_a) is almost equal to ≈3.

B. Geometric Dimensions of Coaxial Electrodes

Fig. 6(a) shows the dimensions of the electrode fabricated for testing with a ratio of 3 for the inner enclosure to the outer

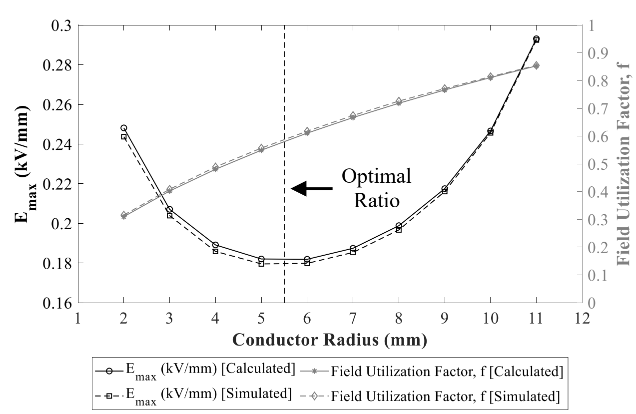

Fig. 5. E_{max} (kV/mm) and field utilization factor of coaxial configuration against conductor radius (mm).

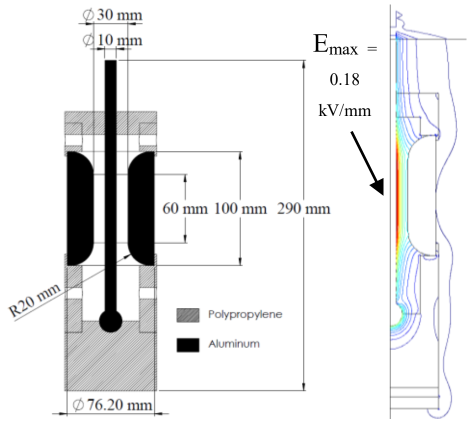

Fig. 6. (a) Reduced-scale prototype dimensions (b) E_{max} (kV/mm) location.

conductor. The conductor and enclosure are both made of aluminum with a mirror-finish and an average surface roughness of 0.2 μm. Polypropylene insulators are used to center the conductor and provide sufficient clearance from the ground. Simulation was performed to ensure all the clearances are sufficient and the maximum electric field location is around the central region of the conductor, as illustrated in Fig. 6(b). This was achieved by keeping a safe distance from the bottom of the pressure vessel, terminating the conductor with a sphere and rounding the edges of the enclosure. These precautions maximize the likelihood of having breakdowns in the central region which is the area of interest for small-scale coaxial electrodes.

V. Experimental Results and Discussion

A. Breakdown Characteristics

Fig. 7 shows that the breakdown trends of SF_6 and 20% C_3F_7CN / 80% CO_2 gas mixture behave in a similar way under positive lightning impulse, i.e. breakdown voltage increases linearly with pressure. As shown in Fig. 7, the C_3F_7CN/CO_2 gas mixture has a breakdown voltage almost equivalent to SF_6. The largest difference between the two gases is at 3 bar (abs) where SF_6 is around 19 kV (11%) higher than the C_3F_7CN/CO_2 gas mixture.

Fig. 8 compares the breakdown voltage of the two gases under negative lightning impulse. Again, breakdown voltage

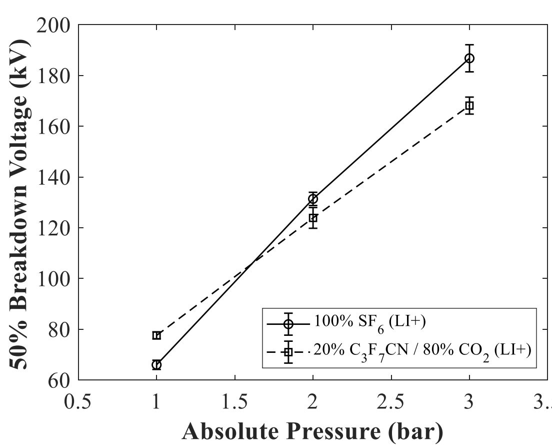

Fig. 7. U_{50} as a function of absolute pressure in coaxial electrode configuration for SF_6 and 20% C_3F_7CN / 80% CO_2 under positive lightning impulse (LI+).

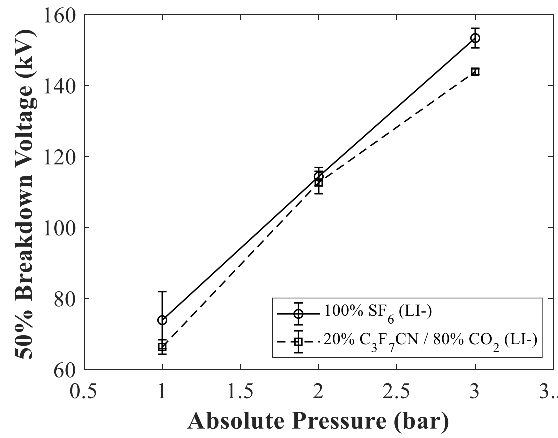

Fig. 8. U_{50} as a function of absolute pressure in coaxial electrode configuration for SF_6 and 20% C_3F_7CN / 80% CO_2 under negative lightning impulse (LI-).

increases linearly with pressure. It shows that under negative lightning impulse the difference between SF_6 and the C_3F_7CN/CO_2 gas mixture is less than it is under the positive polarity. The lowest difference between the two values is at 2 bar (abs) where SF_6 is just 2 kV (1.5%) higher than C_3F_7CN/CO_2.

As shown in Fig. 7 and 8, the results of this paper come into good agreement with previous investigations [3][4] where they tested the breakdown characteristics of similar gas mixtures using disk and sphere-sphere electrode geometries.

B. *Pressure Reduced Breakdown Field Strength $(E_b/p)_{max}$*

The pressure reduced breakdown field strength $(E_b/p)_{max}$ is calculated using (1) by assuming that the breakdown field strength of the coaxial electrode is given with the breakdown voltage value (U_b) where $U_b = U_{50}$. Fig. 9 shows that $(E_b/p)_{max}$ reduces as pressure increases and only the 3 bar, negative polarity value of the C_3F_7CN/CO_2 mixture falls slightly below the $(E/p)_{crit}$ value of SF_6 gas. The $(E/p)_{crit}$ value is where the attachment coefficient (η) of an electronegative gas is equal to

$$\left({}^{E_b}/_{p}\right)_{max} = \frac{U_{50}}{R_a \cdot \ln\left(\frac{R_b}{R_a}\right) \cdot p} (kV/mm \cdot bar) \quad (1)$$

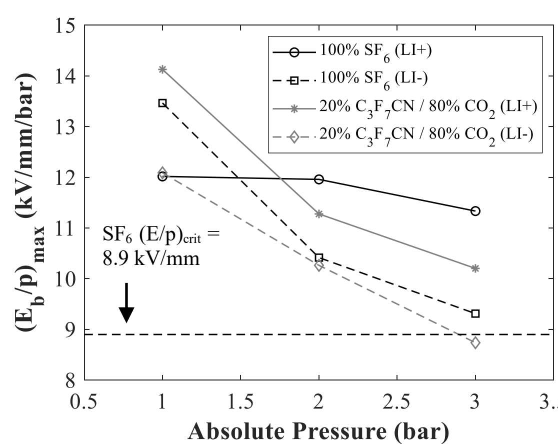

Fig. 9. Pressure reduced breakdown field strength $(E_b/p)_{max}$ as a function of pressure for SF_6 and 20% C_3F_7CN / 80% CO_2 in coaxial electrode configuration under lightning impulse waveform (LI).

the ionization coefficient (α) [α=η] and discharge growth is not likely to occur at this value. An electric field higher than this critical point [$E/p > (E/p)_{crit}$] brings an inbalance between α and η ($\alpha > \eta$) which leads to cumulative ionisation and most likely a breakdown. In contrast, electric fields lower than this value [$E/p < (E/p)_{crit}$] are not likely to lead to a breakdown. Fig. 9 shows that $(E/p)_{crit}$ of 20% C_3F_7CN / 80% CO_2 might be slightly lower, small difference, than pure SF_6 which has to be accounted when designing GIL/GIB for a new gas candidate.

C. *Polarity Effect under Lightning Impulse*

Fig. 10 compares SF_6 and 20% C_3F_7CN / 80% CO_2 gas mixture under lightning impulse of both polarities. As seen from Fig. 10, negative polarity tends to have a lower breakdown voltage than the positive. The distinction in breakdown voltage due to polarity becomes larger as the pressure increases. This is shown in Fig. 10 where the difference between positive and negative breakdown voltages for SF_6 increases from 17 kV to 33 kV from 2 bar to 3 bar, respectively. The same behaviour is noticed for C_3F_7CN/CO_2 mixture where the difference between positive and negative polarities grows from 11 kV at 2 bar to around 24 kV at 3 bar.

Fig. 11 compares 20% C_3F_7CN / 80% CO_2 to 30% CF_3I / 70% CO_2 gas mixture which was investigated in [10] using a similar dimensioned coaxial model. The same difference in the breakdown voltage due to lightning impulse polarity was found in [10]. This suggests that the polarity effect is not occurring because of different gases but because of the specific electric field type tested. The different gas, however, does look to change the magnitude of the difference as it can be seen from Fig. 11 that the distinction between positive and negative polarities for CF_3I/CO_2 is much more evident than the C_3F_7CN/CO_2 gas mixture.

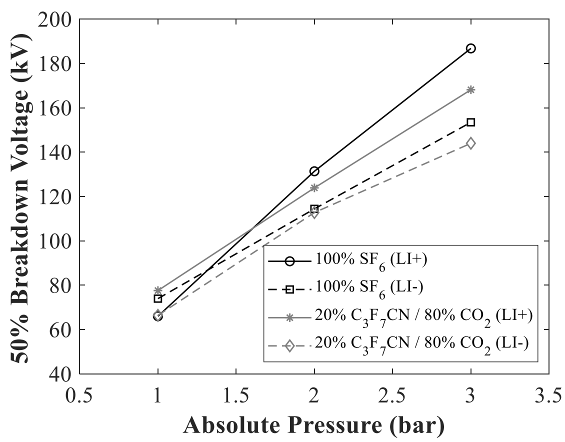

Fig. 10. U_{50} as a function of absolute pressure in coaxial electrodes for SF_6 and 20% C_3F_7CN / 80% CO_2 under lightning impulse.

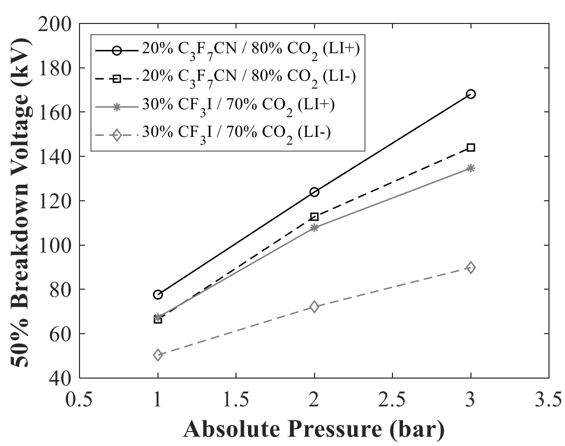

Fig. 11. U_{50} as a function of absolute pressure in coaxial electrodes for 20% C_3F_7CN / 80% CO_2 and 30% CF_3I / 70% CO_2 [10] under lightning impulse.

VI. Conclusion

The results of this paper show that a mixture of buffer gas with 20% C_3F_7CN content can be a promising candidate to replace SF_6 in high voltage applications. Using a quasi-uniform coaxial electrode configuration, the 20% C_3F_7CN / 80% CO_2 mixture has demonstrated to have a breakdown voltage comparable to pure SF_6, especially under negative lightning impulse polarity. Additionally, the breakdown voltage of both gases rises with increasing pressure with a similar rate of change.

This paper has also shown that negative polarity breakdown voltage tends to be lower than positive using this electrode configuration. This indicates that for gas insulated equipment with a coaxial geometry, the negative polarity is more critical in the design consideration.

Acknowledgment

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